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USE OF STEEL SLAGS IN AUTOMOBILE ROAD CONSTRUCTION

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Abstract. Building and, especially, reconstruction and repairs of highways, call for the development of stone materials manufacturing industry. Increasing need for stone materials may be satisfied by a wide use of industrial waste and secondary resources. In road building, slag of ferrous and nonferrous metallurgy is one of the most popular wastes which are increasingly widespread with every year. Such slag is a valuable raw material for preparation of macadam materials and mineral binders serving as a base for asphalt concrete mixtures and manufacturing of cement emulsions, which are widely used in road paving. The research focused on the use of different types of slag in road construction in Ukraine. Possibilities of using crushed rock and sand as recrement slag of different production for preparation of asphalt concrete and cement mixtures to be used for road-base was studied, as well as the use of slag materials for construction of lower category roads. In the given work, the opportunity to recycle electric furnace steel-smelting slag for preparation of asphalt concrete mixtures was defined.

Keywords: automobile road, construction, slag, asphalt concrete, mixture.

1. Introduction

As a constituent part of the national infrastructure, transport has to satisfy human and economic needs in terms of freight transportation and passenger carriage. The transport sector is the underpinning element of supply chains of all industries. Transport services are used by all economic and non-productive activity sectors without any exception.

Development of the transport system is a positive factor for social and economic development of a country. Presently, economic development is hardly possible without an efficient transport system (providing both local and international services). Elements of the transport system and their interaction are described by Sivilevičius (2011).

Sustainable functionality of the transport system is not possible without the following three key components:

- traffic (or freight) participants;
- vehicles;
- transport infrastructure (roads and terminals).

Traffic safety largely depends on vehicles, traffic participants and road infrastructure (Lazda, Smirnovs 2011; Wang *et al.* 2011; Dargužis *et al.* 2011; Sapragonas, Makaras 2011; Zariņš 2011; Keršys *et al.* 2011; Sapragonas, Dargužis 2011; Discetti 2010; Černiauskas *et al.* 2010; Haritonovs *et al.* 2010; Prentkovskis *et al.* 2010; Antov *et al.* 2009; Sokolovskij *et al.* 2007; Pečeliūnas, Prentkovskis 2006; Ibitoye *et al.* 2006, etc.).

As mentioned above, the transport system is inconceivable without a properly developed road network (Dell'Acqua, Russo 2011; Miandoabchi, Farahani 2011; Sohn 2011; Gintalas 2010; Santos *et al.* 2010; Jia *et al.* 2009, etc.) with high-quality coverings (Sivilevičius *et al.* 2011; Sivilevičius 2011; Sivilevičius, Vislavičius 2008, etc.), which deteriorate over time and must be maintained using properly selected technologies and materials (Čygas *et al.* 2011; Mučinis *et al.* 2009; Sivilevičius, Šukevičius 2007, etc.).

Building and, especially, reconstruction and repairs of highways call for the development of stone materials manufacturing industry.

Increasing need for stone materials may be satisfied by a wide use of industrial waste and secondary resources. In road building, slag of ferrous and nonferrous metallurgy is one of the most popular wastes which are increasingly widespread with every year.

Accumulation of a considerable quantity of secondary materials in the form of slag and the necessity to utilise this slag resulted in a number of works seeking for possibilities to use such slag for road construction.

Due to certain properties (chemical, mineralogical structure and frost resistance), slag is a valuable raw material for preparation of macadam materials and mineral binders serving as a base for asphalt concrete mixtures and manufacturing of cement emulsions, which are widely used in road paving.

As cement, crushed materials and mineral powder require considerable material and energy resources at production, use of slag as replacement material will result in considerable reduction in fuel, electric power and manpower costs. In general, the cost price of road-building materials manufactured from slag is 2 times lower in comparison to similar products manufactured from natural rock materials.

Thus, the necessity and urgency for slag recycling in the area of road construction involving considerable materials consumption is beyond question.

2. Literature Review

The problem of utilising (or using) steel (or other metal) slag as an aggregate in asphalt mixtures or for road construction has been investigated by researchers of various countries for many years now. A survey of some papers, dealing with the mentioned problem directly or in-directly, is provided below.

A research carried out in the USA by Hunt and Boyle (2000) described that in 1994, steel slag test and control sections were constructed in Oregon to evaluate the use of steel slag in hot mix asphalt concrete (HMAC). The research covers the construction and five-year performance of a pavement constructed with 30% steel slag. Asphalt concrete can be produced and the pavement constructed readily when crushed steel slag is used as a portion of the aggregate. If the unit cost of steel slag modified mixes is the same as conventional dense graded mixes, overall project costs may increase because of the decrease in coverage by the heavier steel slag mix. For the test section of HMAC constructed with 30% steel slag, the coverage was 15% less than a conventional 'B' mix. Reported increased resistance to rutting and improved skid resistance was not measured during the five years the pavements have been monitored. The differences between the two sections may not be measurable because only 30% steel slag was used in the test mix and the slag was finer than the conventional ½- to ¼-inch (12.7÷6.3 mm) material it replaced. To date, both the control and test sections are performing satisfactorily.

Another research carried out in Turkey by Ahmedzade and Sengoz (2009) presents the impact of steel slag as a coarse aggregate on the properties of hot mix asphalt. Four different asphalt mixtures containing two types of asphalt cement (AC-5 and AC-10) and coarse aggregate (limestone and steel slag) were used to prepare Marshall specimens and to determine the optimum bitumen content. Mechanical properties of all mixtures were evaluated by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength tests. The electrical sensitivity of the specimens was also investigated in accordance with ASTM D257-91. It was observed that steel slag used as a coarse aggregate improved the mechanical properties of asphalt mixtures. Moreover, volume resistivity values demonstrated that the electrical conductivity of steel slag mixtures was better than that of limestone mixtures.

A research carried out by a group of Slovenian and Croatian scientists (Sofilić *et al.* 2011) aimed to explore the feasibility of utilising steel slag as aggregates in asphalt mixtures. Characterisation of electric arc furnace slag was carried out through examination of its physical and chemical properties with a special emphasis on chemical and structural characteristics. Optical microscopy, x-ray diffraction, scanning electron microscopy, energy dispersive spectrometry and γ-spectrometric analysis were employed to study the texture, morphology and composition of steel slag. Volume properties of steel slag were also evaluated as compared to those of natural aggregates. For this purpose, the specimens of electric arc furnace slag were taken from the regular production processes in Croatian steel mill. The results which were obtained by testing geometric, physical-mechanic properties, as well as the properties of duration on the specimen of electric furnace steel slag of Croatian steel mill, when compared to steel slag properties of other steel producers (steel mills in Slovenia) and with properties of natural aggregates, have satisfied the conditions for manufacturing mixtures of the tested steel slag and natural stone, which can be used in asphalt production. In comparison to the natural aggregates, which are used in asphalt mixtures on highways and roads with heavy traffic, the examined steel slag has equally good physical and mechanical properties, while it is significantly better when it comes to resistance to polishing. Special attention has been given to the free CaO and free MgO, which can cause volume instability, thus limiting the use of steel slag in road construction.

A research carried out by Jordanian researchers (Asi *et al.* 2007) was intended to study the effectiveness of using steel slag aggregate in improving the engineering properties of locally produced asphalt concrete mixtures. There are three major steel-manufacturing factories in Jordan. All of their by-product – steel slag – is dumped randomly in open areas, causing many environmental hazards. The research started by evaluating the toxicity and chemical as well as physical properties of the steel slag. Then 0%, 25%, 50%, 75%, and 100% of the limestone coarse aggregate in the asphalt concrete mixtures was replaced by the steel slag aggregate. The effectiveness of the steel slag aggregate was judged by the improvement in indirect tensile strength, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance of the asphalt concrete samples. It was found that replacing up to 75% of the limestone coarse aggregate by SSA improved the mechanical properties of the asphalt concrete mixtures. The results also showed that the 25% replacement was the optimal replacement level.

In a research, which was carried out by American and Australian researchers (Wang *et al.* 2011), air-cooled nickel slag was evaluated for highway construction applications as an aggregate in hot-mix asphalt. The air-cooled nickel slag is a liquid co-product of nickel production that is solidified under ambient conditions. The laboratory evaluation programme, which was carried out to determine the characteristics of the air-cooled nickel slag, included testing of physical and mechanical properties, petrographic examinations, and hot-mix asphalt mixture designs. Accelerated laboratory testing was completed on the mixtures by using an asphalt pavement analyser to assess their performance characteristics. Additional testing included autoclave disruption tests for free lime and free magnesia, chemical and mineralogical analyses, polished stone value, and aggregate abrasion value. This study indicated that suitably processed nickel slag was environmentally, mineralogically, and physically stable. From the accelerated laboratory testing that was completed, it was concluded that the air-cooled nickel slag was suitable for use as coarse and fine aggregates in hot-mix asphalt. The research also presents the use of nickel slag in highway construction.

A research carried out by Omani scientists (Hassan, Al-Jabri 2011) reports a laboratory study investigating the use of granulated copper slag as a fine aggregate in hot-mix asphalt concrete. Marshall-mix design was performed on different blends of aggregate containing up to 40% copper slag. The dynamic modulus E^* test, as a primary material property input in the Mechanistic-Empirical Pavement Design Guide (ME-PDG), was conducted at different frequencies (0.1 to 16 Hz) and temperatures (25 to 60°C). E^* master curves and shift factors were developed for the control and slag mixes. The developed curves were compared with the Witczak predictive E^* model for Levels 2 and 3 of the ME-PDG. The results indicated strength reduction as slag content increases in the mixtures compared to the control mixture. The developed master curves and shift factors were compared with the Witczak predictive model. The results of stripping potential evaluated by the indirect tensile strength indicated a reduction in strength, but the tensile-strength ratio was superior to that of the control mixture. The results indicated a good potential for using copper slag as an aggregate in asphalt mixtures and provided the essential material characterisation for using the material in the ME-PDG method.

Summarising, steel slag aggregate is a 100% recycled and engineered product with a great potential as replacement to naturally occurring aggregates in road construction projects due to its physical and chemical properties. Most projects involving steel slag aggregate were incorporating this aggregate type in lower quality applications such as road-base rather than wearing course. However, steel slag aggregate was reported to exhibit higher porosity, superior adhesion with binder due to its surface structure and chemical content, and favourable shapes. Pore continuity in steel slag aggregate may improve water permeability in asphalt mixtures and improve skid resistance and aquaplaning, while the superior adhesion with bitumen may address the problem of stripping and moisture related damage on pavement. These characteristics may improve the performance of asphalt mixtures and road safety level. Carried out studies also suggested that asphalt mixtures incorporating steel slag aggregate may also improve rutting and cracking resistance. From the economic point of view, utilisation of steel slag as road construction aggregate may reduce the cost of extracting and processing naturally occurring aggregates. The steel industry may also reduce costs for treatment and disposing of a vast number of steel slag stockpiles. With increasing pavement lifespan, the maintenance cost might also reduce, thus providing more funds for other development projects. On its impact at preserving the environment, utilisation of steel slag aggregate in various ways may directly reduce both the dependence on naturally occurring aggregate and the number of raw material-extracting projects. On the other hand, incorporating steel slag in road construction projects may reduce areas required for landfilling (Li *et al.* 2012; Takahashi *et al.* 2011; Schram 2011; Haritonovs *et al.* 2010; Deniz *et al.* 2010; Shen *et al.* 2009; Shatnawi *et al.* 2008; Chaurand *et al.* 2007; Wu *et al.* 2007; Yeremin 2000; Kandhal, Hoffman 1997).

3. Experience of Ukraine and the Research by Authors

In the previous century, the *Draft State National Program* on slag recycling to be applied in road construction was developed in Ukraine.

Since then, slag wastes have been actively used in other industry branches; however the road construction sector had practically no access to these materials. Nowadays, the use of slag materials in road construction and road repair is gaining urgency again.

During the recent years, metallurgical and phosphoric slag has been increasingly used in road construction. Metallurgical slag is usually classified into ferrous (black) and nonferrous slag. Ferrous metallurgical slag is classified into blast-furnace, steel-smelting and ferroalloy types.

The slag structure is the principal factor defining properties of slag, depending on the chemical compound and the cooling mode.

In blast furnace, the crystallised part of slag is presented by more than twenty minerals, with their density exceeding 3 g/cm^3.

Electric steel-smelting slag has a dense micro-porphyric structure, and basically consists of silicates with admixtures of other minerals. Nonferrous metallurgical slag has a vitreous crystallised structure. Phosphoric slag is of a light grey colour. The slag mass is completely crystallised.

The research focused on the use of different types of slag in road construction in Ukraine.

Possibilities of using crushed rock and sand as recrement slag of different production for preparation of asphalt concrete and cement mixtures to be used for road-base was studied, as well as the use of slag materials for construction of lower category roads.

In the given work, the opportunity to recycle electric furnace steel-smelting slag for preparation of asphalt concrete mixtures was defined.

The research was conducted in the following direction:

- the entire mineral part of mixture was replaced with slag materials, i. e. crushed material of 5÷15 grading fraction;
- chipping of 0÷5 grading fraction and mineral powder;
- crushed material and chipping of granite material, slag mineral powder.

The tests were executed using asphalt concrete of type 'B', as the most widespread raw material used for arrangement of wearing surface of road pavement for highways of 1-st and 2-nd categories.

The research was conducted using the following scheme:

- definition of physical and mechanical properties and chemical compound of electric steel-smelting slag of both, crushed material and mineral powder;
- adhesion to bitumen;
- physical and mechanical properties of asphalt concrete.

4. Experimental Research

Experimental research was performed in the laboratory. Chemical compound of electric furnace steel-smelting slag is presented in Table 1 and Fig. 1.

On the basis of chemical compound data, lime factor (M_o), activity module (M_a) and quality factor (K), characterising the hydraulic activity of slag, are estimated:

$$M_o = \frac{CaO + MgO}{SiO_2 + Al_2O_3} = \frac{31.0 + 9.0}{28.3 + 12.0} = 0.99;$$

$$M_a = \frac{Al_2O_3}{SiO_2} = \frac{12.0}{28.3} = 0.42;$$

$$K = \frac{CaO + Al_2O_3 + MgO}{SiO_2} = \frac{31.0 + 12.0 + 9.0}{28.3} = 1.84.$$

Depending on the quality factor and content of compounds, all kinds of slag are divided into three grades, according to the Ukrainian Standard GOST 3476-74 (Table 2 and Fig. 2).

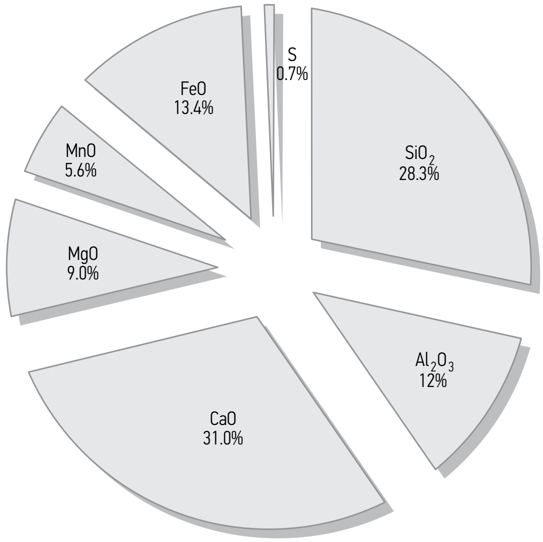

Fig. 1. Chemical compound of electric furnace steel-smelting slag

Table 2. Slag grades

Indicator	Grade		
	1-st	2-nd	3-rd
Quality factor K (Fig. 3), not less than	1.65	1.45	1.20
Content of Al_2O_3 [%], not less than	8.00	7.00	not normalised
Content of MgO [%], not more than	15.00	15.00	15.00
Content of TiO_2 [%], not more than	4.00	4.00	4.00
Content of MnO [%], not more than	2.00	4.00	4.00

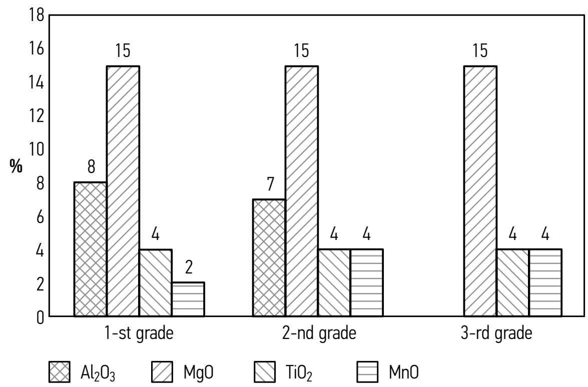

Fig. 2. Slag analysis depending on compounds inclusion, according to the Ukrainian Standard GOST 3476-74

Table 1. Chemical compound of electric furnace steel-smelting slag

Material	Chemical compound [%]							Lime factor, M_o
	SiO_2	Al_2O_3	CaO	MgO	MnO	FeO	S	
Electric furnace steel-smelting slag, dense fine-grained material of grey colour	28.3	12.0	31.0	9.0	5.6	13.4	0.7	1.1

Having analysed the data given in Tables 1 and 2, we may come to a conclusion, that for research purposes, basic electric steel-smelting slag (SiO_2 < 28.3%, M_o > 1) with a surface specific for igneous rocks, as well as a constant chemical compound, is agreeable. Neither decay products or metal granules nor other impurity substances were revealed. As a whole, the chemical compound of electric steel-smelting slag is similar to natural effusion stone materials of basaltic type. According to the quality factor (K = 1.84), the material corresponds to the 1-st grade, except for MnO content (5.6%) that is insignificantly increased.

According to the Departmental Building Rules VBN V.2.3-218-189:2005, electric steel-smelting slag suggested for the research represents a mixture of coarse-grained crushed material and is considered as a basic material, which can be used in road construction for arrangement of road pavement reinforced with both, inorganic (cement and lime) and organic (bitumen) binders.

At the use of electric steel-smelting slag with a high cementing capacity and ability to create a monolithic waterproof basis at compaction and humidifying, cement and lime react as activators.

Physical and mechanical properties of crushed material produced from electric steel-smelting slag are presented in Table 3. For comparison, parallel trials of granite crushed material, taken from the *Klesivsky Quarry* (Ukraine) were executed.

Having analysed the data presented in Table 3, we may come to a conclusion, that physical and mechanical properties (strength, crushability and water absorption) of crushed material produced from recrement slag are higher, than the ones of granite, and they meet the requirements of the Ukrainian Standard DSTU B V.2.7-74-98, which means that this material can be used for arrangement of pavement layers and for road-base manufacturing.

It is known that binding properties of slag produced by metallurgical plants are characterised and defined using the following indicators:

- hydraulicity – strength at compression of samples produced by tamping the mix of crushed slag and water;
- resistance to disintegration of slag mix samples in water;
- swelling of slag (mineral) powder;
- hardening time.

Definition of these indicators was carried out and the research results are presented in Table 4.

Having analysed the data presented in Table 4, we may come to a conclusion, that electric steel-smelting slag has sufficient binding properties, which will prolong working life and enhance strength of constructive layers of road pavements when applied.

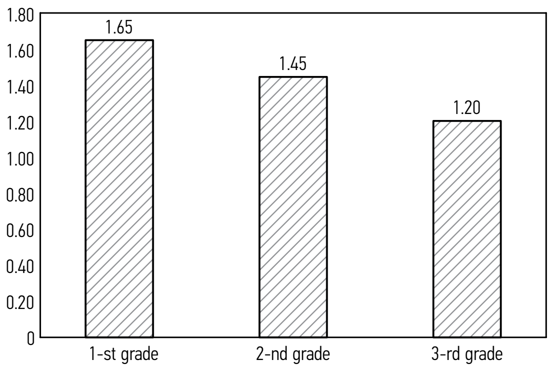

Fig. 3. Quality factor of slags by grades, according to the Ukrainian Standard GOST 3476-74

Table 4. Binding properties of electric steel-smelting slag

Indicators	Test results
Strength at compression [MPa]	8.5
Resistance to disintegration [%] Silicate steel-smelting slag Ferrous steel-smelting slag	 0.9 1.8
Swelling [%], not less than	58
Hardening time (the beginning of hardening), in minutes	14

Table 3. Physical and mechanical characteristics of crushed material produced from electric steel-smelting slag

Indicator	Crushed material produced from electric steel-smelting slag	Granite crushed material (*Klesivsky Quarry*)
Real density [g/cm^3]	3.45	4.20
Average density [g/cm^3]	3.84	4.35
Bulk density [kg/m^3]	1800.00	1850.00
Porosity [%]	5.40	7.50
Water absorption [%]	2.10	3.40
Grade according to frost resistance	High, F 150	High, F 150
Grade according to crushability	M 1200	M 1000
Hardness in 10-point scale [points]	6÷7	–
Grade according to abradability	High, ST-1	High, ST-1
Strength at compression in the cylinder [MPa]	7.40	5.40
Content of lamellar (hearth bottom) and needle-shaped grain	Cube-shaped group, 12	Cube-shaped group, 15
Clay content in clots	–	–

Due to the fact that crushed material and mineral powder produced from slag will be used for preparation of asphalt concrete mixtures, the research of organic binder (bitumen) adhesion properties was carried out.

The research results are presented in Table 5.

According to Table 5, it is obvious that high adhesion of a binder film is retained not at all crushed material surfaces (5 points).

It should also be noted that in case of granite crushed material, the indicator of adhesion is lower.

The procedure of defining physical and mechanical properties of mineral powder produced from slag was carried out according to the Ukrainian Standard DSTU B V.2.7-121-2003.

The research results are presented in Table 6 and Fig 4.

According to the Ukrainian Standard DSTU B V.2.7-121-2003, mineral powder produced from electric steel-smelting slag meets the requirements for powders of 1-st grade, as not activated.

Then, the research on physical and mechanical properties of asphalt concrete of types 'A' and 'B', of asphalt concrete (1-st grade and 2-nd grade) mixture was conducted:

- includes the entire mineral part of slag material (1-st grade);
- crushed material produced from slag, mineral powder produced from electric steel-smelting slag (2-nd grade).

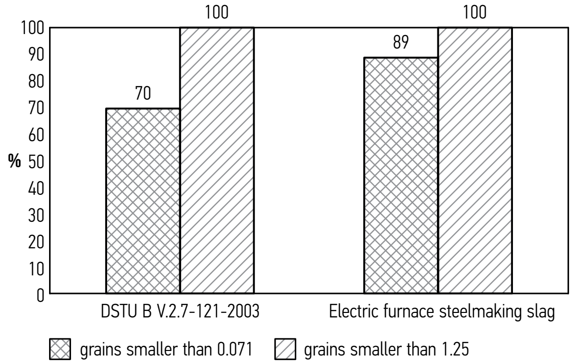

Fig. 4. Content of particles [% of mass] according to the Ukrainian Standard DSTU B V.2.7-119-2003

The research results are presented in Table 7 and Fig. 5.

The research results proved that the asphalt concrete mixture with its mineral part produced from slag is characterised by higher strength indicators but lower water saturation and swelling quality indicators.

Table 5. Definition of cohesion ability of the surface of crushed material produced from slag with bitumen binder (bitumen grade – BND 90/130)

Properties of slag grain surface	Mass of slag grain [g]	Mass of slag grain [g]		Properties of bitumen surface film of rock		Assessment of cohesion ability
		Crushed material with binder film	Including binder film after test	Integrity of film binder, [%] of mass	Integrity degree of binder film	
Thoroughly vitreous	104.2	106.5	106.0	48.5	Binder film remained on the crushed material surface over 50%, in some places the thickness reduced	Satisfactory (3 points)
50% of surface is vitreous	56.3	58.2	57.9	49.5	Binder film remained on the crushed material surface over 50%	Satisfactory (3 points)
Rough, partially vitreous	84.5	88.4	88.0	81.0	Binder film remained on the surface of crushed material	Perfectly (5 points)
Thoroughly rough	45.6	45.9	45.8	96.5	Binder film partially disintegrated from the crushed material surface	Perfectly (5 points)

Table 6. Physical and mechanical properties of mineral powder produced from electric steel-smelting slag

Indicators	Requirements according to the Ukrainian Standard DSTU B V.2.7-121-2003	Results obtained
Content of particles [% of mass], not less than grains smaller than 0.071 mm grains smaller than 1.25 mm	 70 100	 89 100
Porosity at compaction of 40 MPa, [% of volume], not more than	35.0	26.4
Swelling of samples produced of powder and bitumen mix [% of volume], not more than	2.5	1.8
Bitumen content indicator[g], not more than	65.0	59.0
Moisture content [% of mass], not more than	1.0	0.8
Density [g/cm^3]	–	2.74
Water repellency factor	–	0.96
Quantity of argillaceous admixture [%], not more than	5.0	4.9

Table 7. Physical and mechanical properties of asphalt concrete of the I and II compound

Asphalt concrete mixture	Average density [g/cm^3]	Porosity of mineral skeleton [% of volume]	Water saturation [% of volume]	Swelling [% of volume], not more than	Strength limit at compression [MPa], at temperatures			Water resistance factor
					50ºC, not less than	20ºC, not less than	0ºC, not more than	
1-st grade	2.44	14.2	2.8	0.3	0.9	3.8	9.6	0.98
2-nd grade	2.39	16.1	3.1	0.5	0.6	3.2	10.8	0.92
Requirements according to the Ukrainian Standard DSTU B V.2.7-119-2003	–	15÷19	1.5÷3.5	0.5	1.2	2.5	12.0	0.9

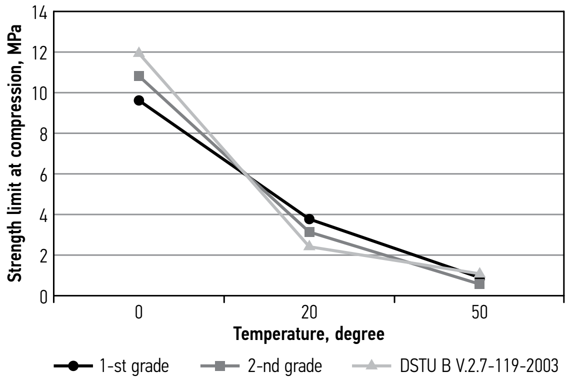

Fig. 5. Changes in compressive strength limit of asphalt concrete of 1-st grade and 2-nd grade, depending on temperature

According to the results of the research, the material may be recommended for preparation of asphalt concrete mixtures to be laid into the base courses of highways of the 1-st and 2-nd categories and for top layers of local roads of the 3-rd and 4-th categories.

5. Conclusions

1. The research showed that the electric furnace steel slag can be used as crushed rock aggregate and mineral powder in road structures for preparation of asphalt mixture. Sufficiently high hydraulic activity allows recommending its use as an inorganic binder with addition of portland cement and lime.
2. Crushed slag, compared with crushed granite, ensures better performance indicators pertaining to road structure layers. For this reason, increase in service life (especially during the first five years) is observed. Thus, due to the use of electric furnace steel slag, durability of road structures can be increased, their cost – significantly reduced, and the construction season – extended.

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