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SOLIDIFIED WASTE WATER TREATED SLUDGE AS PARTIAL REPLACEMENT OF CEMENT IN CONCETE COMPOSITES

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ABSTRACT

In this research, tests of mortar and porous concrete made with solidified waste water treatment sludge (SWWTS) used in two forms as a partial replacement of cement were carried out. SWWTS mainly consisted out of $CaCO_3$ and $Ca(OH)_2$, having no pozzolanic properties. For this reason, it was used both, as produced, and modified by adding Al_2O_3 and $Mg_3Si_4O_{10}(OH)_2$ in certain percentages. One mortar type and two types of porous concrete were tested. For each of the three products two mixtures were prepared: the reference mixture and the mixture made with 30% replacement of cement, while the other components remained the same. Based on the given comparative analysis, conclusions were drawn regarding the structure of porous concrete slabs, which refer to individual analyzed properties, but also to the possibility of applying energy-efficient materials. The obtained results point to the conclusion that the use of SWWTS reduces the values of almost all tested properties of porous concrete (flexural and compressive strength, pull-off strength, abrasion resistance), but also that the modification of SWWTS led to a smaller difference in the results of the samples made with 30% of cement replacement and the reference samples. Although, the use of SWWTS led to the reduction of mechancal properties of concretes, the most important benefit is development of possible way for reuse of this waste material and avoid its disposal in the landfills.

Keywords: Porous concrete, energy-efficient materials, sustainable development, solidification, physical-mechanical properties

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1. INTRODUCTION

Civil engineering is from the ecological community referred to as one of the industries that greatly affects environment, for many reasons. Only through production of cement, as one of the crucial components for preparation of concrete, civil engineering participates in the CO2 global emission with 7%. It is also the third-largest industrial energy consumer in the world [1,2].

It is commonly agreed that it is necessary to reduce the energy consumption in the civil engineering sector, reduce the emission of the gasses, reduce the accumulation of waste, and enable further development and urbanization according to the sustainable development principles [3].

Strong emphasis on the sustainability should be implemented through design, construction of new structures, but also through planning and reorganizing of the already built environments [4].

According to the Report on the environmental condition in Republic of Serbia in 2020 around 9.5 million of tons of waste are produced annually. Waste from thermal processes makes around 87% of the total amount of waste, while civil engineering sector with demolition waste makes around 3% [5]. The only legal waste landfill in Belgrade is in Vinca, and it cannot receive the total amount of waste produced. It is therefor, clear that it is necessary to apply recycling processes on the elements of the construction and demolition waste, and reuse it again in the production of new materials.

Important goal in the coming years is to reduce the exploitation of the natural aggregates, and at the same time acquiring the same price for the concrete prepared with natural and recycled aggregates. Further on, goals would be reduction of the pollution through cement production, reduction of the fly-ash land fills, partial replacement of cement with industrial by-products with pozzolanic properties, etc. [6].

One of the by-products produced through the waste water treatment process is waste water treatment sludge. The sludge is usually treated in the second step though different processes, one of which is solidification. Solidified waste water treated sludge (SWWTS), also known as neutral, is a grayish powder, which has limited value for application. In the last years different trials were performed in order to stop land filling of this material, and to incorporate it in concrete mixtures [7].

At the same time, the whole planet has been exposed to strong, extreme rains, that lead to surface, river and in some cases catastrophic floods. Republic of Serbia, as other countries, has witnessed different meteorological disasters, as presented in Figure 1.

Fig. 1. Floods in Belgrade (source: https://srbija24.com/poplava-autoput/)

Blenkinsop et al. [8] have analyzed 170 scientific studies exploring the link between climate change and extreme rainfall. They have concluded that floods in urban environments are directly influenced by the degree of urbanization, as well as by the size of the basin. Importantly they showed that the risk for the occurrence of the flash flood is induced by the extreme raining, and also by the non-porous surfaces of the streets. Large amount of concrete is used for paving of the new building blocks that prevents the soil from absorbing the water and increases surface runoff and the intensity of short-duration extreme rainfall.

One of the solutions for reduction of the negative consequences of the large scale raining is the use of pervious paving. Porous concrete slabs are prepared with pervious surface, with granulation of aggregate chosen in a way that enables the transportation of the rain water. During the process of filtration through surface layers of the slab, particles of dust and heavy metals are remaining and placed in the pores. Remaining of these particles in the concrete slabs or in the drainage system enables their denitrification. If the slabs are appropriately placed and maintained, the first degree of water treatment can be achieved in this way. Additionally, use of porous concrete reflects the sun radiation, when compared to asphalt concrete, which reduces the heating of the surface.

The main point of research presented in this paper was the possibilities for application of SWWTS from the water treatment plant, as a partial replacement for cement in different concrete composites. In the attempt of improving the runoff of the rain water from the street surfaces, two types of porous concrete slabs were prepared using SWWTS as a partial replacement of cement.

2. MATERIALS AND METHODS

In order to determine the possibility of using SWWTS as a partial replacement of cement, mortars and two types of porous concrete were prepared. In light-aggregate porous concrete (LPC) SWWTS was used as a substitute for cement in the amount of 30%. Before producing mortars (M) and porous concrete with crushed stone aggregate (PC) SWWTS was modified, through mixing with additional components, creating MSWWTS. This new material was also used as a partial replacement of cement in the amount of 30%.

2.1. Materials

Portland cement CEM I 52.5 R without additions, produced by "Moravacem", was used for the preparation of mortar and concrete mixtures.

As a partial replacement of cement - SWWTS was used, in two forms, as produced, and after mixing with additional components. A detailed analysis of the chemical composition of SWWTS was made, and it is shown in the table 1. This material was obtained by chemical treatment of solidified waste water treatment sludge, as shown in Figure 2.

Table 1. Chemical composition of SWWTS [9]

Component	Quantity (%)
Loss on ignition 1000°C	26.93
SiO_2	0.14
Al_2O_3	0.14
Fe_2O_3	0.03
CaO	71.70
MgO	0.51
Na_2O	0.01
K_2O	0.07
SO_3	0.27
Residue	0.20

Modification of neutral was carried out by dry mixing (adding) aluminum oxide, magnesium silicate and a chemical admixture (sealant), according to the following ratio:

- 90% - neutral;
- 6.3% - Al_2O_3;
- 3.0% - $Mg_3Si_4O_{10}(OH)_2$;
- 0.7% - sealant.

Modified neutral (MSWWTS) is a powdery material, light gray in color, with a specific smell. The sludge processing and modification process yield fine particles with 10% of grains smaller than 1,370 µm, 50% of grains smaller than 8.492 µm and 90% of grains smaller than 45.541 µm. The bulk density of applied MSWWTS is 1.79 g/cm^3.

The aim of modifying the SWWTS was to increase the pozzolanic activity of neutral, which in some previous research behaved as an inert substance.

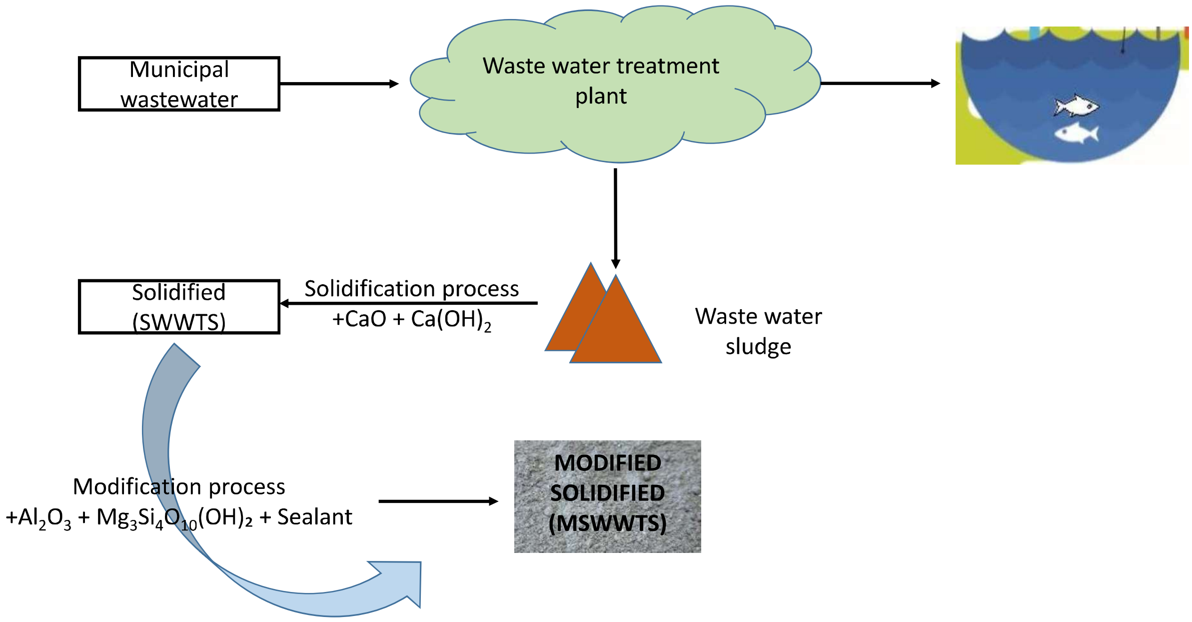

Fig. 2. The process of obtaining modified neutral

Natural river sand was used in all mortar mixtures. Crushed stone aggregate of volcanic origin - andesite - was used as aggregate for porous concrete (PC), while liapore was used for light-aggregate porous concrete (LPC). In order to ensure the permeability of water through the concrete slabs, the aggregate mixture was formed only from two fractions: 2/4 mm and 4/8 mm.

Water from the city water supply and appropriate chemical admixtures were used for production of both mortar and concrete.

For the reference mortar mixture, cement to aggregate ratio was 1:3 by mass. After previous trials, water to cement ratio was adopted to be 0.55. The final proportions, for tested mortar mixtures, are presented in Table 2.

Table 2. Composition of mortar mixtures [10]

Mixture	m_c [kg/m^3]	m_{MSWWTS} [kg/m^3]	m_a [kg/m^3]	m_w [kg/m^3]
Reference	483	-	1450	265
Mortar-30	338	145	1450	265

The production of porous concrete mixtures was carried out at the "Promobet" factory in Mladenovac, in whose prefabrication plant the production of concrete slabs with dimensions of 200x200x60 mm was also carried out (see Figure 3). The exact composition of the concrete in question (the concrete used for products that are placed on the market) is a trade secret. The mass ratio of aggregates and cement in the reference mixes is 2.3 for light-aggregate porous concretes, and 2.5 for ordinary porous concretes. Water-cement factors range from 0.225 to 0.267.

Fig 3. The process of making porous concrete slabs

2.2. Methods

When mixing concrete mixtures with the addition of SWWTS, or MSWWTS, a small amount of red or green pigment was added to the concrete, in order to enable the production of porous flagstones that will visually differ from the reference samples.

The following tests were carried out on the concrete slabs obtained in this way: density, water absorption, compressive strength, splitting tensile strength, flexural tensile strength, pull-off test and abrasion resistance.

2.2.1 Density

Bearing in mind that porous concrete slabs of prismatic shape were made from the concrete in question, the volume of these samples was determined by simple measurement of the dimensions of each slab. Both the dimensions and mass of the samples were measured after drying to a constant mass. The densities of the slab samples in the dry state were calculated as the quotient of the mass and the corresponding volume of the sample.

2.2.2 Water absorption

When measuring water absorption, the samples were saturated with water using the method of gradual immersion in the following time intervals: 1h (1/4 of the height of the sample), 1h (2/4 of the height of the sample), 20h (3/4 of the height of the sample) and another 2h (4/4 of the height of the sample), after which the first measurement of the mass of the water-saturated samples was performed. After this measurement, the samples were re-immersed in water for another 24 hours, after which the mass of the samples was measured again. The procedure was repeated until the same mass was measured in two consecutive readings.

2.2.3 Compressive strength

Compressive strength tests were performed on prismatic samples obtained by cutting from flagstones, as described in part 2.2.1, at the age of the samples of 28 days in all according to SRPS EN 12390-3.

2.2.4 Flexural strength

Flexural tensile strength tests were performed on prismatic samples with approximate dimensions of 60×60×200 mm, which were cut from flagstones. The samples were loaded with a force at mid-span, as shown in Figure 3 left. In the case of mortars, but using 4×4×16 mm prismatic samples, the flexural test was performed (Figure 3 right) According to the same disposition,

Fig. 3 Three-point flexural strength test

2.2.5 Pull-off tensile strength

Tensile strength tests using the pull-off method were performed on flagstones, which were previously cut with a drill with an internal diameter of 50 mm, to a depth of 10 mm. Steel dollies, also 50 mm in diameter, were glued to the samples prepared this way with the aid of strong epoxy adhesive, and then the axial tension force was applied to the dollies. The test was conducted in accordance with the SRPS EN 1542 standard.

2.2.6 Abrasion resistance

Abrasion resistance tests were performed at the Road Institute according to the Boehme method (SRPS EN 14157). The tests were carried out on prismatic samples with approximate dimensions of 70×70×70 mm, obtained by cutting from flagstones. Fine Al_2CO_3 was used as an abrasive powder.

3. RESULTS AND DISCUSSION

The tested concrete mixtures were made with partial cement replacement by SWWTS and MSWWTS in the amount of 30%, while the quantity of aggregate remained the same. However, the quantities of water and admixtures were varied in order to acquire the same workability of mixtures. The obtained results showed that the addition of 30% MSWWTS (i.e. 30% of cement replacement by mass) had a positive effect on concrete consistency. The main reason for this is the grain size of MSWWTS, which provided a certain lubricant effect, i.e. the reduction of the internal friction angle between the aggregate grains, leading to a more liquid consistency of the fresh concrete.

3.1. Density

The average values of density of the reference samples and the samples made with MSWWTS amounted to 1612 kg/m^3 and 1622 kg/m^3, respectively. The almost equal results point to the conclusion that the use of MSWWTS had no significant influence on concrete density.

The corresponding light aggregate concrete mixtures (made with or without SWWTS) had densities of 934 kg/m^3 and 971 kg/m^3, respectively, confirming the previous conclusion.

3.2. Water absorption

The values of water absorption measured after 24 hour saturation are shown in Figure 4.

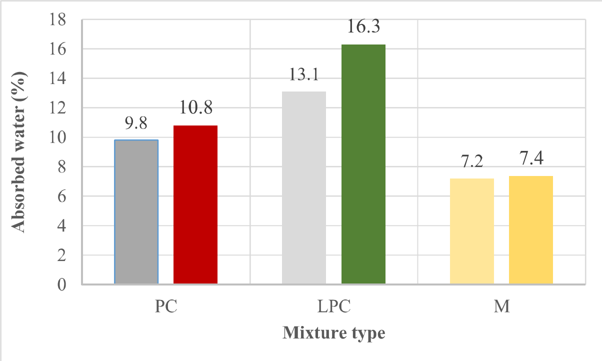

Fig. 4 Water absorption values

From Fig. 4 it can be concluded that mixtures made with the addition of SWWTS and MSWWTS (right columns) have somewhat higher water absorption values than the reference mixture (left columns). However, these differences are not substantial, except in case of the light aggregate porous concrete (LPC). Anyway, considering the fact that these are porous composites, all of the measured water absorption values are significantly higher than the values for ordinary concrete.

3.3. Compressive strength

The average compressive strength results for all tested samples are shown in Figure 5. In all mixtures made with SWWTS or MSWWTS, there is an obvious trend of compressive strength reduction, when compared to the corresponding reference mixtures. In case of porous concrete (PC) the strength reduction amounts to 24%, for light aggregate porous concrete (LPC) it is 45% and for mortar 19%. The obvious reason for such decrease in strength is the 30% lower quantity of cement in the SWWTS and MSWWTS mixtures. The differences in strength reduction percentages between the mixtures are the result of alterations in the mix design.

If we only compare the compressive strength reduction between PC and LPC mixtures, which amounted to 24% and 45%, the conclusion can be drawn that the modification of SWWTS had certain positive effects on the strength of concrete. This could be the consequence of partially initiated pozollanic activity of MSWWTS (compared to relatively inert SWWTS), but this assumption has to be confirmed by future research of pozollanic properties.

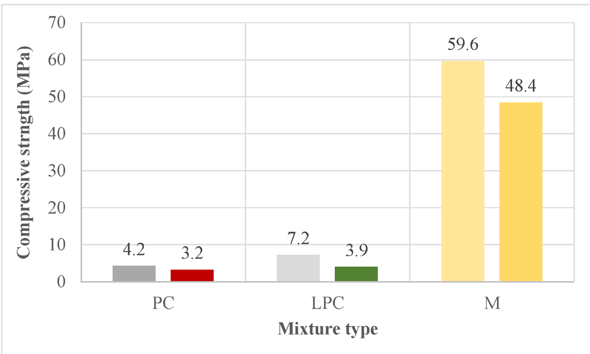

Fig. 5 Compressive strength at the age of 28 days

3.4. Flexural strength

Same as in case of compressive strength testing, the flexural strength of samples made with SWWTS and MSWWTS was lower in comparison with the corresponding reference mixtures (see Fig. 6). The reduction in flexural strength was more evident in the case of concrete than mortar: 46% for PC, 45% for LPC and only 2.5% for M. The reason for such strength reduction is again the lower quantity of cement in these mixtures.

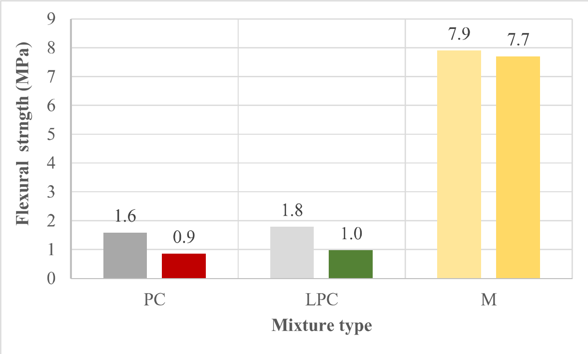

Fig. 6 Flexural strength at the age of 28 days

3.5. Pull-off test

The Pull-off test was performed only on porous concrete samples. The results are shown in Figure 7. The expected trend of strength reduction, which was also noted during testing of other mechanical properties, was confirmed again in this test. For LPC samples (made with SWWTS) this reduction amounted to 48% in comparison to the reference mixture, while for PC samples the strength reduction was much lower, just 11%. The reasons for strength loss are the same, as it was already explained.

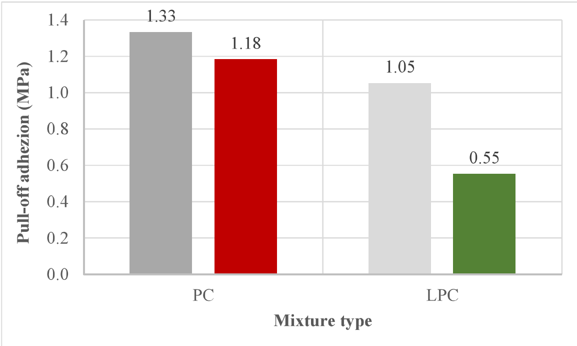

Fig. 7 Pull-off test results

3.6. Abrasion resistance

Figure 8 shows the average values of volume loss after the abrasion resistance test of concrete samples. The obtained results are in total accordance with the previously measured strengths of the same mixtures. This means that mixtures made with partial cement replacement tend to have lower resistance to abrasion, compared to the adequate reference mixtures. The volume losses of LPC (made with SWWTS) and PC (made with MSWWTS) are 41% and 9% higher, respectively, than the corresponding values measured on reference samples.

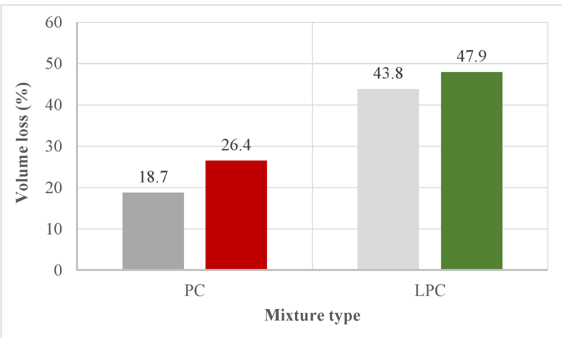

Fig. 8 Volume loss of samples after the abrasion resistance test

4. CONCLUSION

The experimental research presented in this paper is related to mortar mixtures (M), porous concrete mixtures (PC) and light aggregate porous concrete mixtures (LPC). For each of these mortar/concrete types, two different mixtures were made: one reference mixture and the other mixture in which 30% of cement was replaced by SWWTS or MSWWTS. Both SWWTS and MSWWTS were obtained as a by-product after the solidification procedure of waste water treatment sludge.

The main goal of this research was to perform preliminary tests in order to find the answers to the following questions:

- Is it possible to use the by-products from the solidification procedure of waste water treatment sludge as a component material for production of mortar and concrete,
- Is it possible to reduce the quantity of cement (as one of the biggest environmental pollutants), with acceptable deterioration of significant properties of mortar/concrete,
- Is it possible to apply such waste materials for production of porous concrete flagstones of satisfactory quality, which could be applied to diminish the damage caused by the rain induced urban floods.

The conducted experimental research showed that 30% of cement replacement with SWWTS or MSWWTS led to:

- Reduction of all tested mechanical properties in comparison with the reference mixtures; for instance, the loss of compressive strength was 19% for mortar, 24% for PC and 46% for LPC.
- Decrease in abrasion resistance in comparison with the reference samples by 9% (for PC), i.e. 41% (for LPC).

The application of neutral (either pure or modified), had no significant influence on density of mortar or concrete specimens. Also, the neutral modification procedure has led to certain improvement of mechanical properties of porous concrete flagstones, when compared to the same products made with regular (untreated) neutral.

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