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The Utilization of Waste Water from a Concrete Plant in the Production of Cement Composites

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Abstract: This article presents the results of a study dealing with the utilization of sludge water from a concrete plant as a partial replacement for mixing water in the production of cement composites. The replacement of mixing water with sludge water from a concrete plant was carried out in the amounts of 20% and 50%. The following tests were carried out in order to determine the effect of the replacement of mixing water with sludge water from a concrete plant on the physical and mechanical properties of the cement composites: cement mortar consistency, beginning and end of setting, strength characteristics (compressive strength and flexural strength), and thermal properties. The measured values of the strength characteristics of the test specimens after 28 days of age confirm the possibility of replacing mixing water with sludge water from a concrete plant without significantly reducing the compressive and flexural strength.

Keywords: sludge water; concrete; composite; testing

1. Introduction

Reducing the impact of industry on the environment is an integral part of today's life. The issue of producing large quantities of waste water from concrete plants has recently been discussed from an environmental point of view. There are studies focused on waste water produced in this way which can be reused as mixing water in concrete and mortar [1,2]. The results of other studies show that the use of sludge water from concrete plants in concretes based on fly ash and concretes without fly ash with the addition of superplasticizer resulted in a reduced consistency of the concrete mixture during a slump test. Furthermore, it was found that sludge the water from concrete plants had a significant impact on the effect of the superplasticizing additive [3]. In addition, there are experimental and statistical studies comparing concretes and mortars prepared with a certain amount of sludge water from a concrete plant, the results of which have shown that sludge water significantly affected neither the workability of the concrete mix prepared using this method, nor the subsequent strength of the concrete [4,5]. Apart from waste water, concrete plants also produce other waste materials in the form of returned fresh concrete mix. A description of the current methods dealing with the use of fresh concrete waste from concrete plants is presented in [6]. At the same time, there are new sustainable technologies being developed for the purpose of the recycling of fresh concrete waste [7], where even fresh concrete waste with a high content of calcium silicate was classified as a cement paste and used as a medium capturing CO_2 [8], similar to the use of sludge from waste water treatment plants [9]. The use of some types of waste waters and industrial waste materials in the concrete production sector has already been proven in the past [10–17].

The aim is to reduce the costs of concrete mixture production, while maintaining or even improving its properties. This statement is confirmed by the presented research results. The research deals, for example, with the monitoring of the effects of different concentrations of ammonia in mixing water on the physical, chemical, and mechanical properties of different types of cement—such as sulphate resisting cement, ordinary portland cement, and high slag cement—as a result of using sludge water [18,19], recycled water from agitation truck rinsing in concrete plants as a replacement for mixing water in concrete production [20]. The utilization of sludge water as the mixing water is a technically demanding solution if we want to maintain the optimal declared properties and to guarantee the standards for production of high strength concrete. A study focused on this issue also explores the effect of the utilization of sludge water on the properties of high-quality concrete. The results have shown that the strength of concrete prepared using sludge water (of required properties and composition) was comparable to the strength of concrete prepared from mixing water not containing sludge water. When sludge water of this nature is used for concrete purposes, the absorptive capacity of concrete is not affected [21]. A study on the ecotoxicity of concrete with the addition of granular slag as the filler also presents the possibility of the utilization of secondary materials. Ecotoxicological tests are also required to determine the properties so as to verify the practical usability of the mixture with a guarantee of its material non-toxicity for other sources [22]. The results of the studies described above confirm the idea of using secondary raw materials and sludge water in the production of concrete in order to save the natural resources and to reduce the cost of production of 1 m^3 of concrete, while maintaining the physical and mechanical properties of concrete.

2. Materials and Methods

This experimental research dealing with cement composites was based on the results of a research on the properties of sludge water from concrete industry according to ČSN EN 1008 [23] and the results were used to prepare recipes, according to which the test samples were made and the physical and mechanical properties were tested.

Sludge water was added in weight ratios of 20% and 50% of the net water, and water was added to the MERCI lab scale. The composition of the cement composite recipes was as follows: Mix 1 was designed as the reference, Mix 2 contained 20% substituted mixing water, and Mix 3 contained 50% substituted mixing water with sludge water from a concrete plant.

2.1. Properties of Mixing and Sludge Water from a Concrete Plant

Table 1 shows the properties of sludge water and pure mixing water from a concrete plant.

Table 1. The results of analyzes of samples of pure mixing water and sludge water from a concrete plant.

Tested Properties	Pure Mixing Water from a Concrete Plant	Sludge Water from a Concrete Plant	Limit Concentrations According to ČSN EN 1008
pH	6.774	12.538	>4
Temperature	18.5 °C	18.5 °C	-
Conductivity	336.12 µS/cm	13.39 µS/cm	-
Humus substances	acceptable	acceptable	paler than yellow-brown
Chlorides	14.182 mg/L	183.469 mg/L	<600 <2000 <4500 mg/L
Sulphates	40.268 mg/L	1702.1 mg/L	<2000 mg/L
Nitrates	9.4 mg/L	-	<500 mg/L
$CHSK_{Cr}$	5.236 mg/L	-	-
Na	31.326 mg/L	135 mg/L	<1000 mg/L
Pb	0 mg/L	0.1864 mg/L	<100 mg/L
Zn	0.0606 mg/L	0.0264 mg/L	<100 mg/L
Ca	33.18 mg/L	1114.4 mg/L	-
Glucose = sucrose	<100 + <100 mg/L	<100 + <100 mg/L	<100 + <100 mg/L

The concentration limits for the concrete mixing water according to ČSN EN 1008 [23] are also provided for the sake of comparison of the measured concentrations.

2.2. Designed Recipes of Cement Composites

The following three recipes were prepared for the tests of the experimental verification of the possibility of replacing mixing water with sludge water from a concrete plant in the production of cement composites:

- Recipe R1—comparative recipe, consisting of 450 g of CEM I 42.5 R Hranice cement, 1350 g of standardized sand CEN EN 196-1 [24], 225 g of pure mixing water from a concrete plant source;
- Recipe R2—designed mixture consisting of 450 g of CEM I 42.5 R Hranice cement, 1350 g of standardized sand CEN EN 196-1 [24], 180 g of pure mixing water (controlled concrete plant source) and 45 g of sludge water (recycled in the concrete plant by means of recycling equipment used for STETTER agitation truck cleaning, coarse aggregate is filtered out in this water) containing a mix of admixtures from concrete produced in a concrete plant;
- Recipe R3—designed mixture consisting of 450 g of CEM I 42.5 R Hranice cement, 1350 g of standardized sand CEN EN 196-1 [24], 112.5 g of pure mixing water (controlled concrete plant source) and 112.5 g of sludge water (recycled by means of STETTER equipment in the concrete plant, which is designed to clean agitation trucks, coarse aggregate is filtered out in this water) containing a mix of admixtures from concrete produced in a concrete plant.

2.3. Tests of the Physical Characteristics of Cement Composites

2.3.1. Determination of Consistency

The determination of cement mortar consistency was performed according to ČSN EN 1015-3 [25]. The test is based on measuring the spill of jolted mixture of cement mortar on a flat board after 15 compacting strokes on a standardized Betontest jolting table.

2.3.2. Vicat Test

The beginning and end of the cement grout setting with an admixture of sludge water from a concrete plant was tested according to ČSN EN 196-3 A1 [26]. The setting time was determined using the Vicat BC VIC-08 ASC automatic instrument. The time was measured at 5-min intervals immediately after the blending of the mixture components from the beginning of the mixture setting to the end of the mixture setting.

2.3.3. Determination of Thermal Properties

The thermal properties of cement composites based on sludge water from a concrete plant were determined using an Isomet 2114 instrument and an Isomet surface probe with a measuring range of (λ = 1–2.6 W/m·K). The testing was carried out on test specimens with the dimensions of 140 × 160 × 40 mm prepared according to R1, R2, and R3 recipes at an age of 28 days. The test specimens were dried in a drier at 105 °C to a constant weight.

2.3.4. Determination of Strength Characteristics

The flexural strength and compressive strength tests at the end of the beams were carried out in accordance with ČSN EN 196-3 [26]. The determination of the flexural strength and compressive strength was performed after 1, 3, 7, and 28 days of age of the test specimens. Beams with the dimensions of 40 × 40 × 160 mm were used as the test specimens, and they were stored in an aquatic environment.

3. Results and Discussion

3.1. Cement Mortar Consistency

Section 2.2.1 describes the spill method of jolted cement mortar used to determine its consistency. The measured values are presented in a tabular form in Table 2 and in a graphic form in Figure 1.

Table 2. Spill test results.

Sample	R1		R2		R3	
	d_1 (mm)	d_2 (mm)	d_1 (mm)	d_2 (mm)	d_1 (mm)	d_2 (mm)
Diameter	155.00	166.00	156.50	156.50	138.00	140.00
Spill (mm)	161		157		139	

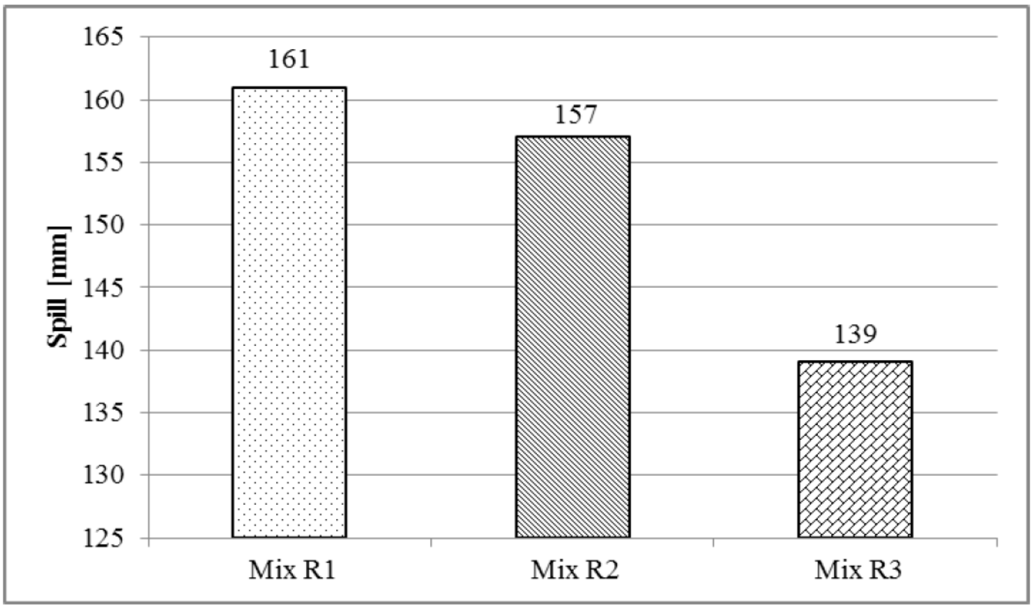

Figure 1. Chart showing the differences among the individual recipes.

Figure 1 clearly shows that:

- 20% replacement of mixing water (R2) with waste (sludge) water from a concrete plant results in a spill value lower by 4 mm, i.e., 2.5%, in comparison with the spill value of R1 Mix (comparative);
- 50% replacement of mixing water (R3) with waste (sludge) water from a concrete plant results in a spill value lower by 22 mm, i.e., 13.7%, in comparison with the R1 Mix value (comparative).

The differences between the individual spill value measurements d_1 and d_2 did not exceed 10%, which means the measurement complies with the requirements of ČSN EN 1015-3 [15].

A decrease in the value of fresh concrete mix spill in case of mixes R2 and R3 in comparison with mix R1, where pure (tap water) mixing water was used, was caused by:

- Replacing pure mixing water with sludge water in the amount of 20% and 50%. The dosing of the mixing water and the other components was carried out according to weight. Due to the fact that sludge water contained about 5.5% of suspended solids in 1 m^3 [27], the dose of mixing water was reduced by the amount of suspended solids, which was reflected in the lower spill value.
- Increased amounts of chlorides in sludge water (183.469 mg/L). It is a known fact that chlorides are involved in shortening the beginning of the setting time.

3.2. Vicat Test of the Beginning and End of the Setting Time

Table 3 and Figure 2 show the results of the beginning and end of the setting of cement mixture based on sludge water from a concrete plant. The presented results show that:

- The intervals of the beginning and the end of the setting of R2 and R3 recipes were comparable, despite having different amounts of added sludge water in the mixing water, with a difference of 30%;
- After replacing 20% and 50% of pure mixing water with sludge water from a concrete plant, the values of the beginning and end times of the setting were equal;
- In comparison with the comparative Recipe R1, the setting of the mixture with sludge water is faster, namely by 15 min.

Table 3. The results of the beginning and end of the experimental recipes setting.

Recipe	Beginning of Setting (min)	End of Setting (min)
R1	195	216
R2	180	201
R3	180	201

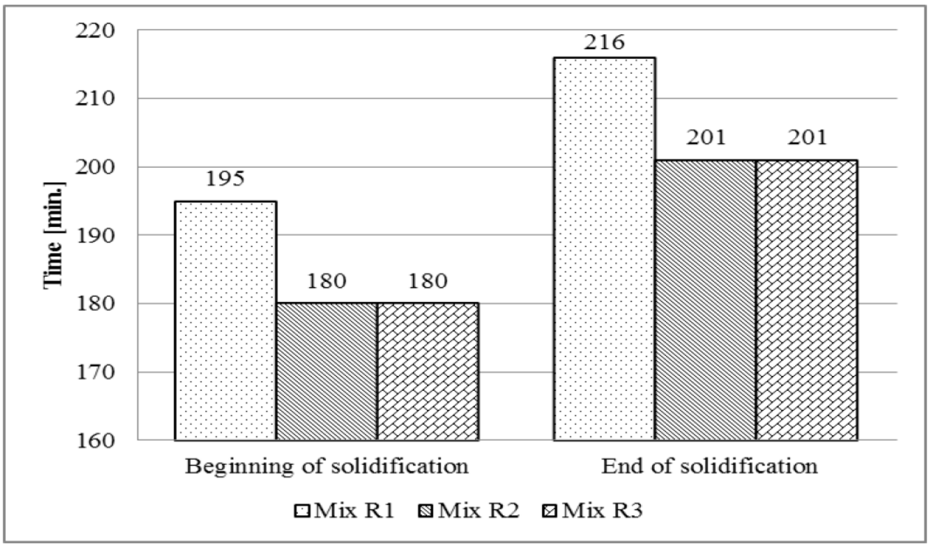

Figure 2. Chart of the measurement of the beginning and end of setting of R1, R2 and R3 mixtures.

3.3. Thermal Properties of Cement Composites

Table 4 shows the measurement results of the thermal properties of cement composites. It should be noted that these are always the average values of five measurements.

Table 4. Thermal properties of cement composites.

Recipe	Sample Age (Days)	Thermal Conductivity Coefficient λ (W/m·K)	Specific Volumetric Heat Capacity cp·10^6 (J/m^3·K)	Thermal Conductivity 10^{-6} (m^2/s)
R1	28	2.426	1.87	1.296
R2	28	2.386	1.88	1.267
R3	28	2.326	1.79	1.297

The table clearly shows that:

- The value of the thermal conductivity coefficient λ fluctuates within the range of 2.326–2.426 W/m·K. The measured values show that the increasing substitution of mixing water with sludge water from a concrete plant is associated with a decreasing value of the thermal conductivity coefficient λ. The thermal conductivity coefficient λ in case of R2 and R3 recipes is lower by 1.6% and 4.1% in comparison with the comparative recipe R1;

- The specific volumetric heat capacity c_p is within the range of 1.79–1.88·10^6 J/m^3·K;
- The thermal conductivity value was within the range of 1.267–1.297·10^6 m^2/s.

The improvement of the thermal properties of the cement composites at the age of 28 days prepared on the basis of sludge water from a concrete plant in the replaced amount of 20% and 50% of pure mixing water (R2 and R3) can be explained by the increased amount of chlorides in the sludge water (183.469 mg/L) resulting in the aeration of fresh concrete mix, and the formation of new pores caused an improvement in the thermal properties (lambda thermal conductivity coefficient), as mentioned above. This assertion will be experimentally verified by determining the air pore size in hardened cement composite according to ČSN EN 480-11 [28].

3.4. Test Results of the Strength Characteristics of Cement Composites

Table 5 and Figures 3–6 present the results of the strength characteristics of the test specimens prepared on the basis of pure mixing water and sludge water from a concrete plant. It should be noted that these are the average values always obtained from one set of test specimens (1 set = 3 pieces of test specimens).

Table 5. Test results of the flexural strength and compressive strength.

Recipe	Sample Age (Days)	Flexural Strength	Compressive Strength
		Rf (MPa)	Rc (MPa)
R1	1	4.66	22.79
R2		4.11	21.45
R3		4.66	24.49
R1	3	6.43	39.90
R2		6.47	38.39
R3		6.11	39.98
R1	7	6.56	45.94
R2		6.97	48.74
R3		6.70	50.94
R1	28	7.62	54.46
R2		7.62	56.24
R3		7.74	56.61

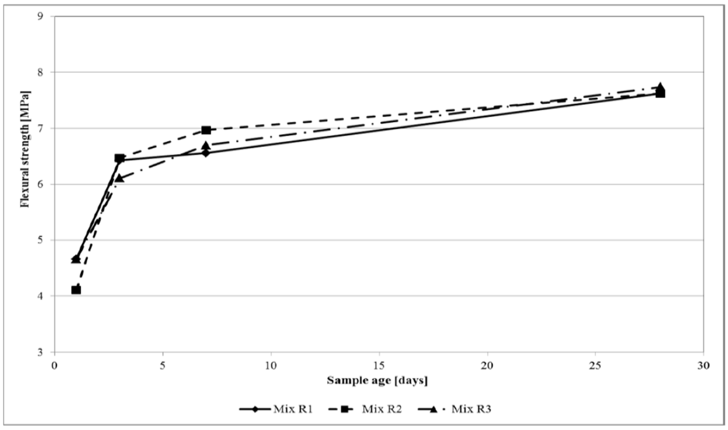

Figure 3. Values of flexural strength.

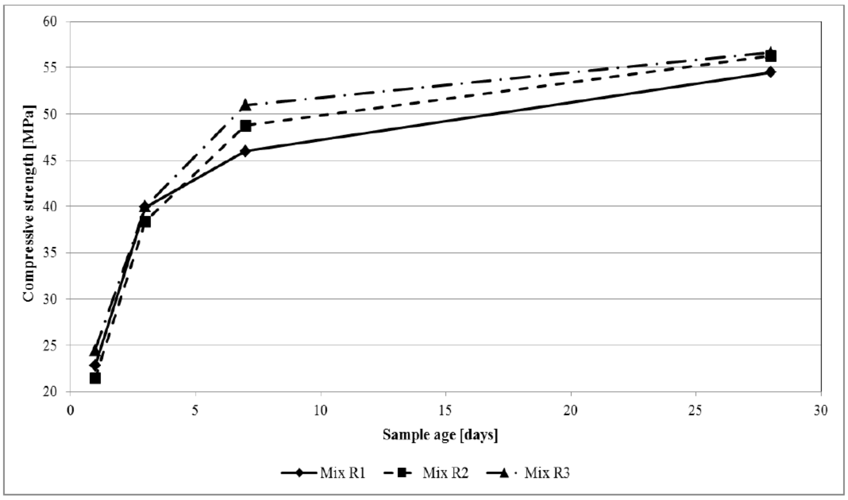

Figure 4. Graph of the increase in compressive strength at the end of the beams.

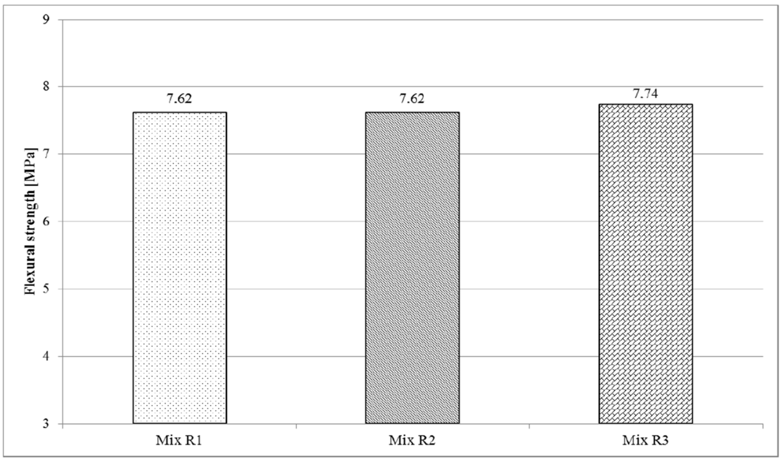

Figure 5. Flexural strengths of the test specimens after 28 days.

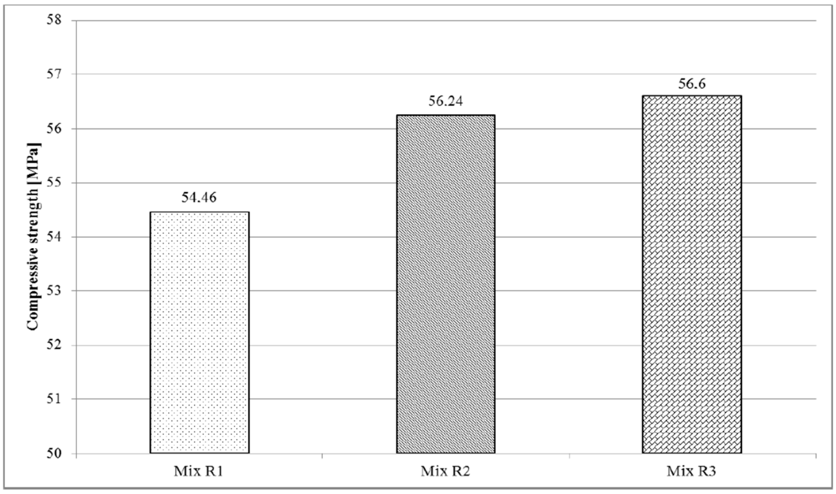

Figure 6. Compressive strength of the test specimens at the end of the beams after 28 days.

Figure 3 presents the flexural strength values. There is an apparent steep increase in the strength of the test specimens after one and three days of age. It is followed by a gradual increase in the flexural strength within the interval from 7 to 28 days. Figure 3 also clearly shows that the test specimens prepared according to recipes R2 and R3 have higher flexural strength after seven days when compared to the values of the comparison recipe R1. After 28 days of age for the test specimens, the flexural strength of all recipes was nearly equal, see Figure 5.

Figure 4 presents the development of the compressive strength at the end of the beams in the time interval of 1, 3, 7, and 28 days of all recipes. The same trend of steep increases in the initial compressive strengths in the time interval of one to three days is evident here, as well as in the flexural strength. After seven days of age, the test specimens show an increase in the compressive strength of recipes R2 (5.7%) and R3 (9.8%) compared to recipe R1. There is a noticeable gradual increase in the compressive strength in the time interval from 7 to 28 days. After 28 days, the compressive strength value at the end of the beams of recipes R2 and R3 was nearly equal, approx. 56 MPa, and shows minimal difference. The increase in compressive strength after 28 days of age of recipe R2 is 1.78 MPa (3.2%) and in case of recipe R3, it is 2.15 MPa (3.8%) compared to recipe R1. This fact is graphically presented in Figure 6.

The replacement of pure mixing water with 20% and 50% of sludge water in mixes R2 and R3 resulted in a higher compressive strength at the ends of the beams by 3.2% and 3.9%. In terms of flexural strength, R2 mix had the same values as the comparative mix R1. In R3 mix, there was a slight increase by 1.57%. The higher compressive strength at the end of the beams can be explained by:

- Higher content of chlorides in sludge water (183.469 mg/L). It is a known fact that chloride-containing concrete additives are highly effective in the hardening process, but they also shorten the beginning and the setting time of fresh concrete mix. The main disadvantage of chloride-based additives is their highly corrosive effect on steel reinforcement, which means they are not suitable for application in the production of reinforced concrete elements and structures.
- Higher amount of suspended solids in sludge water from a concrete plant, which amounts to about 60 kg (5.5%) in 1 m^3 [28].

The mineralogical analysis carried out represents the composition of a solid fraction of sludge water, which affects the resulting properties of the composite because it defines crystallized minerals. These minerals determine the resulting properties of the composite. Figure 7 presents the average values of mineralogical composition of the sludge acquired from the sludge water produced by the concrete plant.

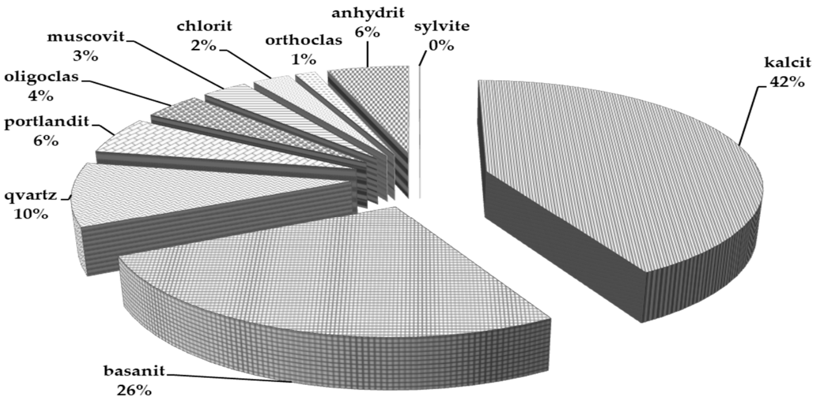

Figure 7. Mineralogical composition of waste water sludge from a concrete plant.

- kalcit—$CaCO_3$, hardness 3, density is 2.7 g/cm^3,
- bassanite—$CaSO_4 \cdot 0.5H_2O$, hydrates togypsum, density is 2.5–2.7 g/cm^3,
- quartz—SiO_2, hardness 7, density 2.6 g/cm^3, soluble in hydrofluoric acid,
- portlandite—$Ca(OH)_2$, hardness 2.5–3, density 2.26 g/cm^3,
- oligoclase An16—$(Ca,Na)(Al,Si)_4O_8$, hardness 6–6.5, density 2.65 g/cm^3,

- chloriteIIb—$(Mg,Fe)_6$ $(Si,Al)_4O_{10}$ $(OH)_8$, hardness-, density 2.5 g/cm^3,
- muscovite—$KA_2(AlSi_3O_{10})(F,OH)_2$, hardness 4, density 2.76–3 g/cm^3,
- orthoclase—$KAlSi_3O_8$, hardness 6, density g/cm^3,
- anhydrite—$CaSO_4$, hardness 3.5, density 2.95 g/cm^3,the highest content was found in the last sample,
- sylvite—KCl, hardness 2, density 1.49 g/cm^3.

4. Conclusions

The results presented in this article confirm the possibility of using sludge water produced in a concrete plant as a partial replacement of mixing water in the amount of 20% and 50% without adversely affecting the physical and mechanical properties of cement composites. The sludge water from a concrete plant has met the requirements for mixing water according to ČSN EN 1008 [6]. The use of sludge water from a concrete plant as a partial replacement of mixing water will:

- decrease the value of cement mortar consistency in case of 20% substitution of mixing water by 2.5%, and by 14% in case of 50% substitution;
- accelerate the initial setting by about 15 min in comparison with the initial setting when pure mixing water is used;
- reduce the value of the thermal conductivity coefficient λ of hardened cement composite by approx. 1.5% in case of 20% substitution and by approx. 4% in case of 50% substitution;
- increase the flexural strength and compressive strength at the end of the beams after seven days;
- equal the flexural strength after 28 days of age of the test specimens;
- increase the compressive strength at the end of the beams after 28 days of age of the test specimens.

Further research will be focused on the production of concrete mixture and concretes based on waste from a concrete plant. If the possibility of replacing the mixing water with sludge water from a concrete plant in the production of concrete is proven, without reducing the physical and mechanical properties of the concrete, the production cost of 1 m^3 of concrete can be reduced, as well as the environmental burden of this industry.

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