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DOI: 10.35117/A_ENG_18_11_08

Suitability of recycled concrete aggregate for transportation infrastructure embankments and improved subgrade

Abstract: The paper presents research in the field of utilizing materials recycled from concrete pavements through crushing and re-incorporating them in road embankments and improved subgrade layers. Crushed concrete rubble is an alternative source of aggregates, replacing natural aggregates. Recycled concrete aggregate was tested with regard to the current national requirements. It was proven that recycled concrete aggregate is a suitable material for incorporation into new unbound and cement-bound layers of the improved subgrade. The problem of utilization recycled concrete aggregate in road embankments is also addressed in the paper. Limitations in the use of recycled concrete aggregate are also shown in the paper.

Keywords: Recycling concrete aggregate; unbound layers; cement bound layers; road embankments

Introduction

Recycled aggregate is the aggregate resulting from the processing of inorganic material used previously in construction; in this case concrete [5]. The world is systematically increasing the recycling of concrete materials. The use of recycled concrete aggregate allows for a significant reduction in the demand for expensive and more difficult access to natural aggregate. In addition, the use of recycled aggregate leads to a practical solution to the environmental problem: it reduces the negative environmental impact associated with the extraction of aggregates from natural resources and reduces the emission of harmful greenhouse gases. The economic benefits obtained in this way cannot be overestimated.

This article presents research on the possibility of reusing recycled aggregates (RCA - Recycling concrete aggregate) of concrete pavements produced in crushers. The application of RCA in unbound and bound cement mixtures to the layers of the improved substrate and to the construction of embankments, including filtration layers, slopes and as reinforcement of the subsoil under the embankments have been analyzed.

It has been shown that in Polish conditions it is possible to use recycled concrete aggregate for making the improved soil and building embankments after verification of the physical and mechanical properties of the obtained concrete aggregate. The use of concrete aggregate for re-incorporation into layers bound with cement and unbound layers, including filtration layers, upper layers of embankments and slopes.

Research on concrete aggregate

The recycled aggregate was obtained from the demolition of existing concrete surfaces from prefabricated and wet poured boards. A view of exemplary demolition boards is shown in Fig.1.

1. View of the pre-crushed plate

Pre-crushed surfaces were crushed using semi-stationary crushers, or mounted to the arm of a tracked excavator (Fig. 2), obtaining fractions similar to typical mixes 0/31,5 and 0/63, depending on the crusher settings (Fig.3).

2. View of the crusher mounted to the excavator's arm

3. Recycled concrete aggregate obtained after crushed plates

On cylindrical samples obtained from crushing core cores, strength parameters, as well as absorbability and bulk density of concretes from road plates, were determined (P1 - prefabricated, P2 - wet poured), compared to structural concrete from footings and foundations of the building (K3). The compressive strength class of concrete compliant with PN-EN 13877-2 [6] is specified on CC30, with reference to prefabricated plates and CC40, in relation to wet poured boards. The class of strength of concrete from elements originating from the construction of foundations of cubature objects was determined on CC20.

The suitability of concrete aggregate for layers of unbound and improved substrate

Physical and mechanical properties of recycled concrete aggregate in basic laboratory tests were determined. The test results were referred to the national requirements of WT-4 [9] and summarized in Table 1. An exemplary curve of granulation of recycled concrete aggregate after crushing in a crusher is shown in Fig.4.

4. An example of a grain curve of concrete aggregate from recycling after crushing with regard to WT-4 requirements

Tab. 1. List of results of testing concrete aggregate from recycling

Tested feature	Norms	Unit	Concrete			Requirements according to WT-4
			P1	P2	K3	auxiliary foundation and foundation improved
Resistance to grinding (10/14)	PN-EN 1097-2:2010	[%]	44,4	32,2	38,6	LA ₅₀ **
Absorbability	PN-EN 1097-6:2013 (pycnometric method)	[%]				WA ₂₄₂
0,063/4			5,1	8,2	9,6	
4/8			5,0	6,7	8,4	
8/16			4,5	5,3	7,5	
16/31,5			4,6	5,8	7,7	
Frost resistance	PN-EN 1367-1:2007 *)	[%]				F10 Recycled aggregates
4/8			4,56	6,76	6,66	
8/16			4,47	3,90	9,16	
16/31,5			2,55	4,48	11,54	

* The frost resistance test is only required for aggregates with a water absorption above 2%

** Does not apply to the substrate improved according to WT4

*** LA35 for KR5 and above according to WT4

It was found that the obtained concrete aggregate does not meet the requirements of absorbability for the substrate upgraded according to WT-4. The frost resistance tests, however, indicate the possibility of using such aggregate without adding rock aggregate (resignation from the requirement of absorbability of 2% under the condition of meeting the requirement of frost resistance for recycled aggregates at the level of 10%). At the same time, it was found that the concrete aggregate obtained from the crumbling of cubic elements has worse resistance to grinding and absorbability and frost resistance, in relation to the aggregate obtained from crushing road plates. This correlation clearly correlates with the lower compressive strength of wells from cubature elements before crushing.

The CBR load capacity index was tested on two batches of recycled concrete from crumbling wet slabs (P2). The results of these tests, with reference to WT-4, are presented in table 2. The load capacity of recycled concrete aggregate with the results of granite aggregate 0/31,5 and the mix of concrete and stone 1:1, also with a grain size of 0/31,5.

Tab. 2. Results of CBR load capacity tests according to PN-EN 13286-47: 2012

CBR [%]	Findings			Requirements
	Recycled concrete aggregate 0/31,5	A mixture of concrete and stone 1:1 0/31,5	Granite aggregate 0/31,5	The substrate improved according to WT-4
BATCH 1	126	141	186	> 40
BATCH 2	90	110		

Significantly higher CBR load capacity is obtained from granite aggregate compared to concrete aggregate. The difference between the results obtained in both batches of recycled concrete aggregate is evident. Such heterogeneity is characteristic for recycled materials, often with an unspecified age, origin and various degrees of depletion. This is a problem often discussed in world literature. In both cases, however, the load capacity requirements set for the WT-4 blends, especially with regard to the improved substrate, have been met with an excess. The filtration coefficient was also tested, which indicated sufficient for the drainage layer, according to WT-4, water permeability at the level of 0.02-0.03 cm/s after sifting from recycled concrete aggregate 0/31.5 silty fraction to 0.063 mm.

Usefulness of recycled concrete aggregate for improved cement boundary layers

The authors conducted soil studies with the addition of recycled concrete aggregate, stabilized with cement according to PN-S-96012: 1997 [8] and mixtures bound with cement to the layers of the improved substrate, according to WT-5 [10].

Detailed results of investigations of cement stabilized soils with the addition of recycled concrete aggregate are presented in [3]. It was possible to limit the amount of cement in a cement-ground mixture after adding recycled concrete aggregate. A significant increase in strength at the content of 40% recycled concrete aggregate has been demonstrated. Depending on the content of cement and recycled concrete aggregate in the ground and cement mix, strengths of C1,5/2.0 - C3/4 were obtained, which according to WT-5 includes the requirements for mixtures for improved substrate layers as well as the auxiliary foundation. The results of strength of soil stabilized with cement, depending on the content of concrete aggregate from recycling and cement in the mix, are shown in Fig.5. A significant effect of the content of recycled concrete aggregate in the ground-cement mixture on the frost resistance of the mixture was also demonstrated (Fig.6).

5. Influence of the concrete aggregate content from recycling in the mixture on compressive strength after 28 days depending on the content of C cement

6. Effect of the content of concrete aggregate from recycling in a mixture on the value of the frost resistance index of cement stabilized mixtures after 14 freezing cycles depending on the cement C content

Usefulness of recycled concrete from recycled to the upper layers of the embankment, reinforcement of embankment bases and reinforcement of embankments

The aggregate research from the recycling of concrete pavements was tested for use in the upper layers of embankments, reinforcing substrates under embankments and strengthening embankment slopes. Friction and cohesion angle tests were carried out. Stability analysis of embankment slopes was made using the aggregate parameters obtained and the conditions and criteria for using this aggregate for reinforcing the embankment slopes were established in order to obtain the required stability.

In order to assess the suitability of the aggregate derived from the recycling of concrete, cohesion and internal friction tests were carried out. These are the parameters that determine the stability of embankment and excavation slopes. Due to the fact that the use of the recycled material itself can be economically unjustified, a study of the mixture of soil and aggregates derived from recycling was carried out. For testing in the shearing apparatus, the soil of questionable suitability for the construction of embankments and reinforcement of slopes (silt clay) and recycled concrete aggregate with a designed grain size of 0/8 mm was used. Shear tests were carried out for soil, recycled concrete aggregate and mixtures of these two materials. The tested mixtures had the following proportions of soil and recycled concrete aggregate: 20/80%, 40/60%, 60/40%, 80/20%. For each of the tested materials, the Proctor compactability was determined. The optimal moisture content and the maximum bulk density of the soil skeleton (aggregates, mixtures) were determined. The results of the tests are presented in Fig.7. Samples intended for direct shear were compacted at the optimum moisture content.

7. Change in the maximum volume density of the skeleton depending on the composition of the mixture

Each of the tested materials was sheared four times at different normal stresses $\sigma = 100, 200, 300$ and 400 kPa. During the test, shear stresses τ was determined at which the sample was cut. The dependence of shear stress on normal is shown in Fig. 8.

8. The dependence of shear stress on normal.

In Fig. 8 linear dependencies are shown: $\tau = c + \sigma \cdot \tan \Phi$ for each mixture. In this way, the angles of internal friction and cohesion were determined. The results of the calculations carried out are shown in Fig. 9-10.

9. Changing the angle of internal friction Φ depending on the composition of the mixture.

10. Change in cohesion C depending on the composition of the mixture.

Laboratory tests of anthropogenic soil material, produced as a result of crushing and screening processes of recycled material of concrete surfaces and mixing it with clay have shown that it has properties of coarse non-cohesive soils or little cohesive soils. It depends on the percentage of added clay to recycled concrete aggregate (from 20 to 80%). It is, therefore, possible to apply it for incorporation into embankment slopes.

In order to assess the suitability of the aggregate derived from the recycling of concrete pavements, stability analyzes of slopes of road embankments of earthworks were carried out. In the face of removal from the Technical Conditions that should be met by public roads and their design [4] of Annex 4, in which the stability conditions of escarpments were specified, the Authors used Eurocode 7 [2]. Designing in accordance with Eurocode 7 requires demonstrating that the computational effects of the interactions are not greater than the corresponding computational resistance R_d :

$$R_d \geq E_d \quad \text{or} \quad \frac{R_d}{E_d} \geq 1 \quad (1)$$

Stability analysis leading to the determination of the minimum value of the stability index $F_{\min}$ should take into account the design values of geotechnical parameters, impacts, and resistances, obtained through the use of partial factors. In commonly used, engineering methods of stability analysis (so-called "stripe" methods) the rotating moment should be treated as a result of interactions M_{Ed} , and the corresponding maintaining moment - as resistance to these interactions M_{Rd} . Stability indicator from the Eurocode 7 definition defines the dependence:

$$F = \frac{M_{Rd}}{M_{Ed}} = \frac{\sum_{i=1}^n R_{ed,i}}{\sum_{i=1}^n (W_{d,i} + Q_{d,i}) \sin \alpha_i} \geq 1 \quad (2)$$

where:

$R_{ed,i}$ – computational soil shear resistance along the base i - this block (stripe),

α_i – the inclination angle of the base i - this block to the level,

$W_{d,i}$ – computational weight i - this block,

$Q_{d,i}$ – external load applied to i - this block.

With this approach, the minimum stability index should not be less than one. The popular Bishop method (simplified), which fulfills the condition of the balance of moments of forces and projections of horizontal forces, is suitable for engineering analysis of road embankment stability. In this method, the stability index after the introduction of the relevant partial coefficients [1] describes a generalized pattern:

$$F = \frac{\sum_{i=1}^n \frac{1}{\gamma_{R,e}} \left[\frac{c_{k,i} b_i}{\gamma_c} + (\gamma_G W_{k,i} + \gamma_G G_{k,i} + \gamma_Q Q_{k,i} - u_{k,i} b_i) \frac{\tan \varphi_{k,i}}{\gamma_\varphi} \right]}{\left(1 + \tan \alpha_i \frac{\tan \varphi_{k,i}}{\gamma_\varphi F} \right) \cos \alpha_i} \quad (3)$$

$$\sum_{i=1}^n (\gamma_G W_{k,i} + \gamma_G G_{k,i} + \gamma_Q Q_{k,i}) \sin \alpha_i$$

where:

$c_{k,i}$ – the characteristic value of the cohesion of the soil found in the base of the i - this block,

$\varphi_{k,i}$ – characteristic value of the angle of internal friction of the soil remaining in the base i - this block,

b_i – width of the i- this block,

α_i – the angle of inclination of the base of the i - this block to the level,

$W_{k,i}$ – the characteristic weight value of the i - this block,

$G_{k,i}$ – characteristic value of the permanent load acting on the i - this block,

$Q_{k,i}$ – characteristic value of the variable load acting on the i - this block.

11. The method of Bishop's method (simplified) [10]

Exemplary stability analysis of road embankment slopes up to 10.0 m high, supported on a supporting foundation (with a slope of 1: 1.5) - showed that they do not require reinforcement (escarpment), provided that the land for the construction of their bodies is used values of shear strength parameters not less than: $\phi = 15 + 17^\circ$ and $c = 17 + 22$ kPa. This corresponds to the given exemplary values of internal friction and cohesion of the mixture of concrete and clay reclamation. However, the bearing capacity of the substrate exerts a large influence on the stability of embankment slopes. It follows that every case of road earthworks requires individual analyzes in terms of their stability and bearing capacity of the ground.

Cohesion and internal friction tests indicate the possibility of using concrete aggregate for building and strengthening embankment slopes. At the same time, the limited suitability of concrete aggregate for improvement of cohesive materials, unsuitable for the construction and strengthening of embankment slopes was found. The addition of economically justified amounts of concrete recycle aggregate (about 20%) to the cohesive material in the on-site mixing technology under construction conditions causes a negligible change in cohesion parameters and the angle of internal friction. At the same time, adding even small amounts (about 20%) of cohesive material to recycled concrete results in a significant decrease in the angle of internal friction. It should be noted that the mix of cohesive material and concrete aggregate is thicker than any of these materials.

In the case of subsoil under the road embankment on mining damage or weak ground (compressible soils), whose load capacity is less than the embankment load, it is necessary to strengthen the ground with a stone mattress wrapped with a geogrid. The mattress should be located at the base of the embankment and filled with recycled material with a grain size of 0/31.5 or 0/63, meeting the requirements as for the main foundation. Aggregate compaction ratio min. 0.98. The thickness of the mattress, as well as the characteristics of the geogrid and the secondary module on the surface of the aggregate layer, should be specified in the design. Aggregate from recycling concrete surfaces can also be used in the upper layers of the embankment provided that the 0/063 mm fraction is rinsed and that the conditions of the filtration coefficient and grain size index are met, according to PN-S-02205 [7].

Summary and Conclusions

The studies and research on the possibility of using materials from the recycling of concrete pavements in crushers included research and analysis of suitability for use in unbound and bonded cement layers of improved soil and for construction of embankments, including filtration layers, slopes and as reinforcement of the ground under embankments.

In the field of concrete testing for recycling, the impact of the origin of recycled concrete aggregate was analyzed. The aggregate obtained from the crushing of road concretes (prefabricated and in situ slabs) and structural aggregates (foundations, footings) was tested. In the case of road concretes, similar physical and mechanical parameters were found. At the same time, worse parameters (strength, absorbability, frost resistance) of structural concrete used in the construction of cubature objects were found. In the case of concretes of unknown origin, it is recommended to test the compressive strength of wells as a predicted assessment of the concrete aggregate properties from recycled crushed. It is recommended to use concretes with an ultimate compression resistance of CC20 for the auxiliary foundation and the improved substrate (both bound and unbound) with simultaneous tensile strength for SC1 splitting.

In the field of research on the use of recycled concrete aggregate for unbound layers, it was found that it can be used in layers of unbound improved substrate (including frost-proof layers),

in mixtures with natural aggregate, or on its own, provided that the resistance to grinding and frost resistance obtained is met. Aggregates according to WT-4. Concrete aggregate obtained from the crushing of road surfaces has better resistance to grinding and absorbability and frost resistance, in relation to the aggregate obtained from the crushing of cubic elements. This correlation clearly correlates with the higher compressive strength of concretes from road surfaces, compared to concretes used in building construction. The conducted research has shown that the aggregate from the recycling of concrete surfaces does not meet the requirements of absorbability for the main, auxiliary and improved substructure of the WT-4, however, it can meet the requirements of frost resistance. It is allowed to waive the requirements of absorbability in the case of recycled concrete aggregate and perform only frost resistance tests. Due to the high heterogeneity of recycled materials, it is recommended for each batch of aggregate obtained to determine the resistance to grinding and frost resistance in relation to the national requirements of WT-4. Aggregate from recycling concrete pavements has a CBR capacity index sufficient for the improved ground according to WT-4. In addition, it is possible to use recycled concrete aggregate for filtration layers of the substrate improved after sieving of silt up to 0.063 mm.

In the field of research on the use of recycled concrete aggregate for cement-bound layers of the improved substrate, it was found that it can be used in cement-bound mixtures or to improve cement-stabilized soils. It is deviated from the requirements of absorbability and frost resistance of the concrete aggregate, in favor of the frost resistance of the finished cement-bound mix/soil stabilized with cement according to WT-5. Ready bounded mixture/cement stabilized soil should meet the strength requirements of WT-5, appropriate for the given layer. In the scope of research on the use of concrete aggregate for cement stabilized soils/cement-bound mixtures for auxiliary foundation layers and the improved substrate, strength tests indicate the possibility of a significant reduction in the amount of binder in the mix after the addition of recycled concrete aggregate. The content of recycled concrete aggregate in mixtures/soils stabilized with cement has a big influence on strength and frost resistance. Depending on the content of recycled concrete aggregate and the amount of cement in the mix, strengths in the range of C1,5/2,0 - C3/4 were obtained, with sufficient frost resistance, with the content of 30% recycled concrete aggregate. These are sufficient requirements according to WT-5 for the improved substrate layers of all traffic categories. At the same time, it was found that increasing the cement content increases the strength of the soil stabilized with cement but does not affect its frost resistance.

In terms of research on the use of recycled concrete aggregate to the top layers of embankments, reinforcement of embankments and construction of embankment slopes, cohesion, and internal friction tests were carried out. It has been shown that the mixture of concrete aggregate and cohesive soil compacts better than each of these materials separately. The exemplary stability analysis of road embankment slopes from such a material, placed on a supporting foundation (at the inclination of slopes 1: 1.5), showed that they do not require reinforcement. At the same time, the limited suitability of concrete aggregate for the improvement of cohesive materials was found, for economic reasons. Conducted tests of aggregates from recycled concrete have shown that it is also possible to apply the tested aggregate to the upper layers of the embankment provided that the 0/063 mm fraction is sifted and the conditions for the filtration coefficient and grain size index are met. It is also possible to reinforce the foundation of the embankment with a "mattress" of concrete aggregate, provided that the requirements for the foundation layers according to WT-4 are met.

This article was created in connection with the implementation of research tasks in the project entitled "The use of recycled materials", as part of the Road Innovation Development (RID) joint

venture, co-financed by the National Center for Research and Development and the General Directorate of National Roads and Motorways.

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