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SCREEN-OUT STONES ACTIVATED WITH MINERAL BINDERS AND USED AS MATERIAL FOR EARTH CONSTRUCTION

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Abstract. The article presents the evaluation of how suitable waste from the production of aggregates in quarries could be in earthwork using the example of screen-outs from Krosno sandstone. The waste, called screen-out, is characterised by an uncontrolled content of dust and clay fractions. Screen-outs have a relatively low bearing ratio (CBR not exceeding 20%) and a tendency to heave due to frost (SE <35). To check whether the geotechnical properties can be improved, mixtures with 2%, 5%, and 8% binders, such as lime, fly ash, and two road binders with lime, fly ash, and cement were prepared. The analysis was based on the results of the CBR and compressive strength tests. The use of mineral binders caused the value of the immediate CBR to increase compared to the screen-out itself from a dozen to as much as 50%. For a binder containing 20% Portland clinker, the CBR was about 60% after 4 days of saturation, while for a binder containing up to 50% Portland clinker, it was over 200%. The value

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of compressive strength after 28 days of maturing ranged from about 100 kPa to 1 MPa for all mixes tested. The lowest values were obtained for screen-outs activated with fly ash, and the highest for road binder with cement content of up to 50%.

Keywords: quarry waste, screen-out, hydraulically bound mixtures, CBR.

Introduction

Stone screen-outs are mineral granular materials obtained in the first phase of screening and crushing of material excavated in quarries. Their significant disadvantage is that they contain uncontrolled amounts of stony and clayey fractions. This leads mainly to a variable grain size distribution, as well as variable geotechnical parameters. Therefore, it is a kind of waste from the production of broken and granulated aggregates (Rezende & Carvalho, 2003; Etim et al. 2021; Ural & Kahveci, 2023). However, with reliable control of the grain size distribution and mineral composition and evaluation of basic properties, the screen-out material can be successfully used in earthworks. Most often, screen-outs are used for the construction of embankments, filling voids and unevenness in engineering works or reclamation of degraded land, etc.

However, sometimes, the screen-out itself is not suitable for direct use in earthworks. Then it is necessary to change its geotechnical properties by mixing a screen-out with appropriately selected additives. This treatment allows increasing the impermeability and strength, which directly contributes to increasing the load-bearing capacity of the layers made. Granular materials can be "improved" by adding other fractions and creating a mixture with appropriate grain size or by using properly selected mineral binders, polymers, or bitumen. Mixtures bound by hydraulic binders are mainly used for road layers. These mixtures are mainly used for layers of improved subgrade in the frost-protection, separation, and improvement (reinforcement) layers.

The aim of the tests was to determine how the geotechnical parameters of the Krosno sandstone screen-out changed after mixing with mineral binders used in road construction. Hydrated lime, calcareous fly ash from the combustion of lignite, and two ready-made mixtures containing hydraulic binders (Stabifen and Drohart 22.5) were used for the tests. The article focuses on the evaluation of the results of the CBR and compressive strength tests.

1. The influence of mineral binders on improving the properties of aggregates and soils

The materials most often used to increase the bearing capacity of screen-outs are mineral binders. Due to their binding properties, the use of cements gives the best results. Stabilization with cement can be used for non-cohesive, low, and medium cohesive soils, as well as for aggregates. This process aims to increase the bearing capacity and reduce the sensitivity to weathering. In the work (Abd Al-Redha Ghani et al., 2018), the use of Portland cement at 5%–15% in a mixture with lime aggregate increased the CBR from 48% to 78% with 5% cement content to almost 100% with 15% cement content. The change in compressive strength ranged from about 3.5 MPa (for 5% cement) to 7.5 MPa (for 15% cement). While the values of compressive strength showed a clear linear dependence on cement content, for 10% and 15% cement content, the difference in the bearing ratio was small, that is, CBR=92% and CBR=98%, respectively. Similar increases in compressive strength were obtained in tests of aggregate mixtures bonded with cement and cement with fly ash, presented among others in the works by Dudek et al., (2018), Witek & Owczarek, (2014), Buczyński & Lech (2015) and Tataranni at al. (2018). When aggregate grain size distribution was properly selected and from 1% to 9% cement, and from 2% to 4% of fly ash from hard coal combustion were added, the compressive strength from about 1 MPa to as high as 29 MPa was obtained. The highest compressive strength values were obtained when only Portland cement, usually CEM I 32.5, was used as the binder. However, the addition of fly ash and/or cement dust (CKD) improves the consistency of the mixture.

The use of lime binder is recommended mainly for cohesive soils with high plasticity. They are also used for pre-improvement of acidic and humic soils, very cohesive soils, and soils with a moisture content significantly higher than the optimum moisture content (Krithiga et al., 2017; Ampera & Aydogmus, 2005). The influence of lime on the improvement of the properties of cohesive soils was also investigated by Utami (2014) and Ahmad (2021Both authors showed a significant increase in the CBR value with 10% lime in the mixture. The higher content of the binder caused a decrease in the bearing ratio. Whereas Bilgen & Altuntas (2023), apart from lime, added powdered waste glass and cement to the bound mixtures. The combined use of all these ingredients allowed increasing the CBR to 83%.

Fly ash, fluidized ash (Vukićević et al., 2015; Kołodziejczyk et al., 2012), and cement dust (Miller & Azad, 2000), which have pozzolanic properties, are also recommended for soil stabilization. Compared to lime and cement, fly ash has much weaker binding properties. In addition, there are certain limitations for the use of fly ash for stabilization, especially with respect to the sulfur content, which may contribute to the formation of ettringite in the hydration products in the soil-ash mixture, thereby reducing its strength (Gawlicki & Wons, 2011; White, 2005). The influence of sulfates contained in the ash on the properties of soil mixtures with lime and ash was studied by scientists (McCarthy et al., 2011). As a result of their research, it was found that the addition of fly ash, even in the amount of 24% to the soil-lime mixture (lime content of 3%), only slightly improved the compressive strength of the prepared samples. However, a very large influence of the amount of added ash on the decrease in swelling was found. Based on the research, it was found that the best ash for soil stabilization was that containing a maximum of 1% of sulfur compounds expressed as SO_3. The test results presented in the work by Kołodziejczyk et al. (2012) allowed for the evaluation of the dynamics of the increase in compressive strength and load-bearing capacity of various soils stabilized with hydraulic binders prepared using fly ash from lignite combustion. The analysis was carried out on the basis of changes in the CBR value for mixtures with the content of mineral binder in the amount of 6% and 8%. The test was carried out immediately after compaction of the mixtures and after seven days of maturing (including the first four days of water saturation). With very satisfactory results, this type of material can be considered fully suitable for the stabilization of low-bearing soils. The CBR increased from about a dozen or so to even over 300%, depending on the soil tested. The use of all types of waste from the energy industry (ash and slags (UPS)) and the metallurgical or cement industry is a very important environmental aspect. However, depending on the technological processes, the composition and properties of these materials are variable, and their nature is difficult to predict. Therefore, the use of such materials should be approached with great caution without a solid assessment of their influence on the durability of the structure (Gawlicki & Małolepszy, 2013; Kamara et al., 2021). The use of ash alone is often not sufficient to achieve an adequate level of bearing capacity. To achieve the expected stabilization effects, they should be used as an additive. Mixtures were made with specially modified fly ash, and the addition of cement, the so-called road binders (Iwański et al., 2016; Li et al., 2019).

2. Research material and methodology

2.1. Screen-out (quarry waste)

The screen-out for the study comes from the Krosno sandstone deposit from the Barwałd quarry. These sandstones consist mainly of quartz grains (about 37%) and lithoclasts (13%), as well as feldspars and micromica (several percent). Glauconite, organic matter, and pyrite occur occasionally. The binder present at about 38% is a carbonate-silica binder containing clay minerals (Rembiś & Smoleńska, 2010). The screen-out is an aggregate with a continuous grain size of 0/12 mm or 0/16 mm. The basic physical and mechanical properties of the screen-out are presented in Table 1. The results come from laboratory tests carried out at the Laboratory for Testing the Properties of Rocks and Stone Products (LBWSiWK) of the AGH University of Science and Technology in Krakow over the last 15 years.

Screen-outs tested in LBWSiWK (Table 1) were characterised by a variable grain size distribution. Some of them had a high content of dust and clay fractions, which resulted in a relatively low value of the sand index (<25). These batches of screen-outs showed a significant tendency to frost heave susceptibility (Ćwiąkała et al., 2016). The screen-outs had a CBR<20% after 96 hours of saturation, which disqualified this material for earthworks in road construction. According to the Catalog of Typical Constructions of Road Surface intended for very light traffic and other

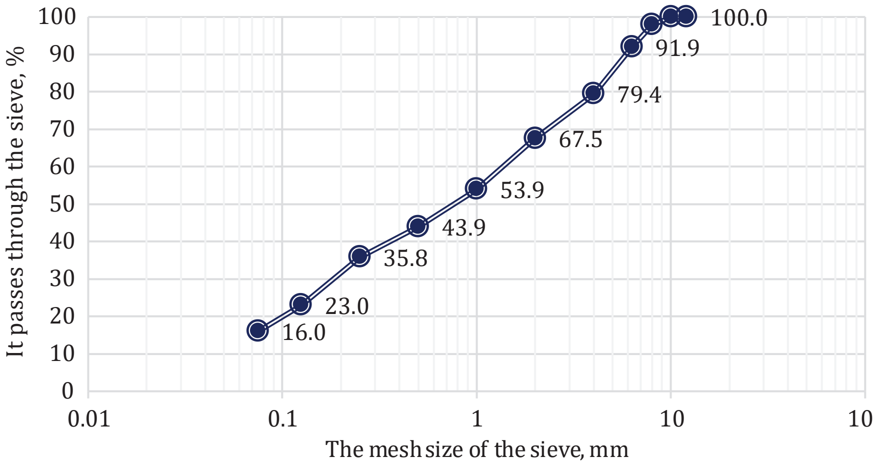

Figure 1. Grain size distribution of the stone screen-out of the 0/16 mm fraction

Table 1. Geotechnical properties of the screen-out (Test reports, 2004–2021)

Property	Unit	Value
Fraction	mm	0/12–0/16
Dust fraction content (grains <0.063 mm)	%	1–25
Clay fraction content (grains <0.002 mm)	%	0–6.5
The maximum volume of the soil matrix (dry solid particles)	g/cm^3	1.876–2.218
Optimum humidity	%	8–11
CBR (California Bearing Ratio)	%	
– immediately after compaction		9.5–23.3
– after 96 h of saturation		6.7–17.8
Angle of internal friction	°	32–34
Cohesion	kPa	22–43
Sand indicator		11–23
Bulk density	g/cm^3	
– loose condition		1.47
– condition after compaction		1.79

parts of roads WR-D-63 (2022), the lowest required CBR for layers of improved subgrade is 20%.

The grain size distribution of the batch of material intended for testing the effect of binding mineral additives on improving the geotechnical properties of the screen-out is shown in Figure 1. The granulometric composition of the tested material was dominated by the sand fraction (51.5%) and gravel fraction (32.5%), while the share of the dust and clay fraction was 16%.

2.2. Binding materials

The following materials were used in the tests aimed at assessing the impact of the type and amount of stabilizer on the improvement of the geotechnical properties of the screen-outs: hydrated lime, lime fly ash, and two ready-made mixtures of road binders. All the materials used are publicly available, and their chemical composition and binding properties meet the requirements of the relevant qualification standards.

Hydrated lime contains at least 80% by weight of active lime and has a volume stability of less than 4 mm (Product catalogue: hydrated lime). Calcareous fly ash came from burning brown coal. The ash consisted of fine grains of spherical shape (97% of the grains passed through the 0.315 mm screen). The main components of lime ash were aluminosilicates (SiO_2 and Al_2O_3), as well as reactive calcium oxide (CaO).

The stability of the volume of the calcareous fly ash was 4 mm (Product catalogue: lime fly ash).

Two ready-made road binders, Stabifen and Drohart 22.5, were also used to stabilize the screen-out. Stabifen consisted mainly of ground quicklime (up to 40%), Portland cement clinker (up to 20%), calcareous fly ash (up to 70%), and calcium sulfate that regulated the process of binding. Thanks to the properly selected composition, the Stabifen hydraulic road binder combines the binding properties of cement and the drying properties of lime. It is intended for the improvement and stabilization of dry and overmoistened heaping soils, as well as dubious and non-frost-susceptible soils. Drohart 22.5 is a binder with properties particularly useful for the preparation of materials for base and auxiliary bases as well as separation layers. It is mainly used in earthworks, road construction, railway traction, airports, and other types of infrastructure. The product consists of Portland cement at 30–50%, pozzolanic additives of type W or V at 50–70%, secondary components, and setting-time regulators (Product catalogue: road binders).

2.3. Test methodology

To determine the effect of the mineral addition on the improvement of the geotechnical properties of the screen-out, mixtures containing 2%, 5%, and 8% of binding materials were prepared. The CBR and compressive strength tests were carried out on the prepared mixtures. All tests involved mixtures with optimal humidity determined by the Proctor method according to PN-EN 13286-2:2010. CBR tests were performed for directly compacted mixes after four days of water saturation. The test of the California bearing capacity was carried out on the basis of the guidelines of the PN-EN 13286-47:2007 standard and consisted in determining the percentage ratio of the force P exerted by a cylindrical pin on a prepared soil sample to a depth of 2.5 mm or 5.0 mm, to the standard force P_s. The California bearing ratio was determined from the following formula (1):

$$CBR = \frac{S}{S_s} \times 100, \quad (1)$$

where: CBR – California bearing capacity, %;

S – force needed to sink a pin into the mixture to a depth of 2.5 mm or 5.0 mm, kN;

S_s – standard force when pin is sunk at depth: 2.5 mm – 13.2 kN, 5.0 mm – 20 kN.

Due to the fact that the CBR was tested immediately after compaction and after four days of saturation in water, the linear swelling capacity of the compacted material was also checked and the change in moisture content of the mixtures after their saturation was determined. Swelling was calculated as the percentage ratio of the change in the height of the sample in the cylinder to the initial height.

The last determination made was the compressive strength of the specimens prepared from compacted mixtures. The compressive strength was determined based on the standard PN-EN 13286-41:2005. These tests were performed on cylindrical samples with a diameter and height of 100 mm (slenderness 1). The samples were compacted by axial compression in a testing machine according to the recommendations of the standard PN-EN 13286-53:2007. Three specimens were prepared from each mix. The compressive strength test was performed after 28 days of maturation in humid conditions.

3. Evaluation of geotechnical properties of screen-outs activated with mineral binders

3.1. Optimum humidity

Optimal humidity was determined on screen-outs and mixtures of screen-outs with binders. The values of optimal humidity and maximum density of the soil matrix are included in Table 2.

Table 2. A summary of the results of determining the optimum moisture content and the maximum bulk density of the soil matrix

Material	Optimum moisture content w_{opt}, %	The maximum bulk density of the soil matrix ρ_{ds}, g/cm^3
Screen-out	9.1	1.99
Screen-out with the addition of 2% lime	10.5	1.97
Screen-out with the addition of 5% lime	11.2	1.95
Screen-out with the addition of 8% lime	11.7	1.94
Screen-out with the addition of 2% fly ash	10.2	2.00
Screen-out with the addition of 5% fly ash	11.4	1.96
Screen-out with the addition of 8% fly ash	12.6	1.91
Screen-out with the addition of 2% binder *Stabifen*	11.3	1.98
Screen-out with the addition of 5% binder *Stabifen*	10.8	1.96
Screen-out with the addition of 8% binder *Stabifen*	11.1	1.95
Screen-out with the addition of 2% binder *Drohart 22,5*	10.7	2.00
Screen-out with the addition of 5% binder *Drohart 22,5*	10.6	1.99
Screen-out with the addition of 8% binder *Drohart 22,5*	10.8	1.98

For both mixtures with the addition of lime and ash, the value of optimal moisture increased with the amount of added binder. For a mixture of screen-outs with the addition of 8% lime, the moisture content was 11.7%, and for the addition of 8% ash, the moisture content was 12.6%. This is due to the drying properties of lime, which is also a component of calcareous fly ash. The more additives were added, the higher was the optimum moisture content, and at the same time, since the bulk density of the additive matrix was lower than that of screen-outs, the bulk density of the entire mixture matrix decreased. Density ρ_d for the screen-outs was 1.99 g/cm^3, while for the screen-outs with the addition of 8% lime it was 1.94 g/cm^3, and for the screen-outs with the addition of 8% ash it was 1.91 g/cm^3.

For the *Stabifen* and *Drohart 22.5* binders, the moisture content of the mixtures varied within a very narrow range of 10.6% to 11.3%. At the same time, the maximum volume density of the matrix slightly decreased. The maximum bulk density of the mixture matrix was at the level of the maximum bulk density of the screen-out matrix.

3.2. California bearing ratio

Figure 2 lists the values of the CBR determined on the specimens immediately after compaction and after 96 hours of water saturation.

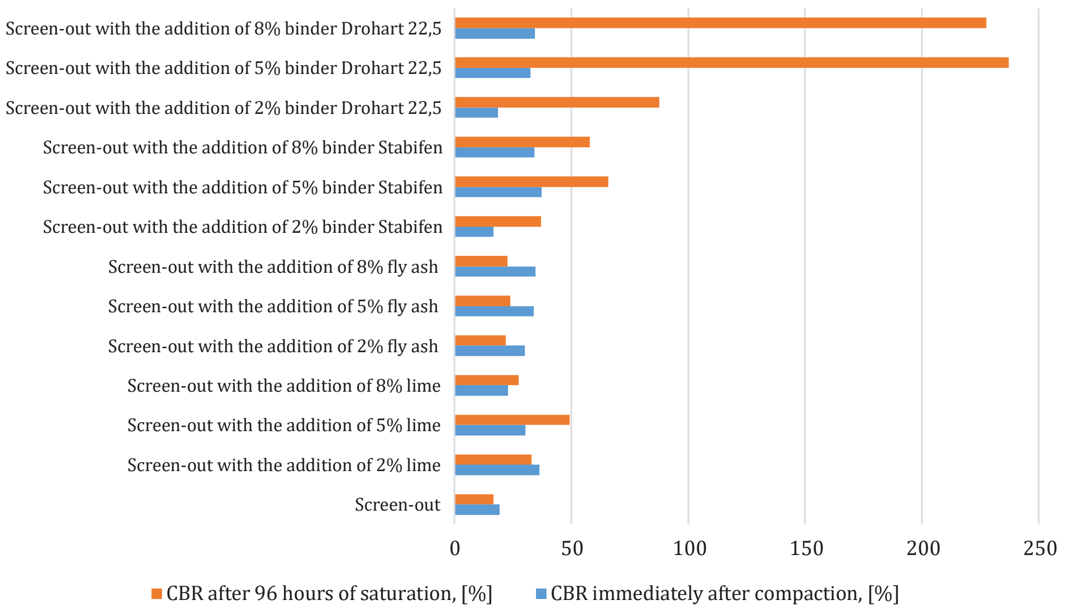

Figure 2. A summary of the results of the CBR determinations

The immediate CBR for the screen-out without additives was 19.3%, while after 96 hours of saturation in water, the value of the index decreased to 16.6%, indicating the adverse effect of moisture increase in the compacted material. The addition of lime and fly ash improved the bearing ratio only immediately after compacting the samples from a dozen to even 50%. This increase resulted from a change in grain size rather than from the bonding process. However, after 4 days of saturation, the samples with added fly ash showed a decrease in the CBR value, while the specimens with lime showed no significant increase in CBR value. In both cases, the CBR value was significantly higher than the CBR value for the screen-out alone. For the road binders, the CBR values increased immediately after compaction at a similar level for the content of 5% and 8% road binders. However, after 4 days of saturation, the CBR values increased compared to the results immediately after compaction: by a factor of two for the *Stabifen* binder and by a factor of seven for *Drohart 22.5*. For the binders containing cement, there were no significant differences in the test results for the contents of 5% and 8%.

3.3. Linear swelling

Table 3 summarises the values of linear swelling and the increase in moisture value of the specimen after 96 hours of saturation.

Table 3. A Summary of the results of linear swelling and changes in moisture content of specimens after 96 hours of saturation

Material	Linear swelling, %	Changes in moisture content, %
Screen-out	0	1.0
Screen-out with the addition of 2% lime	0.16	1.02
Screen-out with the addition of 5% lime	0.10	0.43
Screen-out with the addition of 8% lime	0.11	1.17
Screen-out with the addition of 2% fly ash	0.02	0.68
Screen-out with the addition of 5% fly ash	0.01	0.62
Screen-out with the addition of 8% fly ash	0.02	1.49
Screen-out with the addition of 2% binder *Stabifen*	0.13	0.42
Screen-out with the addition of 5% binder *Stabifen*	0.11	1.13
Screen-out with the addition of 8% binder *Stabifen*	0.17	1.15
Screen-out with the addition of 2% binder *Drohart 22,5*	0.14	0.44
Screen-out with the addition of 5% binder *Drohart 22,5*	0.11	0.58
Screen-out with the addition of 8% binder *Drohart 22,5*	0.18	1.25

The value of linear swelling did not exceed 0.2%, which classifies these mixtures as materials that can be used in earthwork. After 96 hours of specimen saturation, an increase in the moisture content of the compacted mixtures was also observed at a level of about 0.5% to 1.5%, proving the possibility of water penetration (both capillary and seepage) into the layers of the compacted aggregate. In mixtures to which cement-containing binders have been added, the presence of water allows for proper hydration reactions in the mixture.

3.4. Compressive strength

Figure 3 presents the compressive strength values of cylindrical specimens (H/D = 1) made of compacted mixtures of screen-outs and binders.

The analysis of the values of compressive strength of specimens of screen-out mixtures with different binders shows that the highest values of compressive strength were obtained for the road binder *Drohart 22.5,* then similar values for the binder *Stabifen* and lime, and the lowest for ash. For the compressive strength, it can be observed in almost all cases that the higher percentage of the binder, the higher the strength. In the case of a screen-out with 8% lime, the strength value was reduced.

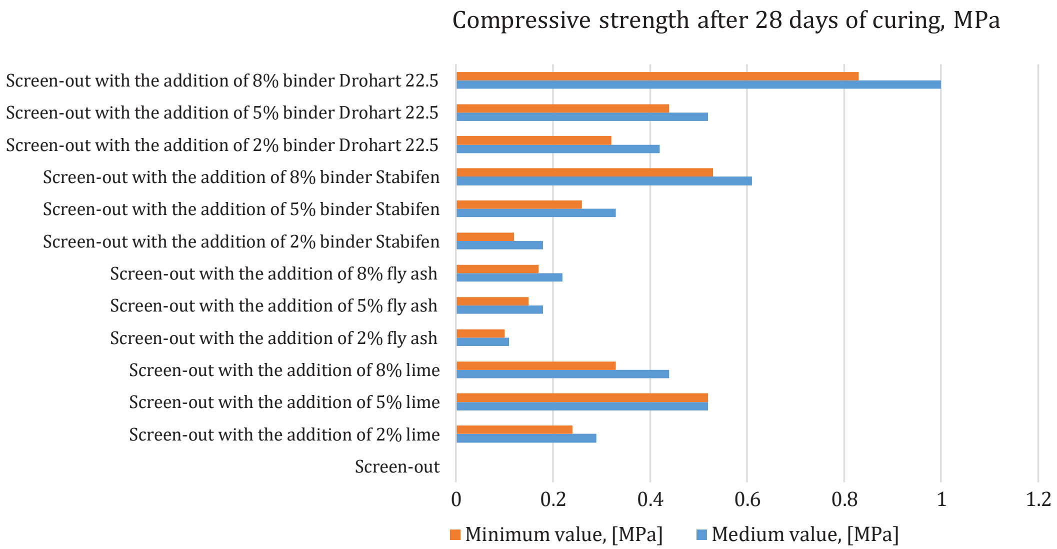

Figure 3. A summary of the compressive strength results

Conclusions

The screen-outs of the Krosno sandstone are characterised by a variable grain size distribution and an uncontrolled content of dust and clay fractions. The low bearing ratio, which does not exceed 20%, precludes the use of this material in road construction. In addition, water has a negative effect on the layers of compressed screen-outs, reducing the bearing ratio by about 20%. Due to the high content of dust and clay fractions, they tend to heave.

The use of mineral binders caused the value of the immediate CBR to increase compared to the screen-out itself from a dozen to as much as 50%. The effect of the setting reactions became apparent after 96 hours of saturation, especially for cement-containing binders. The more cement was contained in the binder, the higher was the bearing ratio. When using a binder containing 20% Portland clinker (*Stabifen*), a CBR of about 60% was obtained, while CBR for a binder containing up to 50% Portland clinker (*Drohart 22.5*) was over 200%. In the CBR tests after 96 hours of saturation, there was no significant difference between the screen-outs containing 5% and 8% of road binder.

The value of compressive strength after 28 days of maturing ranged from about 100 kPa to 1 MPa for all mixes tested. The lowest values were obtained for screen-outs activated with fly ash, and the highest for road binder *Drohart 22.5*. Screen-outs stabilized with cement-containing binders can be considered as material for the construction of the lower layers of the road structure.

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Disclosure Statement

The authors declare that they have no competing financial, professional or personal interests with other parties.

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