DOI 10.51558/2303-5161.2024.12.12.12 Scientific Paper

RECYCLING OF MATERIALS FROM THE EXCAVATION OF THE "POČITELJ" TUNNEL AND INCORPORATION OF THE OBTAINED PRODUCTS IN THE TUNNEL THROUGH CONCRETE AND BLINDING LAYER

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ABSTRACT

In civil engineering or road construction, especially when constructing tunnels, large quantities of excavated material are created. In many cases, this material, if properly treated and processed, can be recycled and reused on site. If this material is not treated as planned from the beginning of the project, but is taken to the landfill and mixed with bad material or construction waste, then when the need for it arises, it is difficult to separate it and return it to the construction process. In the simplest case, the material can be used as an embankment to the extent that it meets the requirements regarding the quality of the embankment material. Better quality material can often be recycled to make fractions for various types of concrete, buffer aggregates or decorative stone walls (architectural stone). In the current example of the "Počitelj" tunnel, through tests of fractions, definition of recipes, recycled material from tunnel excavation was successfully used as aggregate for shotcrete, concrete for inner lining and construction, buffer, bedding for laying pipes and making front slopes from crushed stone. This reduced the purchase and transport of aggregates from local quarries to the minimum possible, thus saving resources, with financial benefit. In summary, through this example, it can be noted that the reuse of tunnel excavation will play an important role for future tunnel projects due to environmental and economic reasons.

Keywords: tunnel, excavation, limestone, concrete, blinding layer, recycling

INTRODUCTION

The strategy of extensive material recycling has already been successfully implemented in the construction of some of the longest tunnels in the world: the Swiss Lötschberg and Gotthard Base Tunnels [1]. There, the construction site's own production was carried out with recycled aggregate, which was mostly produced on the construction site [2]. In other research projects, it could be shown that, with the fulfillment of certain conditions, excavation was used as an aggregate resource for road construction. [3].

A scientific approach to the use of excavated materials extends from the planning and decision-making process of handling excavated materials to technological implementation, focusing on technical development in relation to material analysis and realization of raw materials [4]. Therefore, large international research projects have been carried out in the framework of sustainable production of raw materials and recycling. Not least, structural engineering considerations must be taken into account in tunnel design when using recycled aggregate for construction concrete to meet the design service life of the tunnel structure. [5].

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Especially in terms of saving resources and protecting the environment - the goal must be the maximum share of material recycling and its incorporation, and not its disposal as "tailings" in a landfill. As a result, a high level of material recycling was achieved from the excavation of the "Počitelj" tunnel, which was constructed on the Zenica-Sarajevo-Mostar highway, the Počitelj-Bijača section, the Počitelj-Zvirovići subdivision. Most of the excavated rock material was used there during continuous tunnel excavation with particular importance in terms of quality management due to its use for high quality concrete products such as linings, structural concrete and blinding layer embankment.

Geological characteristics of the terrain in the "Počitelj" tunnel construction zone

Generally speaking, the area belongs to the mountainous terrain, with altitudes ranging from 134.0 to 261.0 m. The maximum elevation of the terrain above the level of the tunnel is 261 m.a.s.l. that is, the maximum height of the upper layer is about 110m.
On the basis of the engineering-geological mapping of the terrain and the core from the exploratory boreholes, in the engineering-geological sense, the following categories were distinguished:

- Eluvial-deluvial formations,
- Degraded geological substrate and
- Geological substrate.

Eluvial-deluvial formations are separated at the surface part of the field. It was created as a result of erosion-denudation processes on the surrounding slopes. According to the results of exploratory drilling, a lithological member of humus clay, red-brown in color, was isolated. Humus clays are represented in the surface parts of the terrain, positioned directly over the weathering crust of the geological substrate. The thickness of the deluvial cover is variable and ranges from 0.50 to 1.20 m.

Degraded geological substrare is represented as disintegrated and decomposed limestone. The thickness of the swollen formations of the degraded geological substrate ranges from up to 3.0 m. From the engineering-geological aspect, these zones build conditionally stable to stable terrains.

Geological substrate represents limestone. Limestone has a massive texture and less often thick-layered. In some places, these rocks have cracked more strongly with the presence of a system of cracks due to the karstification process. Clasts have a layered, bank-like to partially massive texture and a crystalline to cryprocrystalline structure. These are rock masses with fissure-cavernous porosity. The position of the stratification in relation to the disposition of the tunnel route is generally favorable, if one takes into account the construction of the tunnel from the direction of the exit portal. They build stable terrains with favorable mechanical properties.

Recycling of excavated material during the construction of the „Počitelj tunnel“

The length of the right tunnel tube of the "Počitelj" tunnel, including the portal structure, was 1163.0m', while the length of the left tunnel tube was 1192.0m'. The tunnel tubes are connected with three pedestrian crossings and one passage for emergency vehicles. The excavation area on average was approx. 73 m3/m' of the tunnel. If we subtract from the total length the portal construction, and approx. 5m' of degraded geological substrate including eluvial-deluvial formations, we get the total length of both tubes of 2300m', the material of which is recycled. The total amount of material that had to be recycled from excavation can be calculated using the following formula:

$$U = L \cdot P \cdot \gamma$$

Where:

U - total amount of recycled material from excavation (ton.),
L - the total length of both tubes whose material is recycled, in our case is 2,300 (m),
P - average excavation area, in our case is 73 (m^2),
ɣ - volumetric mass with pores and cavities, in our case it is 2,67 (t/m^3).

So we can calculate the total amount of material that had to be recycled from the excavation of the Počitelj tunnel:

$$U = L \cdot P \cdot \gamma = 2300 \cdot 73 \cdot 2{,}67 = 448.293\ (t)$$

When defining the area for dumping excavated material from the tunnel and the area for recycling, care was taken to ensure that it was in the immediate vicinity of the tunnel location itself, in order to reduce transport costs to the lowest possible level and achieve significant benefits. The spatial location of the deposition of excavated material from the Počitelj tunnel is shown in Figure 1.

Figure 1. Location of the excavated material dump and its recycling in relation to the entrance to the tunnel [6]

At the very beginning of the excavation of the tunnel, and before the start of recycling the excavated material, a test of the physical and mechanical characteristics of the rock material from the excavation was carried out. Table 1 shows the physical and mechanical characteristics of the rock from the excavation of the Počitelj tunnel.

Table 1. Physical and mechanical properties of the rock from Pošitelj tunnel excavation [7]

Tested properties	***Test method***	***Test results***	***Quality conditions***	
			Concrete JUS B.B2.009	*Asphalt concrete JUS U.E4.014*
Compressive strength in dry state (MPa)	JUS B.B8.012	max. 207,0 min. 154,0 **avg. 185,0**	min.80 MPa min.160 MPa*	Highway; very difficult and difficult min.160 MPa** average; min.140 MPa** light and very light; min.120 MPa**
Water-saturated compressive strength (MPa)		max. 190,0 min. 150,0 **avg. 165,0**		
Loss of compressive strength (%)	JUS B.B2.009	10,37	max 20 %	-
Frost resistance (Na_2SO_4) (%)	JUS B.B8.002	0,06	max.5 %	max.5 %
Water absorption (%)	JUS B.B8.010	0,30	max.1 %	Highway; very difficult and difficult max. 0,75% average; max. 0,75% light and very light; max. 1%
Volumetric mass with pores and voids (g/cm^3)	JUS B.B8.032	2,67	2-3 g/cm^3	-
Volumetric mass without pores and voids (g/cm^3)		2,70	2-3 g/cm^3	-
Volumetric mass coefficient		0,987	-	-
Porosity (%)		1,303	-	-

Based on the analyzes of the excavated rock, the possibility of using recycled products from the mentioned rock in all types of concrete as well as road construction for making the blinding layer has been confirmed. The arrangement of the selected area on which the rock material from the excavation will be recycled was carried out, and the necessary equipment for the recycling of rock material from the tunnel excavation was mobilized and installed, Figure 2.

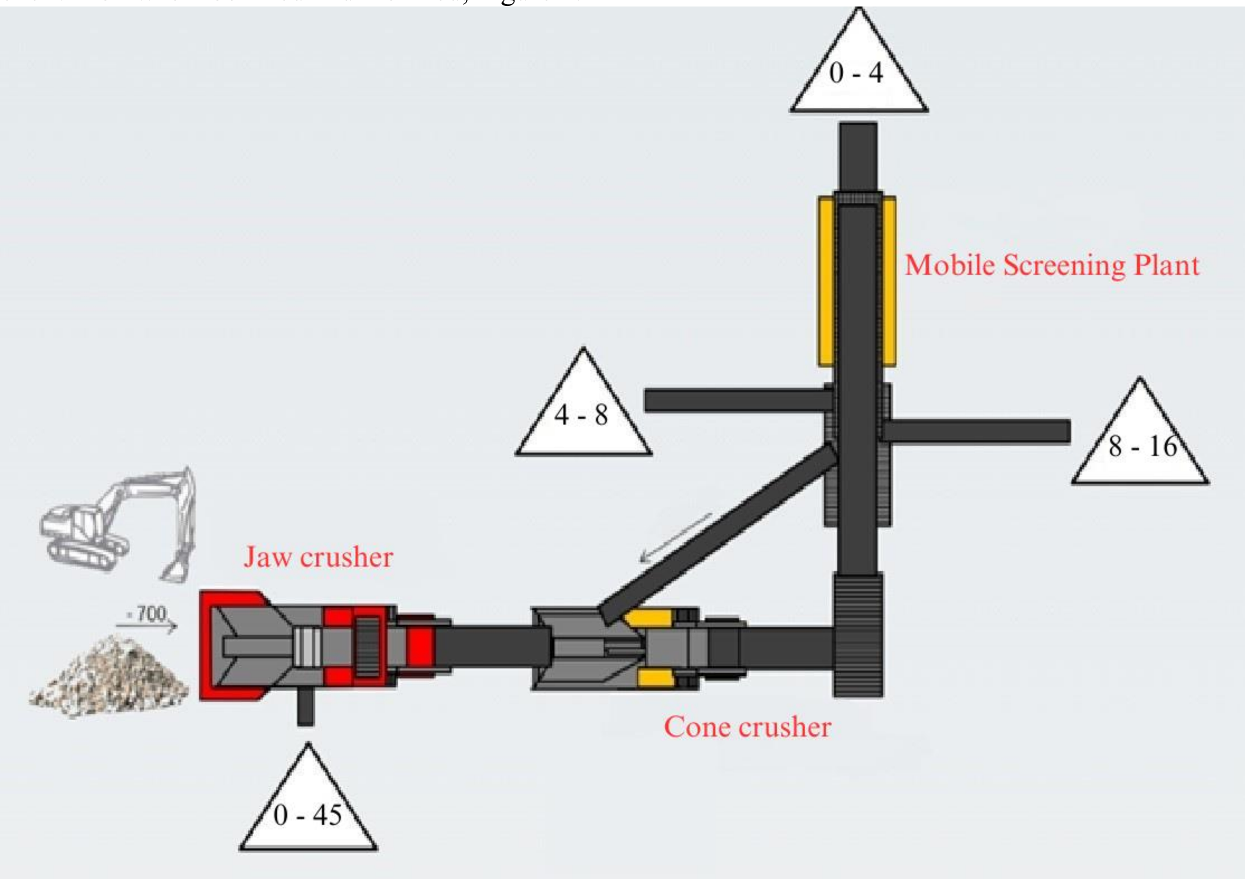

Figure 2. Schematic view of the installed equipment for recycling rock material from tunnel excavation

Demined material from the excavation of the tunnel was transported by trucks to the plateau not far from the entrance to the tunnel (Figure 1), where a material recycling plant was installed as shown in Figure 2. The material delivered by an excavator or a loader was dosed to a jaw crusher where material with a coarseness of 0 -45mm (which was used as a blinding layer) while the over-sieved product of the vibro grid with a granulation of 150 - 45mm was sent to the cone crusher by belt conveyor. In the cone crusher, stone material was additionally crushed to a granulation of 0-20 mm. After the cone crusher, the material was transported by a rubber conveyor to a mobile seeder, where the material delivered from the cone crusher was classified into final fractions: 0-4, 4-8 and 8-16mm. The fraction that is larger than 16 mm is returned by belt conveyor to the cone crusher for additional crushing. The entire amount of excavated material during the excavation of the Počitelj tunnel was recycled. The smaller amount that was excavated at the entrance and exit portal and belongs to eluvial-deluvial formations and degraded substrate was used on the access routes with refinement with limestone granulate.

Incorporation of the products obtained by recycling in the tunnel and access route

Before the actual use of the recycling aggregate, it was necessary to prove its usability, as a result of which aggregate controls were carried out in accordance with the valid technical regulations and requirements of the EN 206-1 standard, as well as the provisions of the cement concrete specification [8]. The results of aggregate tests are shown in the following tables (Table 2).

Table 2. Physical and geometric properties of aggregates [7]

Tested characteristics (According to the guidelines for design, construction, maintenance and supervision on roads Book II: Construction, Part 2: Special technical conditions i Regulations for concrete)	**Test method**	**Test results**		
		Nominal fraction (mm)		
		0/4	4/8	8/16
Proportion of grain size up to 0,063 mm (%)	BAS EN 933-1:2012	**11,5**	**0,5**	**1,0**
Sand equivalent, SE (%)	*BAS EN 933-8+A1:2016	**66**	**-**	**-**
Bulk density, ρ_b (Mg/m^3)	*BAS EN 1097-3:2007	**1,546**	**1,300**	**1,374**
Resistance to crushing, LA (%)	*BAS EN 1097-2:2011	**-**	**-**	**24**
Grain density, ρ_a (Mg/m^3)	*BAS EN 1097-6:2014	**2,726**	**2,721**	**2,742**
Water absorption, WA_{24} (%)		**0,31**	**0,53**	**0,46**
Frost resistance, MS (%)	*BAS EN 1367-2:2011	**-**	**-**	**1,0**
Frost resistance, $N_{a2}SO_4$ (%)	*JUS B.B8.044	**0,47****	**0,48**	**0,50**
The grain shape of the coarse aggregate, SI (%)	*BAS EN 933-4:2011	**-**	**13**	**13**
(**) – examined on the fraction 2/4mm				

Table 3. Granulometric analysis of small aggregates (BAS EN 933-1:2012) [7]

Faction label d/D (mm)	Passing through the sieve (%)										
	0,063	0,09	0,125	0,25	0,5	0,71	1	2	D	1,4D	2D
0/4	**11,5**	**13,6**	**16**	**26**	**42**	**51**	**66**	**89**	**100**	**100**	**100**

Table 4. Granulometric analysis of coarse aggregate (BAS EN 933-1:2012) [7]

Faction label d/D (mm)	Passing through the sieve (%)											
	0,063	0,09	0,125	0,25	0,5	1	2	d/2	d	D	1,4D	2D
4/8	**0,5**	**0,5**	**1**	**1**	**1**	**1**	**1**	**1**	**11**	**97**	**100**	**100**
8/16	**1,0**	**1,0**	**1**	**1**	**1**	**1**	**1**	**1**	**10**	**98**	**100**	**100**

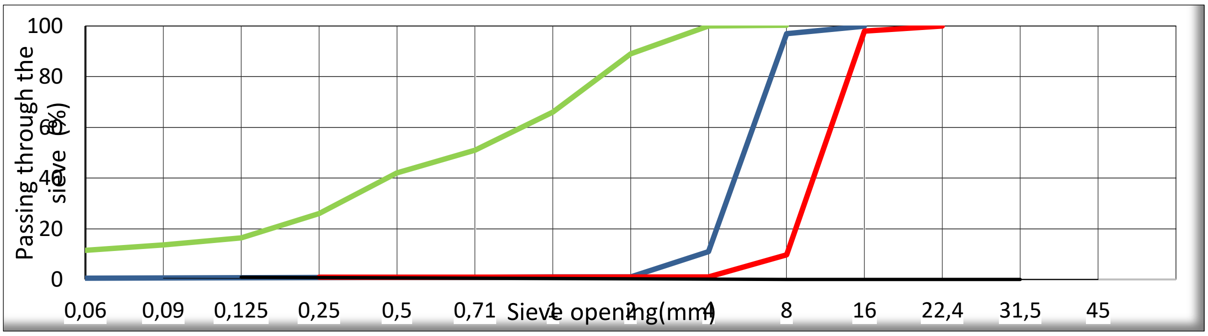

Figure 3. Graphic representation of granulometric composition - (BAS EN 933-1:2012) [7]

Mineral-petrographic and chemical analysis of the fractionated rock aggregate from the excavation of the "Počitelj" tunnel was performed by the Faculty of Mining, Geology and Civil Engineering, University of Tuzla according to standard norms. Table 5 shows the mineral and petrographic composition of the aggregate [9].

Table 5. Mineral-petrographic composition of aggregates

Genetic type	The name of a rock or mineral	Large aggregate		Small aggregate
		Content of mineral-petrographic species in % mass		
		8 - 16	4 - 8	0 - 4
Sedimentary rocks	Gray to brown crystalline limestones. Some of the fragments are coated with limonite scrum. The fracture is irregular, with irregular to shell-like fracture surfaces. Individual fragments are interspersed with cracks (filled with secondary, transparent calcite) of irregular orientation and different diameters. The reaction to dilute HCl acid is violent and immediate. The insoluble residue is negligible.	95	95	96
Minerals	Calcite/secondary, translucent to white	3	3	1
	Limonit (skrama)	2	2	4
TOTAL:		***100***	***100***	***100***

Table 6 gives an overview of the ingredients that could be harmful to the concrete mix to the extent that they would be contained in the fractions.

Table 6. Overview of the presence of ingredients that can be harmful in the concrete mix [9]

The name of the identified potentially harmful components in the aggregate	Large aggregate		Small aggregate
	Content of mineral-petrographic species in % mass		
	8 - 16	4 - 8	0 - 4
INGREDIENTS THAT CAN BE HARMFUL FOR PHYSICAL - MECHANICAL PROPERTIES			
Changed grains (worn and weak grains)	0	0	0
Clay sandstones	0	0	0
Marls and marly carbonates	0	0	0
Clay rocks, mica rocks, phyllites, etc.	0	0	0
Grains with scraps of limonite, clay and opal	2	2	1
Gypsum (gypsum) and anhydrite	0	0	0
Clay and clays	0	0	0
Serpentine, mica and siltstone	0	0	0
Coal	0	0	0
TOTAL:	***2***	***2***	***1***
INGREDIENTS THAT MAY BE REACTIVE			
Opal (Amorphous SiO2)	0	0	0
Tridymite, cristobalite, zeolite	0	0	0
Horns with opal	0	0	0
Acid silicate glasses	0	0	0
Dolomitized limestones with clay minerals	0	0	0
Hydromics (illite and sericite)	0	0	0
TOTAL:	***0***	***0***	***0***
SASTOJCI KOJI MOGU PROUZROKOVATI KOROZIJU ARMATURE U BETONU			
Halite	0	0	0
Silvina	0	0	0
Pyrite oxidized	0	0	0
Marcasite	0	0	0
Pirhotin	0	0	0
Anhydrite	0	0	0
Tuff	0	0	0
TOTAL:	***0***	***0***	***0***

Table 7 shows the results of chemical tests of the fractions obtained by recycling stone material from the excavation of the "Počitelj" tunnel.

Table 7. Results of chemical tests of fractions [9]

Parameters	Units	Methodology	Results	MDK
Fraction soluble in water				
Chlorides	%	JUS.B.B8.042	0,002	0,1 % AB 0,02% PB
Fraction soluble in acid				
Sulfates as SO3	%	JUS.B.B8.042	0,005	-
Total sulfur	%	JUS.B.B8.042	0,15	-
Content of total carbonates	%	JUS.U.B1.026	94,86	-

On the basis of mineral-petrographic tests, it can be concluded that the analyzed fractionated aggregates mostly belong to sedimentary, carbonate rocks: limestones, crystalline structures and homogeneous textures. The aggregate contains little (negligible) limonite scrum. Ingredients that can cause the destruction of concrete, as well as ingredients that can be reactive under certain conditions, have not been identified. Ingredients that can be harmful to physical-mechanical properties are within very low limits. The results of chemical tests indicate low values of chloride and total sulfur regarding the use of fractions for the production of all types of concrete. A high percentage of total carbonate content (94.86%) indicates the purity of the aggregate.

Concrete trial production and installation

Before starting the mass production of concrete, it is necessary to check and prove the recipes of the cement concrete mixture in production on the appropriate production base [5].
Not far from the plateau where the excavated material was recycled during the excavation of the tunnel, the contractor installed a concrete plant for the production of all cement concrete from the fractions obtained from the recycling, figure 4.

Figure 4. Layout of the installed concrete plant for concrete production [6]

Before the trial production and installation of any class of cement concrete, the composition of the specified concrete recipe was adopted at the contractor's concrete plant. In addition to the adoption of the composition of the concrete recipes, it was necessary to establish the correctness of the landfill and production plant for fresh cement concrete mixtures, the correctness of the chosen method of transportation and installation equipment, and to take samples of the mixture at the place of installation to test the characteristics of fresh and hardened cement concrete. In the continuation of the work, a presentation of one of the adopted recipes, which refers to shotcrete C25/30, XC2, Dmax8, C10.2, S4, and the results of the control and testing on the said shotcrete [10] is given.

Table 8. Adopted shotcrete recipe C25/30, XC2, Dmax8, C10.2, S4 [10]

Type of concrete	***MLAZNI BETON C25/30***			
Concrete strength class	C25/30			
v/c factor	0,47			
Concrete composition for 1000 liters of fresh concrete				
		kg/dm³	dm³	kg
Cement:	CEM II/B-W 42,5N, TC Kakanj	3,00	145,20	**450**
Water:	Local water supply	1,00	211,00	**211**
Additive:	Dynamon LZF 4710, MAPEI	1,05	2,83	**3**
Aggregate:		2712	610,60	**1656**
Residual air pores:		0	30,00	**0**
Total			1000	**2320**
Distribution of aggregates by fractions (kg)				
1	0/4 mm	crushed	70 %	**1158**
2	4/8 mm	crushed	30 %	**498**

Table 9. Participation of individual fractions in the shotcrete mixture [10]

Fraction	Part (%)	(%) passes through the opening sieve # (mm)										
		0,063	0,09	0,125	0,25	0,5	1	2	4	8	16	31,5
0/4 mm	70	7,2	8,7	10,6	14,6	21,7	34,1	50,0	69,6	70,0	70,0	70,0
4/8 mm	30	0,2	0,2	0,3	0,3	0,3	0,3	0,3	1,8	27,4	30,0	30,0
TOTAL:	100	7,4	8,9	10,9	14,9	22,0	34,4	50,3	71,4	97,4	100,0	100,0

Figure 5 shows the granulometric curve of the shotcrete mix with Dmax 8mm.

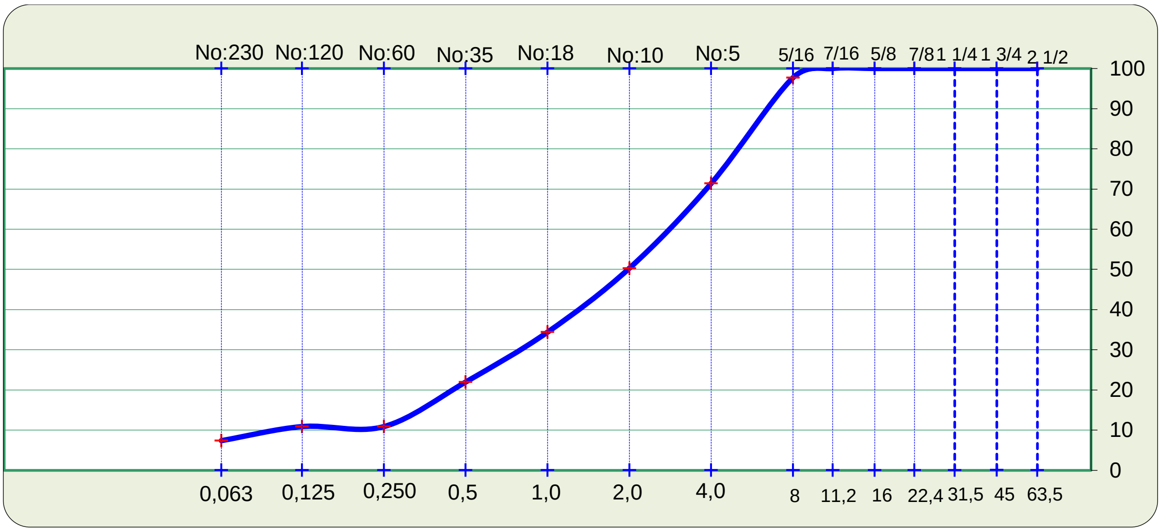

Figure 5. The granulometric curve of the shotcrete mix with Dmax 8mm [10]

Table 10 shows the results of testing the early compressive strength of shotcrete after 60 minutes, while Table 11 shows the results of the strength development of shotcrete at 24 hours.

Tabela 10. Rana pritisna čvrstoća mlaznog betona prema BAS EN 14488-2:2008 [10]

No/ minute	Penetrometer testing (MEYCO)										average value	compressive strength (MPa)
	1	2	3	4	5	6	7	8	9	10		
6	12	10	14	11	12	12	16	9	10	11	11,7	0,18
15	24	26	26	30	28	29	24	30	30	28	27,5	0,42
30	38	38	42	40	42	44	46	36	42	42	41,0	0,62
60	61	57	60	62	55	57	60	62	62	60	59,6	0,91

Table 11. Test of fresh shotcrete by screwing [10]

Time [hours]	screw length [mm]	Screw test										average value
		1	2	3	4	5	6	7	8	9	10	
24	**80**	38	48	48	46	50	42	39	45	41	47	44,4
penetration (mm)		42	32	32	34	30	38	41	35	39	33	35,6
pulling force(N)		4600	3600	3500	4700	2800	4000	3700	4000	2900	3100	3690,0
calc. force (N)		4370	3420	3325	4465	2660	3800	3513	3800	2755	2945	3505,3
compressive strength (MPa)		13,9	14,3	13,9	17,4	11,9	13,4	11,5	14,5	9,5	12,0	**13,2**

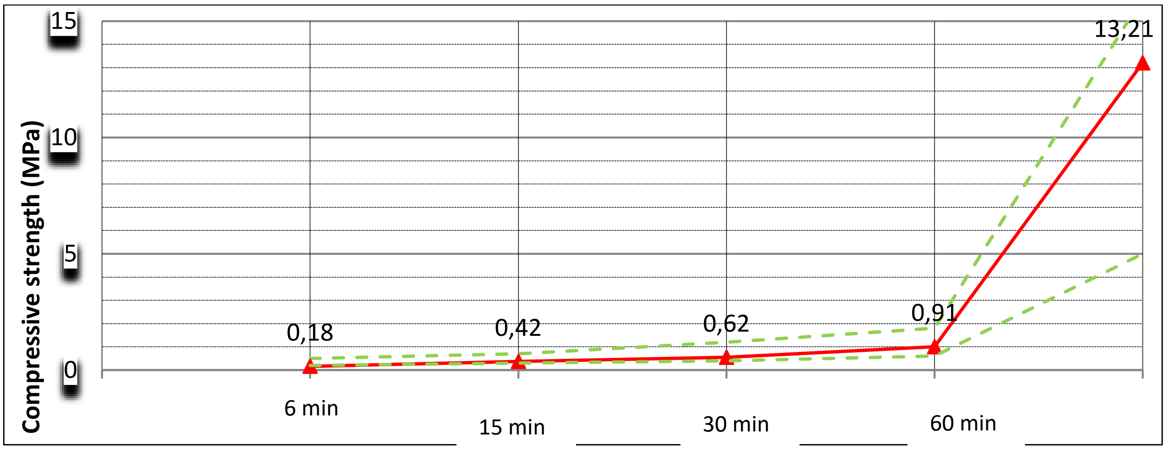

Figure 6. Diagram of increase in strength of shotcrete [10]

Testing of the compressive strength of shotcrete according to the standard BAS EN 12504-1:2020/Cor1:2022, age of samples of 7 days is shown in table 12.

Table 12. Testing the compressive strength of shotcrete, 7 days old [10]

mark	*age (days)*	*diameter (mm)*	*height (mm)*	*weight (g)*	*volumetric mass (kg/m³)*	*breaking force (kN)*	*compressive strength (MPa)*
25-TPC-20	7	99,8	100,2	1821	2324	308,8	39,5
25-TPC-20	7	99,8	100,6	1810	2301	263,2	33,7
25-TPC-20	7	99,8	100,8	1807	2293	245,4	31,4
Medium value:							***34,8***

Testing of the compressive strength of shotcrete according to the standard BAS EN 12504-1:2020/Cor1:2022, age of samples of 28 days is shown in table 13.

Tabela 13. Testing the compressive strength of shotcrete, 28 days old [10]

mark	*age (days)*	*diameter (mm)*	*height (mm)*	*weight (g)*	*volumetric mass (kg/m^3)*	*breaking force (kN)*	*compressive strength (MPa)*
25-TPC-20	28	99,8	100,4	1804	2298	356,0	45,5
25-TPC-20	28	99,8	100,0	1811	2316	407,7	52,1
25-TPC-20	28	99,8	100,2	1819	2322	374,5	47,9
Medium value:							***48,5***

Based on the analysis and test results of the designed shotcrete composition (C25/30, XC2, Dmax8, Cl0.2, S4, composition marks C25/30 MB/III), to conclude that the shotcrete meets all the criteria defined by the relevant technical conditions and standards.

CONCLUSION

Recycling of materials during tunnel excavation is becoming more and more important in the world, including in Bosnia and Herzegovina. This is not only due to the large quantities of excavated rock mass that must otherwise be disposed of in the area, but also due to ecological and economic reasons during the construction of the mentioned tunnels. In times of sustainability, resource efficiency and emissions minimization, it is a logical decision to recycle and reuse the excavated tunnel material as much as possible depending on the characteristics of the rock material.

In this work, it was shown that for the successful implementation of recycling, previous research on the quality of the rock mass in the tunnel excavation zone, as well as adequate technical performance of the concrete processing and mixing plant, is necessary. This is followed by the trial production of aggregates from the excavated raw material with the collection of data on the achieved characteristics of the aggregates and the processing process. The goal here is to test different types of crushers and mills, to find optimal machines for crushing and screening in order to achieve optimal geometric properties of the produced aggregates. Implementation of an efficient and adequate treatment facility plays a key role in the success of recycling implementation. In the case of the current example, a two-stage crushing system using a jaw and cone crusher, as well as sieving on a vibrating sieving with three sieving levels, was applied. A sprinkler system was installed at the complete processing and sieving plant with the aim of reducing the emission of dust emissions into the atmosphere. After optimizing the aggregate quality, concrete testing is required to find concrete mix performances for different types of concrete and applications that ensure high stability and durability of concrete structures.

In the current example of the "Počitelj" tunnel, through tests of fractions, definition of recipes, recycled aggregate was successfully used as aggregate for shotcrete, concrete for inner lining and concrete for structures. This reduced the purchase and transport of aggregates from local quarries to the minimum possible, thus saving resources, with financial benefit. In summary, through this example, it can be noted that the reuse of tunnel excavation will play an important role for future tunnel projects due to environmental and economic reasons.

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