Strength properties of ballast layer, created from new and recycled crushed stone ballast

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Abstract. The objective of the research is a railway ballast layer created from new and recycled ballast particles in different ratio. In order to study the possibility of using recycled ballast grains in ballast layer, it is necessary to carry out laboratory triaxial tests of ballast crushed stone with size of the particles 25-60 mm with different grain shape. Abrasion testing machine allows to reach the effect on new ballast, which is similar to abrasion of ballast particles in the railway track. Therefore, it is possible to create ballast samples from (new) mixed and recycled ballast and estimate which proportion has the strength characteristics, which are close to the ones in ballast layer created only with new ballast particles. The result of the study shows, that it makes sense to return the recycled crushed stone in a mix with a new one in order to reduce the cost on a railway maintenance.

1. Introduction

This study is the continuation of the investigation: “Change of ballast strength properties during particle abrasive wear” [1]. The sustaining capability of railway ballast layer is defined by its strength properties which strongly depend on ballast gradation composition, density, attrition, pollution and other factors [2]. Railway ballasts is subjected to a dynamic train load which leads to significant changes in a shape of ballast grains [3]. In result it reduces ballast strength properties, such as internal friction angle (φ) and specific cohesion (C) [4].

The influence of abrasion on ballast particles was investigated in multiple studies [5]. Most of these studies concern the changing of shape of ballast grains and its influence on ballast layer sustaining capability [6]. Generally, investigators divide the degradation of ballast into groups, such as fragmentation, rounding, abrasion [7], etc. Nevertheless, the engineering behavior of mix of new and recycled crushed stone in the ballast layer still remains unstudied, which makes the results of this investigation first of its kind. The using of recycled crushed stone in a railway ballast layer might significantly reduce the cost on the maintenance and operation of the railway track [8].
2. Materials and methods

The study was carried out using the granite ballast which was selected in the quarries of Leningradskiy region (Russia). Specimens for the tests were created from crushed stone with size of the particles 25-60 mm, flaky grains excluded.

In order to estimate the strength properties of mixed ballast samples it was necessary to determine the values of specific cohesion, $C$, and internal friction angle, $\varphi$, of new and recycled ballast separately. Generally, these investigations are done with using apparatuses of triaxle load frames [9].

For estimation of influence of abrasion of particles of ballast on its strength properties, new ballast was handled in Los – Angeles abrasion testing machine under 100, 200, 500 and 800 round trips in order to give ballast grain the shape according to the rounding category [10].

Determination of strength properties of ballast was executed by the way of triaxle pressure in cell of triaxial load frame using a method of consolidated undrained triaxial test [11] with the maximum quickness of destruction of specimen. Investigations were made in a triaxle load frame STX-600. Lateral pressure on specimen $\sigma_3$ were 40, 60 and 80 kPa. Such tests can be carried out in a triaxial load frame of any design, where it is possible to test a sufficiently voluminous sample with ballast at a stable lateral pressure with the possibility of its regulation [12].

The ballast samples were collected in Jeephegen (Zabaikalskiy region, Russia) and Gavrilovo (Leningradskiy region, Russia) deposits.

Specimens for tests were created from granite ballast with size of the particles 25-60 mm. Density of specimens varied in diapason 1,54-1,62 g/cm$^3$. New ballast and ballast, manipulated in abrasion testing machine were used in specimens.

Functional connections of rate of strain of specimen $\lambda$ from stress deviator $q = \sigma_1 - \sigma_3$ were built for finding a collapse pressure on specimen [13], where $\sigma_1$ – maximum principal stress (load, delivered on specimen vertically), $\sigma_3$ – minimum principal stress (lateral load on specimen). In order to calculate the strength properties, the results were approximated by the dependence of the stress deviator on the lateral pressure by formulas (3) and (4) [14]. From these indicators, $C$ and $\varphi$ were calculated using the formulas (1) and (2).

Particular data of specific cohesion and internal friction angle of ballast were found, using formulas:

$$\tan \varphi_j = \frac{N_j - 1}{2\sqrt{N_j}} \quad (1)$$

$$C_j = \frac{M_j}{2\sqrt{N_j}} \quad (2)$$

Data points of coefficients $N_j$ and $M_j$ were calculated, using formulas (3) – (4). Herewith their calculation was made using a least square method in accordance with at least three results of collapse pressures $\sigma_1$ in a cell of triaxial load frame under different data points of lateral pressure $\sigma_3$.

$$N_j = \frac{k \cdot \sum_{i=1}^{k} \sigma_{1,i} \cdot \sigma_{3,i} - \sum_{i=1}^{k} \sigma_{1,i} \cdot \sum_{i=1}^{k} \sigma_{3,i}}{k \cdot \sum_{i=1}^{k} (\sigma_{3,i})^2 - (\sum_{i=1}^{k} \sigma_{3,i})^2} \quad (3)$$

$$M_j = \frac{1}{k} \left( \sum_{i=1}^{k} \sigma_{1,i} - N_j \cdot \sum_{i=1}^{k} \sigma_{3,i} \right) \quad (4)$$

where $k$ – amount of data points, taken up at least 3 during experiments (under different volumes of lateral pressure).

Using found data points $C$ and $\varphi$ their average meanings were calculated by formula (5):
\[ X = \bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i, \]  
\[ \% \]  
\[ (5) \]

where \( n \) – number of meanings of characteristic, accepted no less than 3; \( X_i \) – particular meanings of characteristics, gotten from results of particular tests.

Then mean-squared departure of these data points from average \( S_c \) and \( S_\varphi \) was found, using formula, (6):

\[ |\bar{X} - X_i| > v \cdot S \]  
\[ (6) \]

where \( v \) – statistical criterion, accepted in accordance with number of values; \( S \) – mean-square deviation of characteristic, calculated, using formula (7):

\[ S = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\bar{X} - X_i)^2} \]  
\[ (7) \]

Statistical check for annulment possible mistakes in specific cohesion and internal friction angle was made, using formula (6). Next, coefficient of variation was calculated, using formula (8):

\[ V = \frac{S}{\bar{X}} \]  
\[ (8) \]

If the value of coefficient of variation for \( C \) and \( \varphi \) separated is no more than 0,30, results of experiments were admitted authentic.

On figure 1 there is example of test-data reduction for finding of specific cohesion and internal friction angle for new granite ballast with building of stress circles and envelope, that characterizes boundary state of stress of specimens.

![Figure 1](image-url)
Table 1 includes summary data of estimation of strength properties of new ballast. Each indicator was obtained in result of three or more test in the same condition and using same gradation composition of ballast after approximation.

For estimation of influence of abrasion of particles of ballast on its strength properties, new ballast was handled in abrasion testing machine under 100, 200, 500 and 800 round trips in order to give ballast grain the shape according to the rounding category [1]. Specimens of recycled ballast were created for tests, while fractional content of specimens from new and recycled ballast was identic. Characteristics of specimens shown in a table 2.

**Table 1 – Summary data of estimation of specific cohesion and internal friction angle of new ballast in a test campaign**

| Code of test campaign | Density of specimens, g/cm³ | Specific cohesion C, kPa | Internal friction angle φ, degr. |
|-----------------------|-----------------------------|--------------------------|----------------------------------|
| TS1                   | 1.60 – 1.62                 | 55                       | 52.4                             |
| TS2                   | 1.59 – 1.61                 | 58                       | 49.8                             |
| TS3                   | 1.58 – 1.62                 | 65                       | 52.6                             |
| TS4                   | 1.59 – 1.61                 | 55                       | 52.4                             |
| TS5                   | 1.59 – 1.62                 | 59                       | 52.3                             |
| TS6                   | 1.57 – 1.60                 | 61                       | 52.8                             |
| TS7                   | 1.59 – 1.61                 | 50                       | 50.8                             |
| TS8                   | 1.58 – 1.60                 | 55                       | 52.4                             |

Average value, $\bar{X}$

Mean-square deviation, $S$

Coefficient of variation, $V$

**Table 2 – Characteristic of recycled ballast for triaxle tests**

| Ballast type, code of test campaign | Fractional content, mm, mass. % | Number of round trips in abrasion testing machine | Density of specimens, g/cm³ |
|------------------------------------|---------------------------------|--------------------------------------------------|------------------------------|
| granite (TS9)                      | 60-70 mm – 4.2%                | 100                                             | 1.59 – 1.61                  |
|                                    | 40-60 mm – 61.1%               |                                                 |                              |
|                                    | 25-40 mm – 34.7%               |                                                 |                              |
|                                    | 60-70 mm – 3.2%                |                                                 |                              |
| granite (TS10)                     | 40-60 mm – 58.6%               | 200                                             | 1.56 – 1.62                  |
|                                    | 25-40 mm – 38.2%               |                                                 |                              |
|                                    | 60-70 mm – 4.8%                |                                                 |                              |
| granite (TS11)                     | 140-60 mm – 64.6%              | 500                                             | 1.57 – 1.59                  |
|                                    | 25-40 mm – 30.6%               |                                                 |                              |
|                                    | 60-70 mm – 3.0%                |                                                 |                              |
| granite (TS12)                     | 40-60 mm – 55.7%               | 800                                             | 1.55 – 1.60                  |
|                                    | 25-40 mm – 41.3%               |                                                 |                              |
3. Results and discussion

Comparison of changing of stress deviator in specimen of ballast upon different degree of handling of specimen of ballast in abrasion testing machine under the equal lateral pressures, $\sigma_3$ is shown on figures 2 and 3.

Figure 2 – Destruction of ballast samples (lateral pressure in cell of triaxial load frame is $40 \text{ kPa}$)

Figure 3 – Destruction of ballast samples (lateral pressure in cell of triaxial load frame is $60 \text{ kPa}$)
Analysis of figures 2 and 3 allows to make a conclusion, that appearance of worn-down particles in a ballast leads to decrease of value of destructive pressure on specimen of ballast. Herewith, ballast with more worn-down edges shows more low values of destructive volume of stress deviator, all other conditions being equal. Specimen, created with new ballast, under lateral pressure of 40 kPa crashes in a cell of triaxial load frame, when value of stress deviator is 662 kPa. Specimen of ballast, handled in abrasion testing machine under 200 round trips, has value of stress deviator of 435 kPa, and ballast, handled 800 round trips – 340 kPa. Consequently, in the first instance braking pressure is 1,5 times less, and in the second instance is 1,9 times less than new ballast. This goes to prove, that strength properties of worn-down ballast are much worse, comparing to new ballast.

Results of calculation of strength properties of worn-down ballast under statical pressure are shown in table 3. Dependency diagrams, that show changing of strength properties of ballast depending on its degree of roundness are built according to data from table 3 (Figure 4).

Table 3 – Summary data of estimation of specific cohesion and internal friction angle of ballast in a test campaign with different degree of abrasion

| Ballast type, code of test campaign | Number of round trips in abrasion testing machine | Specific cohesion $C$, kPa | Internal friction angle $\phi$, degr. |
|----------------------------------|-----------------------------------------------|--------------------------|-------------------------------------|
| Granite, TS1 – new ballast       | -                                             | 55                       | 52,4                                |
| Granite, TS9                     | 100                                           | 51                       | 50,6                                |
| Granite, TS10                    | 200                                           | 46                       | 51,2                                |
| Granite, TS11                    | 500                                           | 21                       | 50,7                                |
| Granite, TS12                    | 800                                           | 9                        | 55,4                                |

The table above shows, that there is expressed functional dependency between the degree of abrasion of particles of ballast and its specific cohesion. It is clear that as particles of ballast get close to a half-rounded and rounded shape, specific cohesion reduces almost to zero. According to the table, new ballast has specific cohesion $C$ equaled 55 kPa, and recycled ballast after handling in abrasion testing machine with 800 round trips, holds specific cohesion of 9 kPa, which is 6 times less, than the new one.

About the internal friction angle can be made a conclusion, that with increasing of degree of roundness $\phi$ practically does not change. Coefficient of variation of gotten values is 0,03.
Putting a mix of a new and recycled ballast in a railway track can provide match of required sustaining capability. Strength properties of mixtures of new and recycled ballast, that define sustaining capability of ballast layer were studied in this investigation. Mixtures for tests were formed from granite ballast in ratio by mass of new and recycled ballast: 70% and 30%, 50% and 50%, 30% and 70%. Recycled ballast was crushed granite, that was handled in abrasion testing machine with 200, 500 and 800 round trips.

Results of estimating of strength properties of mixtures of new and recycled ballast shown in table 4.

**Figure 4** – Strength properties of ballast with different level of handling of ballast in abrasion testing machine
Table 4 – Specific cohesion and internal friction angle of mixtures of new and recycled granite ballast

| Ballast strength properties | 200 round trips | 500 round trips | 800 round trips |
|----------------------------|-----------------|-----------------|-----------------|
| Percentage ratio in mixture of new (numerator) and recycled (denominator) ballast, % | 70/30 | 50/50 | 30/70 | 70/30 | 50/50 | 30/70 | 70/30 | 50/50 | 30/70 |
| \( C, \) kPa | 56 | 57 | 51 | 40 | 31 | 19 | 27 | 20 | 6 |
| \( \varphi, \) deg. | 50,5 | 48,6 | 51,6 | 49,3 | 48,0 | 48,5 | 51,6 | 52,1 | 53,2 |

Results, shown in table 4, conclude that internal friction angle practically does not depend on the extent of abrasion of ballast particles and on average ranges from 48\(^\circ\) to 53\(^\circ\), unlike the specific cohesion, which only slightly decreases when rounding in 200 cycles, but then decreases significantly after 500 round trips even with a 70/30 ratio. Thus, it can be concluded that there is a clear pattern: the greater the degree of ballast abrasion (roundness category), the less its special cohesion and it rapidly decreases with degradation of the grain shape: at a ratio of 70/30 for 200 cycles and 800 cycles, the decrease in the specific cohesion value samples is about 47%. It is also evident that after processing new ballast in an abrasive wear tester with 800 rounds, the special cohesion of ballast formed from 30% of new ballast and 70% of recycled ballast tends to zero.

Conclusions:

1. Increasing of level of abrasion of ballast particles leads to reducing of strength properties of ballast layer. Meanwhile new ballast is characterized by value of specific cohesion 57 kPa, ballast after handling in abrasion testing machine with number of round trips equaled 800, has specific cohesion, equaled practically zero. Without doubts, that affects the sustaining capability of ballast layer. Significant fall of specific cohesion of ballast happens after handling 500 round trips at the abrasion testing machine.

2. Strength properties of ballast layer, formed from new and recycled ballast significantly depend on original level of abrasion of ballast. While using of mixture of 70% of recycled (200 round trips) and 30 % of new ballast it is clearly that strength properties of ballast layer are close to standardized values for a new ballast. At the same time, with any percentage ratio of new ballast with the ballast that was handled in abrasion testing machine under 800 round trips, values of specific cohesion are two and more times less, than new ballast, and with ratio of new and recycled ballast 30/70 %, value of specific cohesion under statical pressure is no more than 6 kPa.

3. Level of abrasion of ballast particles practically does not affect its internal friction angle. Average value of internal friction angle of any ballast, that has standardized fractional content (25-60 mm) and has density 1,55-1,60 g/cm\(^3\) is averagely 51\(^\circ\).

Prospects for further research:

1. Investigation of crushed stone ballast strength properties under vibrodynamic loads
2. Modelling of construction of railway ballast layer, formed from new and recycled crushed stone ballast.
3. Determination of bearing capacity of railway ballast layer, formed from new and recycled crushed stone ballast.
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