Asphalt concrete on the basis of converter slags

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Abstract. The properties of converter slag, its activity and the influence of the degree of decay on the structural and mechanical properties of asphalt concrete are studied. It has been established that asphalt concrete with a degree of decay of converter slag of 1.24 % or less can be used for paving roads. It has increased heat, water and frost resistance, which will significantly increase the service life of roads from the beginning of operation to overhaul.

1. Introduction

In the process of construction, reconstruction and repair of roads, large volumes of conditioning natural mineral raw materials are used in the form of sand, gravel, gravel, mineral powder, the reserves of which are depleted over time. The main costs (about 60–70 %) in the construction of roads fall on the construction of pavement, and primarily on two structural layers: coating and base.

An urgent problem is the use of local materials and industrial waste in road construction. It is possible to reduce the cost of building roads by replacing expensive imported materials with local materials. However, along with this, it must be borne in mind that the coatings and foundations of roads have sufficient durability (reliability). Only in this aspect will the use of local materials and industrial waste give a high economic effect, especially during the period of intensive road construction.

There are no deposits of strong stone materials on the territory of the Lipetsk region, and road organizations mainly use imported road-building materials. At the same time, the Novolipetsk Metallurgical Plant (NLMK) is located in the region, producing millions of tons of slag, including converter slag, annually as by-products.

The use of slag in road construction was considered in [1–4]. A specific feature of converter slag is its susceptibility to varying degrees of silicate, calcareous and ferruginous decomposition, with a large proportion of calcareous decomposition [2, 5]. This feature inhibits the use of converter slag in road construction.

We conducted studies to determine the degree of slag decomposition, which does not adversely affect the structural and mechanical properties of asphalt concrete, which will expand the range of road building materials, improve the environmental situation, reduce the area under dumps, and reduce the cost of building roads.
2. Methods and materials
The converter slag of the oxygen converter shop No. 2 of NLMK is a black-brown material with a dense, less often a porous structure, with a high density. Due to the heterogeneity of converter slag, its physical and mechanical properties vary over a rather wide range (Table 1).

The mineralogical composition of the converter slag is represented mainly by dicalcium silicate, tricalcium silicate, calcium ferrochromate, and the RO phase. The content in the slag of the first two minerals can reach 80\% [5].

| Table 1. Physical properties of converter slags |
|------------------------------------------------|
| **Indicators** | Fraction size, mm | 5–10 | 10–20 | 20–40 |
|------------------------------------------------|
| Average bulk density, g/cm³ | 1.68 | 1.72 | 1.69 |
| Average density, g/cm³ | 3.13–3.57 | 3.31–3.69 | 3.33–3.45 |
| Water absorption, % of the volume | 1.40–1.90 | 1.00–1.46 | 1.10–1.90 |
| Voidness, % of volume | 45.5–51.2 | 46.6–52.4 | 45.9–51.5 |

One of the characteristics of slag materials is their activity. We conducted studies on the influence of the age of slag from the moment of its receipt on hydraulic activity.

To this end, the slag material was ground in a ball mill to fineness grinding mineral powder. Samples of diameter and height were prepared from the obtained slag flour with a sealing load of 10 MPa and a water-slag ratio of 0.16.

After manufacturing, the samples were kept for 7 days in air, and then placed in humid conditions. Before the test, the samples were placed for two days in water and the compressive strengths were determined. The test results of the activity of slag materials depending on the age of the slag from which the slag flour is made, and on the exposure time of the samples in wet conditions are presented in Table 2.

| Table 2. Influence of slag age on its hydraulic activity |
|--------------------------------------------------------|
| The age of the slag from which the slag flour is made, days | The compressive strength, MPa, of samples stored under wet conditions, days |
|--------------------------------------------------------|
| 20 | 28 | 60 | 120 | 360 |
| 7 | 1.23 | 2.00 | 9.05 | 8.05 | 14.50 |
| 20 | 1.48 | 1.96 | 8.08 | 9.20 | 15.00 |
| 30 | 1.70 | 2.30 | 9.60 | 10.11 | 17.00 |
| 60 | 1.70 | 2.20 | 9.90 | 10.00 | 17.60 |
| 90 | 1.58 | 2.20 | 9.00 | 9.30 | 16.50 |
| 120 | 1.50 | 2.00 | 8.80 | 9.10 | 17.00 |
| 180 | 1.44 | 2.00 | 8.70 | 8.80 | 17.50 |
| 270 | 1.33 | 1.90 | 9.20 | 9.40 | 18.90 |
| 320 | 1.28 | 1.60 | 7.50 | – | – |
| 360 | – | – | – | – | – |

An analysis of the results presented in table 2 indicates that the converter slag is classified as inactive slag, since the compressive strength at 30 days is less than 6 MPa. With increasing storage time of samples of slag flour in wet conditions, its strength increases, especially intensively after 30 days.

The age of the converter slag at the time of its grinding into slag flour also has a significant effect on the tensile strength. The maximum tensile strength is observed for samples at all test ages prepared from converter slag, the age of which at the time of grinding into slag flour is 60–90 days. This is explained by both the carbonization of free lime and the hydrolysis and hydration of slag minerals [1].

Silicate decomposition of slag occurs during the transition of dicalcium silicate from the β-form to the γ-form, which causes an increase in the volume of the substance and creates high internal stresses – pieces of slag crack, and some break up into flour. Glandular decomposition occurs after wetting the slag.
with water, when iron sulfide passes into ferrous hydroxide and pieces of slag crack under the influence of internal stresses. Lime decay occurs when the minerals of the converter slag interact with water. The decay time is long, since it occurs at the points of contact of inclusions of free lime and metal with atmospheric moisture. During the thermal treatment of slag for 6 hours, according to GOST 3344, all types of decay occur [6].

The influence of the degree of decomposition on the mechanical properties (crushability, abrasion, and frost resistance) of converter slag of a fraction of 5–10 mm was studied at different periods of slag aging under natural conditions (Table 3).

By crushing and wear, crushed stone from converter slag belongs to the 1st class of strength [6].

The analysis of the results of table 3 indicates that, despite the decay, the frost resistance of the converter slag exceeds 100 cycles.

The study of the physical and mechanical properties of asphalt concrete was carried out according to the standard method taking into account the specific features of converter slag (decomposition, chemical and hydraulic activity) [7].

The stability of the physico-mechanical properties of asphalt mixtures based on converter slag depends on the degree of decomposition. The greatest decay of converter slag is observed in the initial period from the moment of its receipt. With an increase in shelf life, the decay rate decreases.

In order to clarify the degree of decomposition at which converter slag can be used, the samples were made from slag aged for different periods in air. After each aging period, the degree of slag decomposition in the autoclave was established, the samples were molded, and the properties of asphalt concrete at the age of 2 days were determined. In addition, the physical and mechanical properties were studied after exposure to air for 28, 60, 90, and 180 days. Such a research technique will make it possible to judge the change in the properties of asphalt concrete on converter slag depending on the degree of decay.

For research, a fine-grained asphalt mixture of type B was selected, selected from the curves of dense mixtures, the composition of the mineral part of which consisted entirely of converter slag: slag fr. 5-10 mm – 40 %, slag sand fr. 0–5 mm – 50 %, mineral powder from converter slag – 10 %, bitumen grade BND 90/130 – 7 % (in excess of 100 % of the mineral part) [8].

| Age of slag, days | The degree of decay, % | The number of freezing cycles | Loss in mass, % | Crushability, % | Wear in the shelf drum, % |
|------------------|------------------------|-------------------------------|----------------|----------------|--------------------------|
| 7                | 7.1                    | 0                             | 0.35           | –              | 7.8                      | 17.0                     |
|                  |                        | 15                            | 0.75           | –              | –                        | –                        |
|                  |                        | 25                            | 1.00           | –              | –                        | –                        |
|                  |                        | 50                            | 1.00           | –              | –                        | –                        |
|                  |                        | 75                            | 1.25           | –              | –                        | –                        |
|                  |                        | 100                           | 1.25           | –              | 14.2                     | 17.0                     |
| 40               | 3.7                    | 0                             | 0.50           | –              | 12.3                     | 16.9                     |
|                  |                        | 15                            | 0.25           | –              | 13.1                     | 16.1                     |
| 90               | 1.5                    | 0                             | 0.10           | –              | –                        | –                        |
|                  |                        | 15                            | 0.10           | –              | 6.8                      | 15.8                     |
| 150              | 1.4                    | 0                             | 0.10           | –              | 7.2                      | 15.8                     |
|                  |                        | 15                            | 0.10           | –              | –                        | –                        |
| 180              | 1.3                    | 0                             | 0.10           | –              | 6.8                      | 15.8                     |
|                  |                        | 15                            | 0.10           | –              | 7.2                      | 15.8                     |
| 320              | 1.25                   | 0                             | 0.10           | –              | –                        | –                        |

3. Results
For a more detailed study of the structural and mechanical properties of asphalt concrete based on converter slags with an unstable crystalline structure, the samples were formed from asphalt mixtures
with different slag exposure (1, 2, 4, and 7 months) and tested at the age of 2, 28, 60, 90, 180 days from the date of manufacture (Table 4).

Analysis of the data given in table. 4 shows that samples of asphalt mixtures with a slag decomposition rate of 5.3 % have fairly high compressive strengths at temperatures of 20 and 50 °C, low water saturation, and high coefficients of water resistance and long-term water resistance. A certain increase in tensile strength over time, especially at a temperature of 50 °C, is explained by hydration processes and the interaction of bitumen functional groups with calcium and magnesium oxides of converter slag [9, 10].

The bitumen membrane on the surface of the slag material prevents the penetration of moisture, and therefore there is no visible damage to asphalt during prolonged storage in air. However, when steaming in an autoclave, asphalt concrete samples are completely destroyed. Cracks, chips, yields of slag decomposition products appear on them.

With a decrease in the degree of decay to 2.4 %, samples of asphalt concrete can withstand autoclaving, but the values of compressive strengths sharply decreased below those required by the standard. This indicates an unstable structure of slag asphalt concrete and the possibility of its destruction during operation of asphalt concrete pavements (Fig. 1).

With a degree of decomposition of converter slag of 1.27 %, asphalt concrete maintains stable properties when samples are exposed to air and after autoclaving. After steaming in an autoclave, the samples do not change shape and no cracks or chips are observed on them.

As our studies have shown, such a degree of decay occurs approximately no earlier than after 7–8 months of storage of converter slag in air with intensive watering.

Thus, it follows from the foregoing that converter slag with a degree of decay of not more than 1.2–1.3 % is allowed for the production of asphalt concrete.

Insufficient corrosion resistance of asphalt leads to premature destruction of coatings. Asphalt concrete collapses intensively with prolonged exposure to water and alternate freezing-thawing [11]. Since converter slag has an unstable structure, the long-term exposure to water should accelerate these processes.

The study of long-term exposure to water was carried out with slag with different degrees of decomposition and duration of water saturation of 2, 28, 90 and 180 days (Table 5).

As a rule, with increasing storage time of samples in water, water saturation increases. This is due to the partial decompression of the samples during water saturation and the creation of pore reserves during slag decomposition, which were previously inaccessible to water migration.

With an increase in the duration of water saturation with a degree of decay of slag of 1.7 % or more, the compressive strength decreases, but remains above the requirements of the standard. However, on samples with a slag decomposition rate of 5.4 % after 180 days, cracks and chips are observed (Fig. 2a). Swelling is observed on samples made from slag with a decay rate of 1.7 % (Fig. 2 b), and these phenomena are not observed on samples from slag with a decay rate of 1.27 % (Fig. 2 c).

The compressive strengths of asphalt concrete at a temperature of 20 °C at a slag decomposition rate of 1.27 % are reduced to a water saturation duration of 28 days. and then increase. This is due to the hydraulic activity of the slag. Bitumen actively interacts with hydration products, and at the phase separation a strong adhesive contact is formed that is resistant to prolonged exposure to water.
Table 4. Influence of the degree of decomposition of the converter slag and the age of the samples on the physical and mechanical properties of asphalt concrete

| Age of samples, days | Average density, g/cm³ | Water saturation, % volume | Swelling, % of volume | Tensile strengths in compression, MPa, at temperature, °C | Coefficients: water resistance / long water resistance |
|----------------------|------------------------|---------------------------|----------------------|--------------------------------------------------------|--------------------------------------------------|
|                      |                        |                           |                      | 20 50                                                  |                                                  |
| 2                    | 3.19                   | 0.68                      | 0.70                 | 4.1 1.0                                                | 0.98/1.15                                       |
| 28                   | 3.14                   | 1.51                      | 0.46                 | 4.7 1.8                                                | 0.94/1.17                                       |
| 90                   | 3.17                   | 0.98                      | 0.91                 | 4.3 1.8                                                | 0.98/1.13                                       |
|                      |                        |                           |                      |                                                      |                                                  |
|                      |                        |                           |                      | 20 50                                                  |                                                  |
| 2                    | 2.85                   | 3.81                      | 0.72                 | 5.2 2.1                                                | 0.98/0.86                                       |
| 28                   | 2.83                   | 3.88                      | 0.19                 | 6.4 1.8                                                | 0.81/0.83                                       |
| 60                   | 2.83                   | 4.18                      | 0.58                 | 6.6 2.2                                                | 0.82/0.98                                       |
| 90                   | 2.85                   | 4.70                      | 0.34                 | 7.1 2.1                                                | 0.83/0.75                                       |
|                      |                        |                           |                      |                                                      |                                                  |
|                      |                        |                           |                      | 20 50                                                  |                                                  |
| 2                    | 2.71                   | 6.05                      | 0.00                 | 1.7 0.6                                                | 1.11/1.05                                       |
| 28                   | 2.80                   | 5.49                      | 0.09                 | 4.2 2.1                                                | 0.97/0.98                                       |
| 60                   | 2.87                   | 4.06                      | 0.07                 | 4.3 2.2                                                | 0.93/0.91                                       |
| 90                   | 2.96                   | 3.03                      | 0.00                 | 5.5 1.5                                                | 0.85/1.02                                       |
| 180                  | 2.81                   | 5.87                      | 1.76                 | 5.0 1.1                                                | 0.77/1.08                                       |
|                      | 2.82                   | 4.13                      | 0.89                 | 4.8 1.2                                                | 0.91/0.91                                       |
|                      |                        |                           |                      |                                                      |                                                  |
|                      |                        |                           |                      | 20 50                                                  |                                                  |
| 2                    | 2.75                   | 7.63                      | 0.70                 | 2.6 0.9                                                | 0.88/0.97                                       |
| 28                   | 2.68                   | 3.17                      | 0.00                 | 6.1 2.8                                                | 0.9/1.15                                        |
| 60                   | 2.66                   | 3.57                      | 0.32                 | 6.0 3.0                                                | 1.07/1.15                                       |
| 90                   | 2.67                   | 3.66                      | 0.94                 | 7.2 2.5                                                | 1.11/1.11                                       |
| 180                  | 2.67                   | 1.74                      | 0.00                 | 10.9 2.6                                               | 0.86/1.05                                       |
|                      | 2.67                   | 2.99                      | 0.00                 | 8.1 2.6                                               | 0.85/0.75                                       |
|                      |                        |                           |                      |                                                      |                                                  |
|                      |                        |                           |                      | 20 50                                                  |                                                  |
| 2                    | 2.58                   | 7.58                      | 0.00                 | 5.6 1.5                                                | 1.07/1.10                                       |

The study of frost resistance was carried out with slag with a different degree of decay and the number of freeze-thaw cycles (Table 6).

As can be seen from the presented results, with an increase in the number of freeze-thaw cycles, the water saturation of asphalt concrete increases. This phenomenon is explained not only by the softening of asphalt concrete due to the transition of water into ice and an increase in its volume, but by the calcareous decay of slag grains. The absence of a pattern of changes in water saturation from the aging time of the converter slag to the moment of its use for the manufacture of asphalt concrete can be explained by the uneven distribution of lime in the slag mass.

According to the main indicators of physical and mechanical properties, asphalt concrete based on converter slag with a different degree of decay satisfies the requirements of the standard.

With a degree of decay of slag of 5.3 and 2.4 %, the compressive strength of asphalt concrete decreases, but remains within the requirements of the standard. The decrease in tensile strength after exposure to freeze-thaw cycles is associated both with decompression of asphalt concrete (destruction) and with the decay of slag.

At a slag decomposition rate of 1.7 and 1.27 %, the compressive strengths increase after exposure to freeze-thaw cycles. This is explained by the processes of hydrolysis and hydration of slag, the physicochemical interaction between the functional groups of bitumen and slag minerals with the formation of organomineral compounds (structural processes prevail over destructive ones).
Table 5. Influence of the degree of decomposition of the converter slag and the duration of water saturation on the physical and mechanical properties of asphalt concrete

| Duration of water saturation, days | Average density, g/cm³ | Water saturation, % volume | Swelling, % volume | Tensile strengths in compression, MPa, at temperature, °C | Water resistance factors |
|-----------------------------------|------------------------|---------------------------|-------------------|----------------------------------------------------------|--------------------------|
|                                  |                        |                           |                   | 20                                          | 50                       |
| slag age 1 month, decay 5.3 %    |                        |                           |                   |                                             |                          |
| 2                                 | 3.04                   | 1.70                      | 0.66              | 4.9                                        | 2.2                      | 1.43                     |
| 28                                | 3.04                   | 4.33                      | 0.46              | 5.7                                        | 1.5                      | 1.20                     |
| 90                                | 3.03                   | 3.43                      | 0.00              | 5.7                                        | 1.5                      | 1.42                     |
| 180                               | 3.04                   | 7.70                      | 1.01              | 2.7                                        | 1.3                      | -                        |
| slag age 2 months, decay 2.4 %    |                        |                           |                   |                                             |                          |
| 2                                 | 2.79                   | 4.06                      | 2.86              | 6.5                                        | 2.2                      | 1.03                     |
| 28                                | 2.82                   | 6.50                      | 2.40              | 5.2                                        | 1.3                      | 0.89                     |
| 60                                | 2.83                   | 6.27                      | 2.51              | 4.5                                        | 1.3                      | 0.81                     |
| 90                                | 2.82                   | 10.83                     | 6.69              | 4.7                                        | 1.1                      | 0.54                     |
| slag age 4 months, decay 1.7 %    |                        |                           |                   |                                             |                          |
| 2                                 | 2.83                   | 2.25                      | 0.54              | 6.4                                        | 2.0                      | 1.29                     |
| 28                                | 2.81                   | 6.55                      | 0.00              | 6.3                                        | 1.6                      | 1.55                     |
| 60                                | 2.78                   | 4.50                      | 2.16              | 4.3                                        | 1.6                      | 1.13                     |
| 90                                | 2.83                   | 7.65                      | 4.67              | 3.4                                        | 1.2                      | 1.18                     |
| 180                               | 2.83                   | 10.63                     | 6.89              | 3.6                                        | 1.0                      | 1.00                     |
| slag age 7 months, decay 1.27 %   |                        |                           |                   |                                             |                          |
| 2                                 | 2.67                   | 1.78                      | 0.02              | 7.1                                        | 2.9                      | 1.44                     |
| 28                                | 2.68                   | 4.26                      | 0.58              | 4.7                                        | 2.6                      | 0.87                     |
| 60                                | 2.66                   | 3.34                      | 0.74              | 6.4                                        | 2.2                      | 0.80                     |
| 90                                | 2.68                   | 2.73                      | 0.13              | 7.5                                        | 1.9                      | 1.70                     |
| 180                               | 2.67                   | 2.97                      | 0.05              | 7.9                                        | 2.1                      | 1.81                     |

Table 6. Influence of decomposition of converter slag decomposition and number of freezing-thawing cycles on the physical and mechanical properties of asphalt concrete

| Number of freeze-thaw cycles | Average density, g/cm³ | Water saturation, % volume | Tensile strengths in compression, MPa, at temperature, °C | Water resistance factors | Frost factors |
|-----------------------------|------------------------|---------------------------|----------------------------------------------------------|--------------------------|---------------|
|                             |                        |                           | 20                                          | 50                       |
| slag age 1 month, decay 5.3 %|                        |                           |                                             |                          |
| 25                          | 3.03                   | 1.40                      | 5.5                                        | 2.0                      | 1.05          | 1.17           |
| 50                          | 2.99                   | 2.33                      | 4.8                                        | 1.8                      | 0.87          | 0.97           |
| 100                         | 2.79                   | 2.67                      | 3.6                                        | 1.6                      | 1.14          | 0.95           |
| slag age 2 months, decay 2.4 %|                        |                           |                                             |                          |
| 25                          | 2.80                   | 4.81                      | 6.8                                        | 1.5                      | 0.93          | 0.98           |
| 50                          | 2.70                   | 8.15                      | 5.8                                        | 1.7                      | 0.62          | 0.75           |
| 75                          | 2.69                   | 7.79                      | 5.2                                        | 1.5                      | 0.73          | 0.69           |
| 100                         | 2.61                   | 9.39                      | 3.6                                        | 1.0                      | 1.02          | 0.52           |
| slag age 4 months, decay 1.7 %|                        |                           |                                             |                          |
| 25                          | 2.88                   | 3.15                      | 4.1                                        | 1.9                      | 1.00          | 0.89           |
| 50                          | 2.82                   | 3.93                      | 4.0                                        | 3.0                      | 1.00          | 0.89           |
| 75                          | 2.79                   | 5.67                      | 4.5                                        | 1.6                      | 1.26          | 0.82           |
| slag age 7 months, decay 1.27 %|                        |                           |                                             |                          |
| 25                          | 2.68                   | 3.14                      | 6.9                                        | 2.0                      | 0.81          | 1.50           |
| 50                          | 2.70                   | 2.47                      | 8.8                                        | 2.0                      | 0.94          | 1.22           |
| 75                          | 2.67                   | 3.26                      | 10.2                                       | 2.5                      | 0.72          | 0.95           |
| 100                         | 2.66                   | 3.42                      | 10.9                                       | 2.6                      | 0.86          | 0.82           |
Figure 2. The condition of asphalt concrete after 180 days of water saturation with a degree of decomposition of converter slag of 5.4 % (a); 1.7 % (b); 1.27 % (c)

Figure 3. The condition of asphalt concrete after 100 cycles of freezing and thawing with a degree of decomposition of converter slag of 5.4 % (a); 1.7 % (b); 1.27 % (c)

However, the state of asphalt concrete samples with different degrees of decay after freezing-thawing cycles is different. With a slag decomposition rate of 5.7 %, intense cracking, chips, cracks, and roughness of the surface of asphalt concrete are observed (Fig. 3a). With a decrease in the degree of slag decomposition to 1.7 % (Fig. 3b), the intensity of crack formation and turbulence of asphalt concrete decreases significantly. Cracks appear much less frequently. At a slag decomposition rate of 1.27 %, no cracks or turbulence were observed on the samples of asphalt concrete (Fig. 3c). Therefore, when studying the frost resistance of asphalt concrete based on converter slags, attention should be paid not only to changes in physical and mechanical properties, but also to those conditions under
which the integrity of asphalt concrete samples is preserved after repeated freezing and thawing cycles.

4. Conclusion
1. Converter slag with a degree of decay of less than 1.27 % can be used in road construction for the installation of asphalt concrete pavements. Asphalt concrete has a high heat, water and frost resistance.
2. The possibility of using converter slag will expand the range of local building materials, which will lead to a decrease in the cost of building roads.
3. The use of converter slag will significantly improve the environmental situation, reduce the area occupied by dumps.

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