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ARTICLE

ECO–FRIENDLY HIGH–PERFORMANCE PAVEMENT MATERIALS

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ABSTRACT

Background: *Prolonging the service life of construction units allows reduces the consumption of natural resources; thus, building material that is both more durable than conventional ones and does not induce negative environmental impacts is eco–friendly. Considering road construction, the primary drawback of sulfur-extended asphalt concrete is the emission of toxic gases.* ***Methods:*** *We have performed the necessary measurement of the emission of toxic gases (with ANKAD 7664 Micro-06 analyzer) and examined the primary operational properties of sulfur-extended asphalt concrete (AASHTO TP 63 and AASHTO T 324 tests).* ***Results:*** *It is revealed that proposed complex admixture significantly reduces emission of toxic gases, especially the emission of hydrogen sulfide. Moreover, the proposed sulfur-based admixture increases resistance to rutting (in 1.3-3.7 times), compressive strength, splitting tensile strength and fatigue limit. The anomalous (negative) correlations between strain capacity, fatigue life and fracture toughness are also revealed; such correlations are beneficial for building material.* ***Conclusions:*** *In the present work we have proposed the complex modifier that addresses the primary drawback of sulfur-extended asphalt concrete; it is also shown that admixture of such modifier contributes the increase of most operational properties.*

KEY WORDS
sulfur–extended asphalt, green construction, high–performance pavement

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INTRODUCTION

The social concept of sustainability means living in such a way as to meet the needs of the present without compromising the ability of future generations [1]. Sustainability is about building a society in which a proper balance is created between economic, social and ecological aims [2]. The sustainability concept now became to appear on constant basis, especially in those areas of industry which are the most energy–intensive. The construction, obviously, is one of such areas.

The building material can be considered as eco–friendly if its energy, economic, and environmental performance are better than for traditional ones [1]. Prolonging the service life of buildings and construction units allows to safeguard the natural resources against depletion. Together with keeping the environmental impact at low level, usage of high–performance building materials is one of the ways to sustainable construction [3-6].

Due to the growth of load on automotive roads, modern construction industry needs efficient materials for pavements. Advantages of the concretes that are based on sulfur–extended asphalts (SEA) are the natural effects caused by physicochemical properties, availability and low cost of technical sulfur [7]. Because of numerous alterations in chemical and phase composition of bitumen, and also due to relatively intensive interaction at the phase interface, SEA–based pavements are characterized by improved operational properties. However, widespread use of ordinary SEA is not possible because of environmental impacts. The emission of hydrogen sulfide and sulfur dioxide takes place both during the concrete mix preparation and pavement production stages [7-10].

The goals of the present work are to address the primary SEA drawback and also to discuss the properties of SEA concretes that demonstrate the operational performance and durability of such materials.

MATERIALS AND METHODS

The emission of toxic gases was measured by ANKAD 7664 Micro-06 analyzer. During measurements, special procedures were used for keeping the evaporation area constant. Duration of measurements depends on production, transportation and placement conditions of the mix and should be at least one hour.

The specimens of SEA were prepared from gabbro–diabase chipping of fraction 5–20 mm (77% by mass in mineral part), granite screenings of fraction 0.315–5 mm (11% by mass in mineral part), diatomite powder of average particle size 7 um (12% by mass in mineral part), bitumen and sulfur modifier in form of pellets [Fig. 1]. The amount of sulfur in complex binder ranges from 0 to 40% by mass [Table 1].

Table 1: Formulae of SEA concrete specimens

Component	Mix #1	Mix #2	Mix #3	Mix #4
Bitumen, % above mineral part	5.50	4.87	4.49	4.05
Sulfur modifier, % above mineral part	0	1.37	2.21	3.18
Amount of sulfur in binder, %	0	20	30	40

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Fig. 1: Pellets of the SEA modifier.

Cylindrical specimens of diameter 150 mm and height 75 mm (AASHTO TP 63 test) and 65 mm (AASHTO T 324 test) were compacted for the tests.

To examine the resistance to rutting, we have performed two tests according to AASHTO TP 63 “Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer” and AASHTO T 324 “Hamburg Testing”. Modified APA asphalt pavement analyzer that allows to carry out both tests is used. The APA is a thermostatically controlled device designed to determine the properties of hot mix asphalt by applying repetitive linear loads to compacted test specimens through a loaded wheel [11].

The measurements of the mechanical properties were performed according to RU GOST 31015.

The examination of fatigue life and several other operational properties related to the resistance to dynamic loads were performed according to the EN 12697–24 “Bituminous mixtures. Test methods for hot mix asphalt. Resistance to fatigue,” and “Pavement Technology” (hereafter PT) methods. Both these methods are adequately representing the loads of the real traffic flow. In addition, fracture toughness (splitting tensile strength) was determined in accordance with RU GOST 12801–98.

The EN 12697–24 indirect tensile tests were carried out with Dynapave 78-B7130 servo-hydraulic dynamic testing system [12]. Cylindrical SEA concrete samples with diameter of 150 mm and height of 70 mm were tested at 20 ^{0}C. The samples were exposed to repetitive sinusoidal load [Fig. 2]; such load is causing tensile stress in the direction that is perpendicular to the load axis. The test completes at the moment of vertical crack growth. The fatigue limit is determined as the total number of load cycles that precede the destruction of the sample. Total horizontal deformation is also registered during the test.

The PT fatigue test method was designed by Pavement Technology, Inc to be performed by asphalt pavement analyzer [12][19][21]. The samples for the test are beams of 75 mm by 125 mm by 300 mm in size (during the test, three beams are simultaneously examined [Fig. 3]. After compaction, test specimens were aged for 120 hours at a temperature of 85 ^{0}C. The test itself consists of repetitive wheel tracking [Fig. 4]. The wheel load was 1113 N, test temperature was 20 ^{0}C. The test completes if at least one of the following conditions is met: some predefined number of cycles is reached; the beam breaks; beam deflection rate of change in vertical direction is above 1.0 mm after 10 cycles.

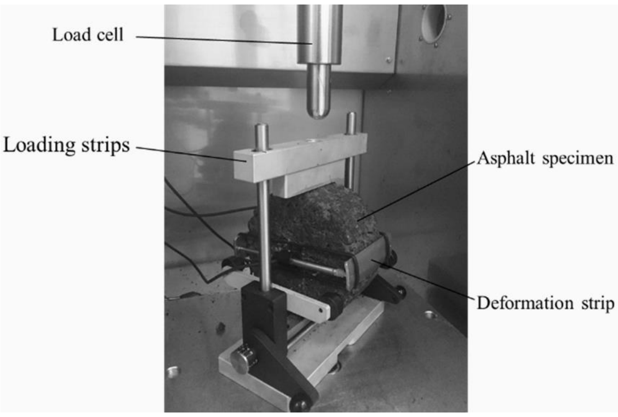

Fig. 2: Sample load for EN 12697–24 indirect tensile test.

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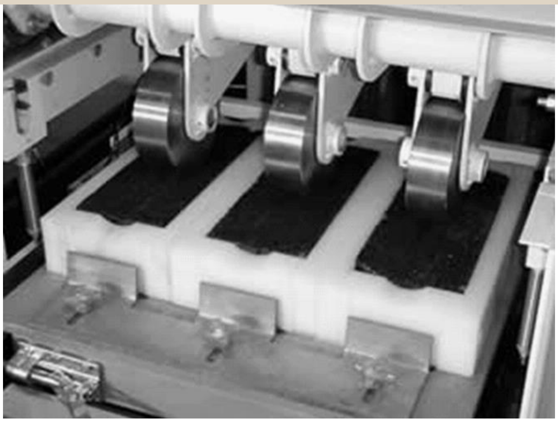

Fig. 3: Experimental setup for PT fatigue test method.

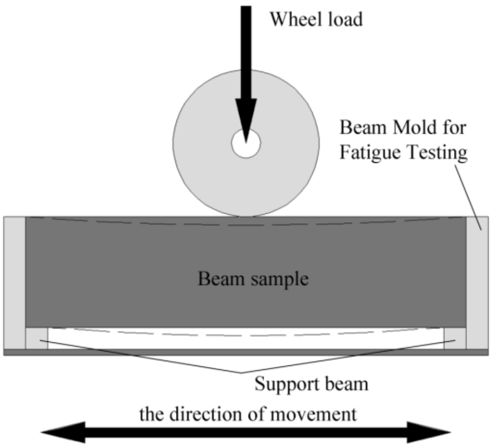

Fig. 4: Sample load for PT fatigue test method.

RESULTS

Suppressing the emission of toxic gases

To ascertain the influence between SEA composition, technology and emission of toxic gases we have to examine the processes [Fig. 5] that are occurring during preparation and placement of pavements.

$$2H^{+} + S^{2-} = H_2S \; +21\ \text{kJ/mol} \qquad \text{(a)}$$

$$S_8 \xrightarrow{-33\ \text{kJ/mol}} S_6 \xrightarrow{-88\ \text{kJ/mol}} S_4 \xrightarrow{-92\ \text{kJ/mol}} S_2 \qquad \text{(b)}$$

$$S + O_2 = SO_2 \; +297\ \text{kJ/mol} \qquad \text{(c)}$$

$$2H_2S + SO_2 = 3S + 2H_2O \; +234\ \text{kJ/mol} \qquad \text{(d)}$$

$$2H_2S + 3O_2 = 2H_2O + 2SO_2 \; +1124\ \text{kJ/mol} \qquad \text{(e)}$$

$$H_2O \leftrightarrow H^{+} + OH^{-} \; -493\ \text{kJ/mol} \qquad \text{(f)}$$

Fig. 5: Chemical processes occurring in SEA.

Dehydrogenation of bitumen leads to the formation of hydrogen sulfide [Fig. 5(a)]. At the same time, S_8 ring transforms to radicals. Excess in content of unstable S_2 and S_4 molecules leads to high reactivity [Fig. 5(b)] and formation of sulfur dioxide [Fig. 5(c)]. The reactions between sulfur dioxide and hydrogen sulfide [Fig. 5d], and also oxidation of hydrogen sulfide [Fig. 5(e)] are also possible. The hydrogen that is formed by dissociation of water (f) can react with sulfur ions, forming hydrogen sulfide (a). Analysis of the energy balance for various paths of H_2S and SO_2 formation shows that the lowest level of energy consumption corresponds to trajectory “reaction (a) → reaction (e) → reaction (f).”

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To suppress the emission of toxic gases, it is possible to use complex sulfur–based modifier consisting of sulfur and chemical neutralizers, e.g. iron salts [9, 10, 13] [20].

We propose to use complex neutralizer that consists of component "A" for preventing the dehydrogenation of bitumen, and component "B" for bonding the hydrogen sulfide and sulfur dioxide into complexes. The availability and local cost of components were taken into account during the selection of particular substances as components "A" and "B". In our research such substances are mixtures of oxides of amphoteric metals. The amount of neutralizer in sulfur is 10% by mass. The measurement results are summarized in [Table 2].

Table 2: Emission of sulfur dioxide and hydrogen sulfide

Parameter	After 15 min.	After 30 min.	After 60 min.
Value of SO_2 emission, mg/m^3	2.0	6.0	8.6
Multiplicity of reduction for SO_2	9.8	4.3	2.6
Value of H_2S emission, mg/m^3	0.6	2.1	3.0
Multiplicity of reduction for H_2S	11.0	7.1	6.1

As if follows from the results, the proposed complex admixture significantly reduces emission of toxic gases, especially the emission of hydrogen sulfide (about order of magnitude).

Resistance to rutting

Six specimens for each composition of asphalt concrete were tested. The value of rut depth for each composition is calculated as an average for the six specimens. The experimental dependencies are presented on [Fig. 6] and [Fig. 7].

As it follows from the obtained results, resistance to rutting of the SEA concrete is significantly higher than for ordinary asphalt concrete (reference mix #1). For the AASHTO TP 63 test method, rutting resistance is 1.7, 2.4 and 3.7 times higher for the mixes 2–4, respectively.

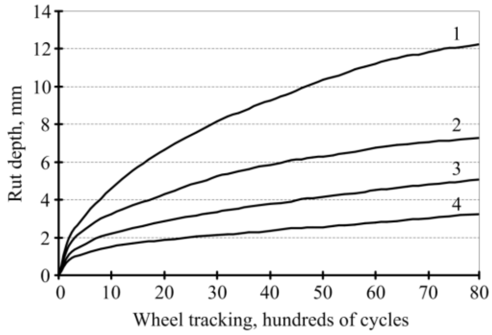

Fig. 6: AASHTO TP 63 results: rut depth for mixes from #1 to #4.

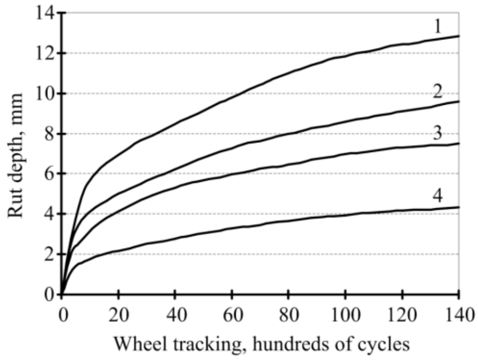

Fig. 7: AASHTO T 324 results: rut depth for mixes from #1 to #4.

According to AASHTO TP 63, the allowable rut depth should be no more than 12 mm after 8000 wheel cycles. For the control specimen such rut depth has reached after the 7800 wheel cycles. For the SEA such rut depth does not reached even after the 10000 wheel cycles; the maximum depths are 7.38, 5 58 and 3.64 mm for the mixes 2–4, respectively.

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For the AASHTO T 324 test, rutting resistance of the SEA concrete is 1.3, 1.7 and 3.0 times higher if compared with reference samples. AASHTO T 324 states that allowable rut depth should be no more than 12 mm after 12000 wheel cycles; for the control specimen of asphalt concrete such rut depth has reached after the 14000 wheel cycles. For the SEA concrete such rut depth does not reached even after 20000 wheel cycles: the maximum depths are 10.8, 8.1 and 4.5 mm, for the mixes 2–4, respectively.

Mechanical properties

We have determined the values of mechanical properties for the previously described samples. Results are summarized in [Table 3].

Table 3: Mechanical properties of sea concretes

Property	Mix #1	Mix #2	Mix #3	Mix #4
Compressive strength at 20 ^{0}C, MPa	3.34	3.35	4.15	5.30
Compressive strength at 50 ^{0}C, MPa	1.67	1.72	2.19	2.82
Clutch shear at 50 ^{0}C, MPa	0.29	0.29	0.38	0.54

As it can be seen from [Table 3], compressive strength of SEA concrete both at 20 ^{0}C and at 50 ^{0}C is considerably higher that of reference Mix #1; depending on the sulfur content, the excess can be as high as 68%.

Resistance to dynamic loads

During operation of asphalt pavements the gradual decline of their strength and other physical and mechanical properties takes place. Such decline is because of the irreversible destruction process of the material structure. The destruction of asphalt concrete under repeated cyclic loading is caused by the fatigue processes, i.e. formation and accumulation of micro–scale defects and the subsequent formation of macroscopic defects [13-18].

The fatigue life is one of the primary parameters that determine the duration of the maintenance–free period of pavement. For the SEA concretes, still there is not enough data concerning the fatigue life. It is obvious, though, that discovering the sulfur effect on the fatigue life of the asphalt concrete is necessary for the design of longer-lasting and durable material.

For the previously described four series of SEA concretes we have carried out the assessment of the fatigue life parameters according to the methods that are described in previous section. The experimental results are summarized in [Table 4].

Table 4: Fatigue life parameters of SEA concretes

Property	Mix #1	Mix #2	Mix #3	Mix #4
EN 12697–24 cycles	1066	1280	4123	6315
EN 12697–24 deformation, mm	1.96	0.63	0.60	0.54
PT cycles	933	814	2807	4620
PT beam deflection, mm	7.6	2.98	2.45	1.40
Splitting tensile strength, MPa	3.21	3.89	3.82	3.71

The formation of spatial cross-linked network may take place when the amount of sulfur in complex binder is in range from 20% to 40%. Such a network contributes the increase of almost all operational properties, including fatigue strength.

As it can be seen from [Table 4], fatigue life parameters increase together with the amount of sulfur in SEA concrete. Starting from Mix #2, for both test methods there are linear dependencies between amount of sulfur and number of load cycles before failure. The corresponding regression models are:

$$N_1(c) = -3646 + 252c\,, \qquad (1)$$

$$N_2(c) = -2962 + 190c\,, \qquad (1)$$

where N_1 and N_1 are numbers of load cycles before failure for EN 12697–24 and PT methods, respectively; c is the amount of sulfur in complex binder, %.

These models can only be used for $20 \le c \le 40$. The corresponding parameters of both models are near to each other; this reflects the fact that both methods give consistent results. For series #4, the number of cycles preceding the start of irreversible deformation and main crack growth, if compared with values for reference series #1, is about 5 and 6 times higher, depending on the test method. Both methods are also indicating that increase of the content of sulfur leads to decrease of deformability. Deformations at the failure point are lowered in 3.3 and 3.6 times (EN 12697-24) and in 3.1 and 5.4 times (PT method), for series #3 and #4, respectively.

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However, as it is evident from the last row of [Table 4], the excess of sulfur may also lead to negative effects. In particular, the values of low-temperature properties (e.g., tensile strength at 0 ºC) of SEA concretes slightly decline. Yet, this decline is relatively small (about 5% for series #2 and #4) and even for series #4 the absolute value of tensile strength is still higher than for reference series. Thus, whilst most materials demonstrate positive correlation between strain capacity and fracture toughness, SEA concrete demonstrate negative one. The correlation between fatigue life and strain capacity is also negative.

CONCLUSION

Prolonging the service life of the roads reduces the consumption of natural resources, thus any building material that is more durable and without environmental impacts should be considered as eco–friendly. Both advantages and drawbacks of SEA concretes are currently well known; from the ecological point of view, the primary drawback is the emission of toxic gases during production and placement.

In the present work we have proposed the complex sulfur modifier that eliminates such drawback. It is shown that admixture of this modifier contributes the increase of almost all operational properties, including resistance to rutting, compressive strength, splitting tensile strength and fatigue limit. In particular, resistance to rutting can be in 1.3-3.7 times higher. The anomalous (negative) correlations between strain capacity, fatigue life and fracture toughness are also revealed; such correlations are beneficial for building material.

CONFLICT OF INTEREST

The authors declare no competing interests in relation to the work.

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