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LIGHTWEIGHT AGGREGATES MADE FROM FLY ASH USING THE COLD-BOND PROCESS AND THEIR USE IN LIGHTWEIGHT CONCRETE

LAHKI AGREGATI IZDELANI IZ ELEKTROFILTRSKEGA PEPELA S POSTOPKOM HLADNEGA VEZANJA IN NJIHOVA UPORABA ZA LAHKE BETONE

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Aggregates made from fly ash have been developed by means of the cold-bonding process, with the addition of Portland cement as a binder at (10, 20, and 30) % of mass fractions, and by pouring the mixtures into moulds. After curing for 28 d the samples were processed into aggregate by crushing and sieving. An aggregate containing a weight percentage of 10 % of cement was additionally produced by pelletization on a granulating plate. The density, water-adsorption capacity, porosity, compressive strengths, and frost resistance of the samples were determined. The aggregates prepared by both routes were then used to make concrete samples, whose properties were then compared to those of conventional concrete made using limestone aggregate. The compressive strength of the concrete made with the granulated aggregate reached 16.0 MPa after 28 d, whereas that of the concrete made with crushed aggregate amounted to 24.1 MPa, and that of the conventional concrete was 34.6 MPa.

Keywords: fly ash, lightweight aggregates, density, compressive strength, frost resistance

Agregati izdelani iz elektrofiltrskega pepela so bili razviti s postopkom hladnega vezanja, z dodatkom (10, 20 in 30) % masnega deleža Portland cementa kot veziva in z ulivanjem mešanice v modele. Po 28 dnevnem strjevanju vzorcev so bili vzorci predelani v agregat z drobljenjem in sejanjem. Sestava, ki je vsebovala 10 masnih % cementa, je bila še dodatno peletizirana na plošči za granuliranje. Določene so bile: gostota, kapaciteta absorpcije vode, poroznost, tlačna trdnost in odpornost na zamrzovanje. Sestave, izdelane na oba naćina, so bile uporabljene za izdelavo betonskih vzorcev, katerih lastnosti so bile primerjane z lastnostmi običajno izdelanega betona z uporabo sestave apnenca. Tlačna trdnost betona, izdelanega z granulirano sestavo, je dosegla 16,0 MPa po 28 dneh, medtem, ko je pri betonu izdelanem iz drobljenega agregata, znašala 24,1 MPa, pri običajnem betonu pa je bila 34,6 MPa.

Ključne besede: elektrofiltrski pepel, lahki agregati, gostota, tlačna trdnost, odpornost na zamrzovanje

1 INTRODUCTION

Although, if it has a suitable composition, fly ash can be added to cement to form a "blended cement", much of this ash is still deposited on landfill sites, causing an environmental burden. Apart from this, according to the European Waste Catalogue[1] fly ash is labelled as hazardous waste, so that even higher costs are incurred for landfilling. Because of these facts, more and more scientists have been trying to find new ways in which such ash could be used, e.g., for the development of alkali-activated materials, which are frequently named geopolymers[2,3], but also for the production of artificial aggregates.[4–13] Artificial aggregates can be obtained simply by the crushing and grinding of industrial waste if the basic starting material is bulk waste. If, however, the basic starting material is a fine powder, such as fly ash, such aggregate can be produced by several different routes, as follows:

1) by high-temperature procedures, e.g., foaming and/or sintering at elevated temperatures of approx. 1200 °C,
2) by a hydrothermal process at a temperature of approx. 250 °C (autoclaving),
3) by the cold bonding process, where consolidation takes place at room temperature.

In the last case a binding agent needs to be added to the mixture in order to achieve such consolidation. This agent is usually cement and/or water glass.[14–18]

In the first two processes a lot of energy is consumed, so that recently more effort has been put into investigations of cold-bonding processes.

The most common method for the preparation of aggregates from dust waste (e.g., fly ash) is granulation on a pelletization plate. The efficiency of granulation depends on the fineness of the fly ash, speed and time of rotation of the plate, as well as its inclination and the diameter of the plate [8,12,15,19]. From the point of view of costs, another more favourable method exists, in which there is no need for a pelletization plate, or for dry waste powder. This alternative method consists of mixing the raw material with a binder, and pouring the mixture into models. After the consolidation, setting, and hardening processes have been completed, the samples are crushed and sieved into different fractions.

Aggregates obtained in the above-described ways (especially granulation) almost always have lower densities. According to the definitions given in the standard EN 13055-1:2002 [20], lightweight aggregates (LWAs) are those whose maximum particle density does not exceed 2000 kg/m^3, and whose loose bulk density does not exceed 1200 kg/m^3.

For some decades lightweight aggregates have been used in concrete instead of ordinary aggregates, mainly because of their contribution to the improvement of thermo-insulation properties. Apart from this, if LWAs are used, then a reduction can be achieved in the concrete's own weight, which can be important in earthquake-prone areas, as well as in cases where the subsoil beneath the foundations has a low bearing capacity. During the last decade much attention has been paid to the role of LWAs with open porosity in the internal curing of concrete. This is because lightweight aggregates with such porosity can serve as water reservoirs, which are available for later hydration, thus leading to higher compressive strengths.[21–23] Many authors used lightweight aggregates made of fly ash in concreate to investigate the strength and durability of hardened concrete, and the influence of a lightweight fly-ash aggregate microstructure on the properties of concrete.[24–29] As expected, the compressive strength of LWAC is lower than the one produced by natural aggregate, even though LWAC can anyway serve as a structural concrete.[25] If fly-ash aggregate is sintered, it reaches a higher compressive strength of the aggregate itself, and consequently a higher compressive strength of the concrete is achieved.[26] For cold bonded (non fired) aggregate it is also reported that chloride penetration could be somewhat higher.[27] It is well recognized that by applying a sintering process the properties of LWAs are improved significantly,[27,29] but it shall be noted that the firing process contributes to a much higher production cost, and on the other hand it negatively influences the environmental impacts (contributing to higher CO_2 footprints).

The aim of the present work was to verify the usability of locally available fly ash (which due to the high loss on ignition is not suitable as an additive for cement) for the production of a lightweight aggregate, and to compare the results of the aggregate obtained by the granulation process to those obtained in the case when fly ash, together with a binding agent, is first poured into moulds and later crushed. The frost resistance of such an aggregate was also tested and optimised. The behaviour of both types of aggregate in the concrete matrix was also investigated.

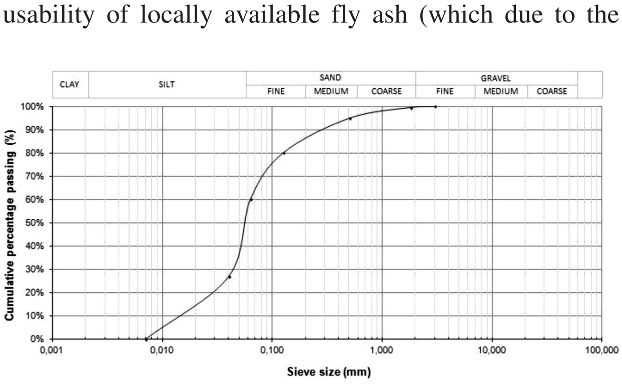

Figure 1: The sieving curve corresponding to the investigated fly ash
Slika 1: Sejalna krivulja preiskovanega elektrofiltrskega pepela

2 EXPERIMENTAL PART

2.1 Basic starting materials

The basic starting material that was used to develop the investigated LWAs was fly ash, which was obtained as a by-product in the combustion of brown Indonesian coal. This particular type of fly ash contains only low amounts of sulphur. The results of a chemical analysis showed that this fly ash contains the following chemical components in the stated mass percentages: SiO_2 27.57 %, Al_2O_3 8.3 7%, Fe_2O_3 16.24 %, MgO 7.06 %, CaO 22.99 %, Na_2O 0.67 %, K_2O 2.67 %, and TiO_2 0.5 %. The loss on ignition amounts to 12.57 %. Because of its chemical composition, this type of fly ash is classified, according to EN 450-1[30], as an alumino-silicate fly ash. According to the results of a mineralogical analysis, it consists of a glassy phase (67 %), brownmillerite (9.1 %), quartz (8.3 %), lime (6.1 %), anhydrite (3.2 %), calcite, portlandite, and hematite.

The particle size distribution was determined by sieving the ash through sieves with diameters of 1.8 mm, 0.5 mm, 0.125 mm, 0.063 mm and 0.04 mm, as is shown in **Figure 1**. Most of the particles in the fly ash were smaller than 1 mm, 40 % of them being smaller than 0.04 mm. The Blaine finesse was determined according to EN 196-6 and it amounted to 2989 cm^2/g.

Table 1: Composition of mixtures for the preparation of the LWA
Tabela 1: Sestava mešanic za pripravo LWA

Composition	Mixture	Fly Ash (g)	Cement (g)	Water (g)
PT1	90 % FA + 10 % CEM	3600	400	2000
PT2	80 % FA + 20 % CEM	3200	800	2000
PT3	70 % FA + 30 % CEM	2800	1200	2000
GT1	90 % FA + 10 % CEM	3600	400	Added as necessary for the needs of the granulation process

The binding agent cement CEM I was added in different proportions, as shown in **Table 1**. A Cementol Hiperplast 179 superplasticizer was also used.

For the frost-resistance improvement a commercial air entraining admixture Cementol ETA S was added.

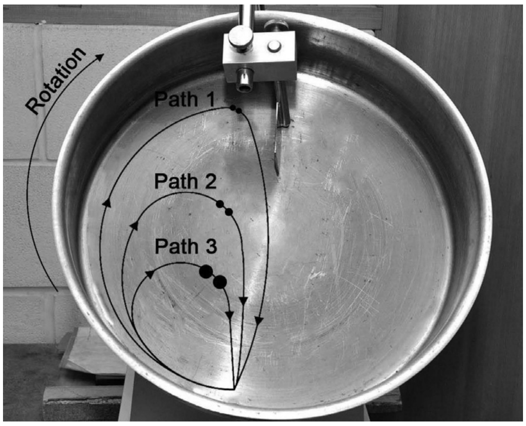

Figure 2: The granulating plate with a schematic presentation of the granulation process

Slika 2: Krožnik za granuliranje s shematskim prikazom procesa granulacije

2.2 Procedures for the production of the investigated LWA

The aggregates were produced by means of two different methods.

The aggregate that was designated "PT" was produced from prisms, which were made by first mixing the fly ash with the selected binder and water, and then pouring the mixture into standard mortar moulds. After curing in a climatic chamber at a temperature of 21 °C and a relative humidity of 94 % for 28 d, the prisms were crushed and then sieved into fractions of 0–1 mm, 1–2 mm, 2–4 mm, and 4–8 mm. The aggregate that was designated "GT" was produced by the pelletization procedure[31], using a rotating plate (**Figure 2**).

During the granulation phase the tilting angle was fixed at 60°, the mixer speed was 48 min^{-1}, and the mixing time was 2 min. The fly ash had been previously mixed with cement, and was then poured slowly onto the plate. During the granulation process, water droplets were added by spraying.

Both types of aggregate are shown in **Figure 3a** (the PT aggregate) and **3b** (the GT aggregate).

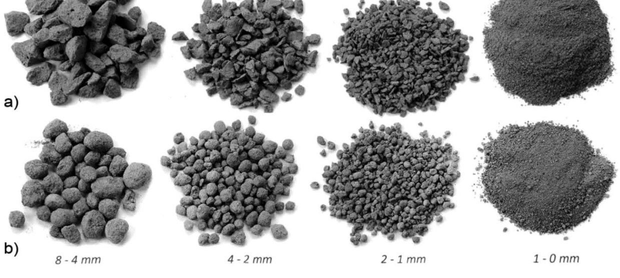

Figure 3: The final products: a) PT- made from crushed aggregate and b) GT- made from granulated aggregate

Slika 3: Končni proizvodi: a) PT – izdelan iz zdrobljenega agregata in b) GT – izdelan iz granuliranega agregata

Normal-weight aggregate, i.e., dense limestone aggregate from the Laže quarry in SW Slovenia, was used for the preparation of the blank concrete samples.

2.3 Characterization of the investigated aggregates

The porosity, pore size distribution, apparent density, and bulk density of the prepared aggregates were determined by means of mercury intrusion porosimetry (MIP). Particles having a size of approximately 1 cm^3 for each of the prepared artificial aggregates were dried in an oven for 24 h at 110 °C, and then analysed by means of MIP Autopore IV 9500 equipment (Micrometrics).

The microstructure of the polished cross-sections of the aggregate samples were examined using the back-scattered electron (BSE) image mode of a low-vacuum scanning electron microscope (SEM) using JEOL 5500 LV equipment.

The water absorption of all three types of crushed aggregate (PT1, PT2, PT3) and of the granulated aggregate was determined by measuring the dry mass m_{dry} and the wet mass after immersion for 24 h in water (this is the saturated surface-dry mass m_{sat}). It was calculated from Equation (1):

$$W = \frac{m_{sat} - m_{dry}}{m_{dry}} \cdot 100 \qquad (1)$$

The mechanical properties of the prisms were evaluated according to EN 196-1:2005[32], whereas the compressive strength of the granules was determined after curing the granulates in a climatic chamber at 21 °C and a relative humidity of 94 % for 28 d, according to the procedure described by C. R. Cheeseman[5], where individual granules are loaded to failure between two parallel plates. For the calculation of the compressive strength the following Equation (2) was used:

$$R_c = \frac{2{,}8 \cdot F_c}{h^2 \cdot \pi} \qquad (2)$$

where F_c is the load causing failure (i.e., fracture), h is the spherical diameter of the granule, and the value of 2.8 is a shape factor.

The frost resistance of the aggregate was determined according to EN 13055-1:2002 [20] on two parallels, where in each parallel 400 g of dry samples (mass M_1) of the fraction 4–8 mm was immersed in water for 4 h. After that the samples were exposed to 20 cycles of freezing-thawing, from –18 °C to +18 °C. After 20 cycles the samples were dried and sieved through a sieve with apertures of 2 mm. The remains on the sieve represent the mass M_2. The percentage of mass loss due to the freezing action (F) is calculated using Equation (3):

$$F = \frac{M_1 - M_2}{M_2} \cdot 100 \qquad (3)$$

The mechanical properties of the prisms were determined by means of a 300-kN ToniNorm compression testing machine.

The bulk densities and strength tests of the concrete samples were determined on standard prisms for mortars of (4 × 4 × 16) cm.

2.4 Preparation of the fly-ash aggregate concrete mixes

The compositions of the concrete mixes that were prepared from the two different types of artificial aggregate (PT1-C, and GT1-C), and that of the mix made using natural limestone aggregate (LMS-C), are shown in **Table 2**.

Table 2: Composition of the concrete specimens made by different types of aggregate
Tabela 2: Sestava betonskih vzorcev, izdelanih z različnimi vrstami agregatov

Sample designation	PT1-C	GT1-C	LMS-C
Type of aggregate	crushed	granulated	crushed
Mass (g)			
Aggregate	5188	3269	9595
Cement	1505	1505	1505
Fly ash	645	645	645
Water in the aggregate	917	1531	0
Added water	1110	769	1227
Super plasticizer	7.5	7.5	7.5
w/c ratio			
w/c ratio (with water in the aggregate)	0.94	1.07	0.57
w/c ratio (without water in the aggregate)	0.52	0.36	0.57

The contents of the individual fractions of the aggregates were determined according to the curves specified in the standard SIST 1026:2008 [33] (curve B for the crushed aggregate, and curve A for the granulated aggregate (**Figure 4**)).

Because of the high water absorption of the lightweight aggregates, prior to mixing they were immersed in water for 30 min and then drained in order to remove the surface water. Taking into account the k-value concept for the fly ash (according to EN 206: 2013[34]), a maximum of 30 % of the cement binder was replaced by fly ash as an additive. Compressive strength tests according to the standard EN 196-1:2005[32], as well as density tests, were performed on hardened test specimens after (7, 28, and 90) days. In all cases the test specimens were cured in a climatic chamber at a temperature of 21 °C and a relative humidity of 94 %.

3 RESULTS

3.1 Characterization of the aggregates

The densities and porosities of the investigated aggregates, determined by MIP, are shown in **Table 3**. The pore size distributions for the artificial aggregates are shown in **Figure 5**.

Table 3: Density and porosity of the investigated aggregates, as determined by MIP
Tabela 3: Gostota in poroznost preiskovanih agregatov, določene z MIP

Sample designation	Total intrusion volume (cm^3/g)	Total pore area (m^2/g)	Average pore diameter (μm)	Bulk density (g/cm^3)	Apperent density (g/cm^3)	Porosity (%)
PT1	0.3899	33.171	0.047	1.182	2.1923	46.08
PT2	0.3710	46.925	0.0316	1.258	2.359	46.67
PT3	0.3178	50.231	0.0253	1.333	2.313	42.37
GT1	0.6429	31.4	0.0819	0.9195	2.2487	59.11

If the results obtained for the aggregates PT1, PT2, and PT 3 are compared, it can be seen that in the case of a higher amount of added binder (cement), the density of the aggregate is higher, and the porosity is lower. It can be further seen, comparing GT1 and PT1, that the granulated aggregate has a lower density and higher porosity than the crushed aggregate.

For instance the density of the granulated aggregate was 0.9 g/cm^3, whereas that of the aggregates obtained by crushing was significantly higher, i.e., 1.2 g/cm^3. However, both of these two aggregates, i.e., PT1 and

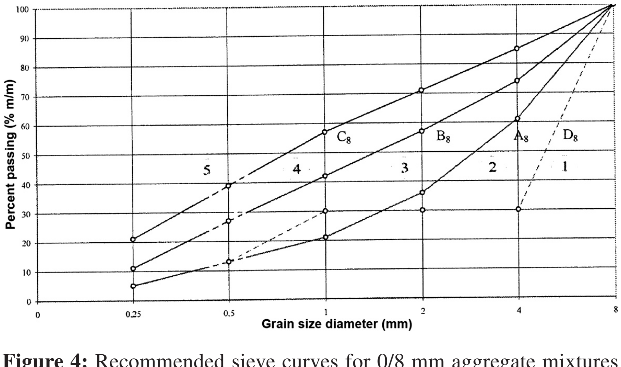

Figure 4: Recommended sieve curves for 0/8 mm aggregate mixtures taken from SIST 1026:2008[33]
Slika 4: Priporočene sejalne krivulje za 0/8 mm mešanico agregatov, vzeta iz SIST 1026:2008[33]

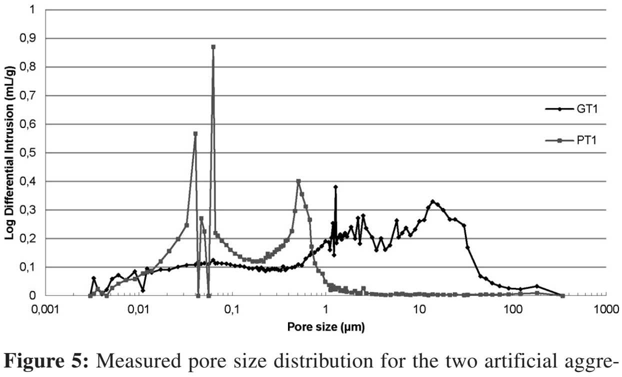

Figure 5: Measured pore size distribution for the two artificial aggregates
Slika 5: Izmerjena razporeditev velikosti por v dveh izdelanih agregatih

GT1, can be classified as lightweight aggregates according to EN 13055-1:2002.[20] The measured porosity of the aggregate PT1 was found to be equal to 46.1 %, whereas that of the aggregate GT1 amounted to 59.1 %.

From **Figure 5** it can be seen that, in the case of aggregate PT1, almost all the pores have sizes of less than 1 µm, the average pore size being 0.047 µm, whereas in the case of aggregate GT1, the pore sizes ranged between 0.003 µm and 100 µm. The average pore size of aggregate GT1 was 0.082 µm.

The measured water absorption of the crushed aggregate was, as expected from the density of the aggregates, less than that of the granulated aggregate. In the case of the aggregate sample PT1 the water absorption amounted to 38.4 % (in the case of the samples PT2 and PT3: 35.9 % and 30.7 % respectively), whereas in the case of aggregate sample GT1 it amounted to 57.8 %. According to these results the porosity of the aggregates can be classified as being open. It is clear that the content of the binder has an effect on the water absorption of the aggregate.

The results of the tensile and compressive strength tests performed on the aggregates are presented in **Table 4**. As could be expected, the results show that the crushing strength increases with the binder content. The tensile strength of the crushed aggregates (samples PT1, PT2, PT3) ranged between 2.2 MPa and 4.6 MPa, whereas their compressive strengths ranged between 12.6 MPa and 30.6 MPa. In the case of the granulated aggregate granules (sample GT1) only the compressive strength was determined, by measurements that were performed on single granules. For this reason the value cannot be directly compared to the values obtained in the case of the PT samples. It amounted to 0.96 MPa.

Table 4: Crushing strengths of the aggregate samples
Tabela 4: Trdnost vzorcev agregatov pri drobljenju

Sample designation	Bending strength		Compressive strength	
	after 7 d curing at 94 % humidity (MPa)	after 28 d curing at 94 % humidity (MPa)	after 7 d curing at 94 % humidity (MPa)	after 28 d curing at 94 % humidity (MPa)
PT1	2.1	2.2	6.8	12.6
PT2	2.9	3.2	11.1	18.6
PT3	4.1	4.6	19.5	30.6
GT1	/	/	/	0.96

The results of the SEM investigation confirmed the differences in the microstructure between the crushed aggregate and the granulated aggregate. The microstructure of sample PT1 was found to be more homogeneous than that of sample GT1 (**Figure 6**). In both figures grains of fly ash can still be seen. In the case of sample GT1 several smaller granules are bonded together to form a larger granule, with large associated air pores inside, which contributes to the higher porosity of the granulated aggregate.

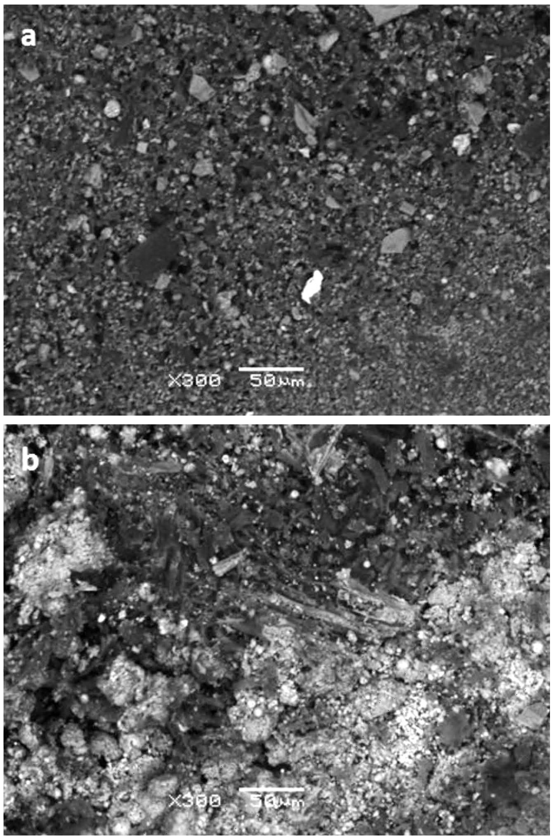

Figure 6: BSE SEM images of samples: a) PT1 and b) GT1of the investigated aggregates, shown at the same magnification
Slika 6: BSE SEM-posnetek vzorcev: a) PT1 in b) GT1, preiskovanih agregatov, prikazanih pri enaki povečavi

Comparing the properties of the granulated aggregate to the properties of the crushed aggregate it can be noted that the crushed aggregate has better mechanical properties and a lower porosity, which could be partially ascribed to the process of pelletization (if not all the parameters are optimal), but also to the fact that during pelletization the *w/c* factor is not uniformly distributed throughout the single granules of aggregate, which introduce weak points at the microstructural level. By the mixing, pouring and crushing process of aggregate production a more uniform w/c and microstructure of aggregate is obtained.

3.2 Characterization of the hardened concrete test specimens

In **Table 5**, the results for the compressive and bending strengths are presented for hardened test specimens of the concrete mixes, which were made from LWAC, whose preparation is defined in **Table 2**. The strength of the concrete made with limestone aggregate is higher than that of the concrete made using the artificial LW crushed or granulated aggregate, despite the highest water-to-cement ratio. However, when crushed aggregate is used, the bending and compressive strengths of the hardened concrete made from them are considerably higher than those that can be achieved with granulated aggregate. This is confirmed by the results that are shown in Table 5, where, despite the much lower water-to-cement ratio of test specimen GT1-C (0.36), the obtained strengths are still much lower than those corresponding to test specimen PT1-C, which had a water-to-cement ratio of 0.52.

Table 5: Determined compressive and tensile strengths of the concrete test specimens

Tabela 5: Določene tlačne in upogibne trdnosti preizkušanih vzorcev betona

Test specimen designation		PT1-C	GT1-C	LMS-C
Tensile strength (MPa)	after 7 d curing at 94 % humidity	2.9	2.6	5.6
	after 28 d curing at 94 % humidity	3.5	2.7	6.4
	after 90 d curing at 94 % humidity	3.6	2.8	7.4
Compressive strength (MPa)	after 7 d curing at 94 % humidity	19.0	13.5	28.7
	after 28 d curing at 94 % humidity	24.1	16.0	34.6
	after 90 d curing at 94 % humidity	25.3	17.1	40.5

The density of the concrete made with crushed aggregate amounted to 1610 kg/m^3, whereas that of the concrete made with granulated aggregate was 1490 kg/m^3. As expected, the density of the concrete made with natural limestone aggregate (LMS-C) was much higher, and amounted to 2290 kg/m^3 (Table 6).

Generic values for the thermal properties can be obtained from the standard EN 1745:2012[34,35] (**Table A.9** for lightweight aggregate concrete, and **Table A.2** for dense aggregate concrete) – the assigned values for the different types of concrete prepared within the scope of this investigation are also given in **Table 6**.

Table 6: Density of the different types of concrete together with the corresponding thermal properties, based on the generic values given in the standard EN 1745[35]

Tabela 6: Gostota različnih vrst betonov skupaj z njihovimi toplotnimi lastnostmi, na osnovi generičnih vrednosti danih v standardu EN 1745[35]

Sample designation		PT1-C	GT1-C	LMS-C
Density (kg/m^3)	After 90 d curing	1610	1490	2290
$\lambda_{10,dry}$ (W/mK)	Acc. to EN 1745	0.84	0.73	1.36

According to the properties obtained in the case of test specimen PT1-C (a tensile strength of 3.5 MPa, a compressive strength of 24.1 MPa, and a density of 1610 kg/m^3), this type of concrete can be classified as a medium-strength concrete with a low density and improved thermal insulation properties.

SEM investigations of the concrete did not show significant differences in the microstructures of the concrete that had been made with crushed aggregate or granulated aggregate (**Figure 7**). The observed cement matrix is homogeneous with relicts of portlandite, and adhered well to the aggregate. Interlocking of the cement matrix with the porous crushed aggregate (PT1), where the cement paste entered the crushed grains, was more pronounced than in the case when the rounded granulated aggregate (GT 1) was used.[36]

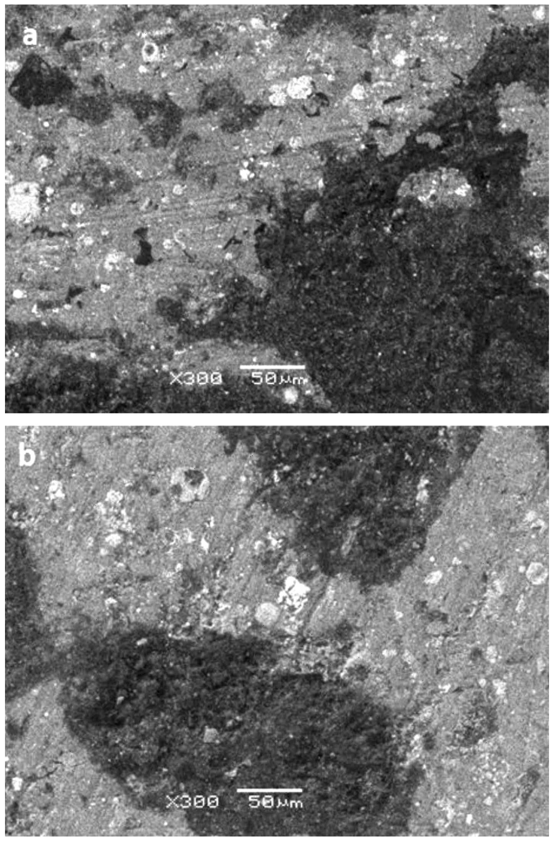

Figure 7: BSE SEM-images of: a) the test specimens PT1-B and b) GT1-B, shown at the same magnification

Slika 7: BSE SEM-posnetek preizkusnih vzorcev: a) PT1 – B in b) GT1 – B, prikazan pri enaki povečavi

3.3 Determination and optimization of aggregate frost resistance

The frost resistance of an aggregate depends to a large extent on the pore structure of its grains. It is well-known that aggregates with a lower porosity and a greater proportion of fine pores possess better frost resistance.[37]

The results of the tests that were performed in order to determine the frost resistance of the investigated aggregate indicated a significant loss of mass upon freezing (**Table 7**), which was especially severe in the case of the granulated aggregate (GT1), where the loss of mass amounted to 96.7 %. The very high loss of mass (96.7 %) on freezing of the granulated fly ash aggregates could be ascribed to the very high porosity (water absorption of 57.8 %) and the very low crushing strength (0.96 MPa).

Samples that were obtained by pouring the mixtures into moulds, and after that crushing and sieving (they were designated PT), resulted in a somewhat improved frost resistance due to the lower initial porosity, as well as better mechanical properties. However, in this case, too, the loss of mass was significant (from 19.1 % to 31.5 %). In the case of sample PT 1 improvements in the frost resistance were searched for in two directions. In the first test (sample PT 1a), the fly ash was additionally sieved onto a 0.125 mm sieve (in this way the majority of the organic particles were removed; loss on ignition decreased from the original value of 10.17 % to 3.3 %), and then processed in the same way as PT 1. In second test (sample PT 1+ ETA S) the sample of fly ash was not additionally processed by sieving, but instead a commercially available air entraining admixture (normally used for the improvement of the frost resistance of concrete) was added, whose mass amounted to 0.1 % of the mass of the cement. Both approaches significantly improved the frost resistance of the aggregate. The sieving away of particles above 0.125 mm resulted in a mass loss of 8.1 % after freezing thawing , whereas the adding of an air-entrapping agent resulted in a mass loss of 1.8 % after freezing.

Table 7: Loss of mass after 20 cycles of freezing-thawing
Tabela 7: Izguba mase po 20 ciklih zmrzovanja-taljenja

Sample designation	Loss of mass (%)
GT1	96.7
PT1	19.1
PT1a	8.1
PT2	31,5
PT3	25,9
PT1+ETA S	1,8

4 CONCLUSIONS

Based on the results of the performed investigations, it can be concluded that in the case of pouring and crushing (PT), aggregates of higher density and strength can be obtained in comparison with aggregates that can be obtained by granulation (GT). In the case of crushing, polygonally shaped aggregates are obtained, which can improve the interlocking effect with the cement matrix.

Both of the two types of investigated aggregate (PT and GT) were highly porous (with porosities of 38.4 %, and 57.8 %, respectively), and their porosity was of the open type. In such cases water can be stored within the aggregate grains, which can then be available for subsequent hydration. Open porosity can also contribute to a stronger interfacial zone between the aggregate and the cement matrix.

The frost resistance of such aggregates is influenced by their content of organic particles, but it can be significantly improved by removing part of the organic particles and /or by adding a commercially admixture for frost-resistance improvement.

The application of such aggregates in concrete has confirmed their usability in the construction sector by the utilization of nearly 80 % of fly ash in concrete (partly as an additive to cement, with its main share in the aggregate).

The methodology described in the paper for the use of fly ash could also be used for other kinds of waste dust that are generated, for example, in the construction industry, in agriculture, and in the refractory industry.

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