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Sustainable Lightweight Concrete Designed with Modified Solidified Wastewater Sludge as Partial Replacement of Cement

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Abstract: The requirement for high-quality drinking water and the treatment of wastewater prior to discharge into the environment results in the generation of sludge. As with any high-volume materials, beneficial reuse applications are being sought to promote sustainable environmental solutions. This research examined the possibilities of producing sustainable lightweight concrete using modified solidified wastewater sludge as a partial replacement of cement. Wastewater sludge was modified by the addition of aluminum oxide and magnesium silicate hydrate. The properties of the modified wastewater sludge were examined, as well as the influence of the partial cement replacement with the sludge in lightweight concrete. Besides testing the physical and mechanical properties of four mortar mixtures, an additional analysis of the willingness of final users to accept novel material containing wastewater sludge was addressed. The results obtained for the mortar samples indicate that 20% cement replacement is the upper limit for the modified sludge's application. The lightweight concrete prepared with the modified sludge (in the amount of 20%) was tested in a hardened state. The water permeability was reduced by 33.3% with the addition of the modified sludge. Both tested concrete mixtures showed good frost resistance. The maximal measured reduction in the compressive strengths was 7.6%. Citizens' perceptions and responses regarding the beneficial reuse of materials emphasize the importance of comprehensive education for their future acceptance.

Keywords: cement replacement; lightweight concrete; solid waste management; wastewater sludge; sustainable solutions for cement-based composites; human factor in sustainable solutions

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Academic Editors: Marc A. Rosen and Shengwen Tang

Received: 2 September 2024
Revised: 24 December 2024
Accepted: 8 January 2025
Published: 24 January 2025

Citation: Škondrić, M.; Radević, A.; Savić, A.; Naunović, Z.; Radovanović, Ž.; Svetozarević, S.; Rajaković- Ognjanović, V.. Sustainable Lightweight Concrete Designed with Modified Solidified Wastewater Sludge as Partial Replacement of Cement. *Sustainability* **2025**, *17*, 945. https://doi.org/10.3390/su17030945

1. Introduction

Considering the finite nature of natural resources such as wood, sand, gravel and stone, the construction industry faces a potential future shortage of building materials. As new construction sites emerge, these challenges intensify, underscoring the growing importance of effective construction and demolition (C&D) waste management and recycling within the construction industry, since the repercussions of improper C&D waste management are profound [1]. Along with waste materials that are already accepted as potential partial replacements of cement, such as fly ash, ground granulated blast furnace slag, silica fume, metakaolin, rice husk ash, etc. [2], there are other waste materials whose potential in this field is yet to be developed.

1.1. Wastewater Sludge (WWS)

Wastewater sludge (WWS) and drinking water sludge (DWS) are two by-products whose production is growing each year. The developed solutions for their disposal are soil application, sea dumping, landfilling and incineration [3]. Nevertheless, all of these proposed ways for treating sludge have major drawbacks [3]. The most prominent application areas for wastewater sludge in building materials are soil stabilization, concrete manufacturing, brick production, paving material preparation, and lightweight aggregate production [4–9]. After the identification of the most important physical, chemical and morphological properties of the sludge, it was concluded that its properties could be improved by pre-processing or by using additional mineral admixtures or other waste materials, such as fly ash, ground granulated blast furnace slag, metakaolin, rice and husk ash [3]. The most used pre-processing treatment is incineration. Different studies show that wastewater sludge ash (WWSA) can be used with a very low percentage replacement in cement. This is why another type of pre-treatment is used, through mixing WWSA with various mineral admixtures [10]. Another proposed solution is the pre-treatment of sludge directly in cement kilns and its application as a component material in cement production [11]. For different applications of dried sludge, the comparison of the costs per ton is presented in Table 1 [12,13]. The costs were calculated as a sum of the capital expenditures and operation expenditures, such as maintenance, power consumption or production, heat consumption or production, reagents, personnel, analyses, transportation and the disposal of residues.

Table 1. The costs of different applications of dried sludge per ton.

Type of Application	Cost per Ton (EUR)
Agricultural use	40–60
Landfilling	60–100
Incineration	60–100
Use of dry sludge in cement kilns	10–40
Anaerobic digestion of sewage sludge integrated with wet oxidation	230–415

Lynn at al. [7] performed a detailed analysis of the potential use of WWSA, and the authors concluded that WWSA addition, whether as a cement or aggregate replacement, leads to a reduction in the mechanical properties of both mortars and concrete. The recommended replacement ratio was up to 15%. The other conclusion was that WWSA, as a porous material, has a potential application as a lightweight aggregate (in both forms, as produced and ground).

The physical and chemical composition and pozzolanic activity of the sludge depends on the quality of the initial treated water and the type of processes applied during its treatment, as well as the design of the treatment plant, the time of year and the climate, as previously elaborated and published [14].

Apart from incineration [15], one post-treatment method for WWS and DWS is solidification. During the solidification process, WWS and DWS are exposed to a temperature of 90 °C and different solidification agents. The most commonly applied agents are calcium oxide and calcium hydroxide. The costs for this kind of product after treatment with chemical agents is 132.5 EUR/ton. Material obtained in this way is referred to as solidified wastewater sludge (SWS). As shown by Nakic et al. [16], its chemical composition differs greatly from the usual composition of WWS, DWS and WWSA. Previous research showed that SWS used as a partial cement replacement in cement composites, even in amounts lower than 20%, led to a reduction in mechanical properties and an increase in permeability and the water penetration depth when compared to a reference mixture [10]. The possibilities of the application of SWS as a partial replacement of cement in pervious concrete pavers have been previously investigated [17]. A replacement of cement between 10 and 30% caused the decrease of up to 50% for all of the tested mechanical properties when compared to the reference mixture.

The first objective of the present research was to improve the properties of SWS without additional energy consumption through incineration, and then perform all of the necessary analyses and laboratory trials in order to confirm the possibility of modified solidified wastewater sludge (MWS)'s application as a partial replacement of cement.

1.2. Lightweight Concrete and Its Application

Since the improvement of the thermal properties of building materials became an important issue in light of energy efficiency, lightweight concretes (LWCs) regained their place in the research community, as well as for real-life applications [18]. Some of the most pronounced advantages of lightweight concrete are its structural stability, a decrease in the dead load, its economic viability and its (relatively) low thermal conductivity, and if adequately prepared, LWAs improve the workability of concrete [18]. Apart from the above-mentioned, the application of LWC gained importance in the construction industry due to the possible replacement of cement and aggregates with other materials without much compromising the mechanical properties of concrete. The production of LWC allows for the implementation and usage of low- or even zero-cost raw materials, with a relatively low influence on the properties of LWC [19–22].

Different types of waste materials have been used as partial replacements of cement in LWC: silica fume, fly ash, ground granulated blast furnace slag, metakaolin, rice husk ash, palm oil fuel ash, pumice powder and volcanic ash, crushed natural pozzolan, perlite powder, glass powder, paper sludge ash and calcined pyrophyllite [23,24]. Mo et al. [23] performed a detailed overview of SCM usage in lightweight aggregate concrete. Based on their work, the influence of different SCMs in concrete prepared with an expanded clay aggregate was analyzed. It was concluded that the partial replacement of cement with fly ash in an amount up to 15% and ground granulated blast furnace slag up to 40% already led to an increase in the compressive strength of lightweight concrete after 28 days. When metakaolin was used as a cement replacement, an increase in the compressive strength was already noticeable after 7 days. The use of pumice powder and volcanic ash led to a decrease in the compressive strength. Apart from the stated results, special attention was paid to the durability of the LWC when different SCMs were applied.

In previous research, the possibilities of using solidified wastewater sludge (SWS) as a partial replacement of cement in pervious concrete mixtures were investigated [17]. It was concluded that this waste product showed an inorganic nature and that it was nonhazardous for the environment. Nevertheless, the addition of SWS led to a linear decrease in all mechanical parameters with no pozzolanic activity detected. Therefore, the partial replacement of cement in cement composites was decided to be, in the current study, performed with MWS, which incorporates, beside SWS, the addition of aluminum oxide, magnesium silicate hydrate and a water retention admixture. In order to assess the influence of the partial replacement of cement with MWS on the basic fresh and hardened state properties of cement composites, four mortar mixtures based on the standard cement mortar recipe were prepared. Further on, the possibility that the design of the lightweight concrete would fulfill the requirements for the structural application while incorporating MWS was tested.

In the final step, since the exploration of the willingness of final users to adopt innovative technologies, especially those including the usage of waste materials, is an often-overlooked area of research, the readiness of final users to embrace the solution proposed by this research was also investigated.

In this way, the objective, which was set to explore the potential of MWS as a partial replacement of cement in the production of LWC that complies with standards for energy-efficient building materials, was pursued in all important physical, chemical, environmental and social aspects.

2. Experimental Work

The experiments in the current research were divided into two parts. The first part covered detailed physical, mineralogical and chemical analyses of the MWS. The second part covered the analyses of the physical and mechanical properties and durability based on the choice of an optimal lightweight concrete mixture that was produced with cement partially replaced with MWS.

Figure 1 (inspired by [3]) presents the link between the previously conducted research and the research presented in the current paper and supports the explained objectives of the study.

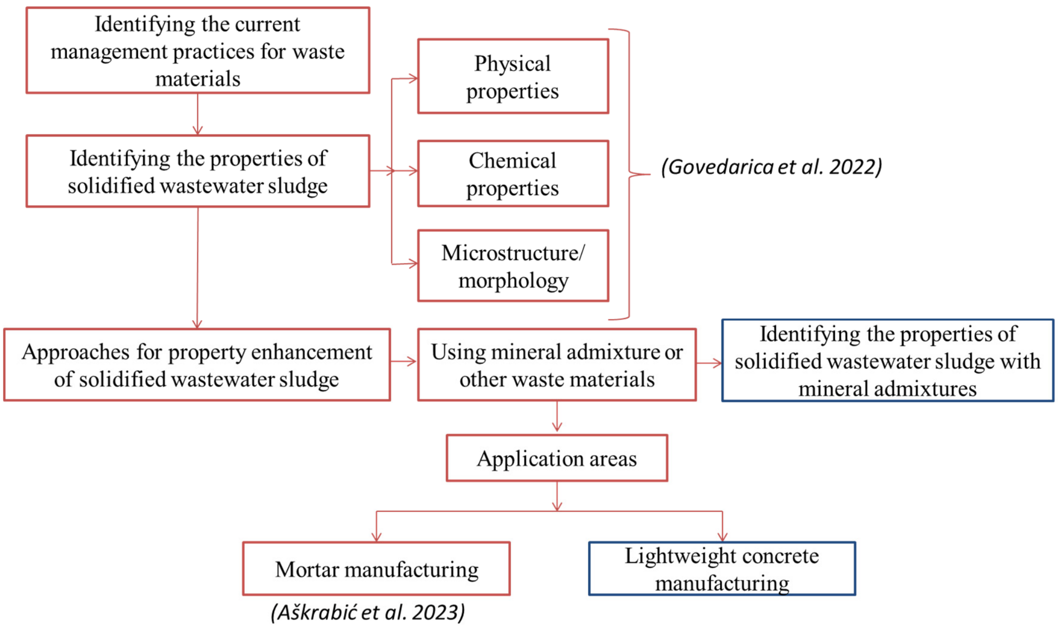

Figure 1. A schematic presentation of the research that the authors conducted in previous studies (in red squares) and in the present study (in blue squares) [17,25].

In order to perceive the influence of the MWS on cementitious composites, four mortar mixtures were prepared, in which cement was replaced in the amounts of 10, 20 and 30%. One mixture was used as a reference, without the replacement of cement. For the concrete analyses, two series were produced, a reference mixture and a mixture where cement was replaced with 20% MWS. Additionally, the social aspect of the waste materials being incorporated in buildings and human surroundings was also addressed. Photographs of the component materials used, the production processes, the prepared samples and the testing equipment are presented in Figure 2.

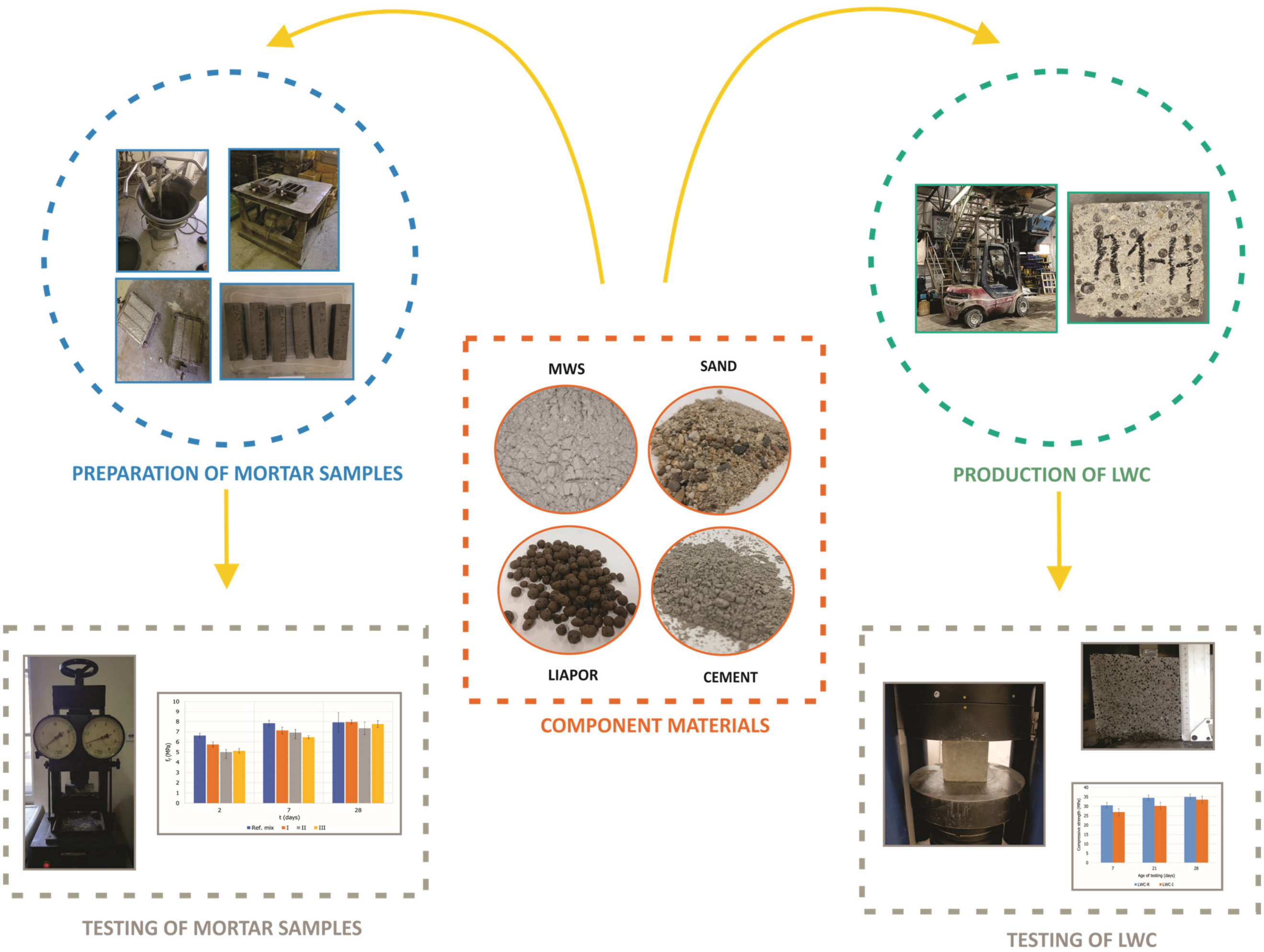

Figure 2. The component materials, samples and testing equipment used in the experimental work.

2.1. Materials

Solidified wastewater sludge (SWS) is a light-gray powder with hydrophobic properties. The chemical composition of the SWS is presented in Table 2.

Table 2. The chemical composition of SWS and sand.

Oxide	SWS (%)	Sand (0/4 mm) (%)
Loss on ignition at 1000 °C	26.9	2.78
CaO	71.7	4.21
SiO_2	0.14	80.5
Al_2O_3	0.14	3.90
Fe_2O_3	0.03	4.32
MgO	0.51	1.38
SO_3	0.27	0.04
K_2O	0.07	1.10
Na_2O	0.01	1.09
TiO_2	-	0.21

The chemical composition of SWS and sand was determined in the external certified lab. SWS was mixed with aluminum oxide produced by "Centrohem", Stara Pazova, Serbia, magnesium silicate hydrate produced by "Tehnochem", Belgrade, Serbia, and a water-retaining admixture, forming the modified solidified wastewater sludge (MWS). The mixture contained 90% SWS, 6.25% Al_2O_3, 3% $Mg_3Si_4O_{10}(OH)_2$ and 0.75% of a water retainer.

A PC 52.5R cement was used for the mortar sample production, while CEM II 42.5 R (A-L) was used for the lightweight concrete mixtures, both produced by "MoravaCem", Belgrade, Serbia. River sand originating from the Danube river, with grains sized from 0 to 4 mm, was used as an aggregate. The loose bulk density of the sand was 1640 kg/m^3. The chemical composition of the sand is presented in Table 2. An expanded clay aggregate, produced by "Liapor", Hallerndorf, Germany, with a grain size between 1 and 4 mm was employed as an aggregate, together with the river sand, in concrete mixtures. The loose bulk density of this aggregate was 450 ± 65 kg/m^3, with a water absorption after 24 h of 11 ± 4%. Tap water was used in all mixtures, together with a superplasticizer produced by TKK, Srpenica, Slovenia.

2.2. The Preparation of the Mortar and Concrete Samples

The mortar mixtures were prepared based on the standard cement mortar design. In order to obtain adequate workability for the mortars, a water/cement ratio of 0.55 was adopted. The composition of the mixtures is presented in Table 3 [25]. In the mortar mixtures designated as I, II and III, cement was partially replaced with MWS in the amounts of 10%, 20% and 30%, respectively, while the water/binder ratio was kept constant. Samples were cured in a humid environment during the first 24 h and then in water until the age of 14 days.

Table 3. The mass composition of the mortar mixtures, presented in kilograms per m^3.

Mixture	MWS%	Cement	MWS	Aggregate	Water [kg/m^3]
R *	0	483	-	1450	265
I	10	435	48	1450	265
II	20	386	97	1450	265
III	30	338	145	1450	265

* R—reference mixture for comparison.

Based on the results obtained for the mortar samples, MWS was used as a partial replacement of cement in the amount of 20% by mass in the lightweight concrete mixture (Table 4). The mixture containing MWS (labeled as LWC-I) was designed with the following principles: (1) the water-to-cement ratio (0.49) and the total amount of the powder material (430 kg/m^3) were to remain the same as in the reference mixture (labeled as LWC-R), and (2) the bulk density and the consistency of both concrete mixtures were to remain the same. In order to achieve this, the amount of aggregates was varied. Due to the differences in the bulk densities of MWS and cement, the expanded clay aggregate was reduced by 18% and the amount of sand increased.

Table 4. The composition of the tested mixtures for lightweight concrete (kg/m^3).

Material	LWC-R	LWC-I
Cement—CEM II 42.5 R (A-L)	430	345
MWS	0	86
Expanded clay—1/4 mm	240	200
River sand—0/4 mm	970	1050
Water	210	168
Superplasticizer	2.15	2.15
Bulk density	1850	1849

2.3. Methods

2.3.1. Component Materials

The analyses of the components covered the following instrumental techniques and methods: the particle size and particle size distribution, elemental analysis (XRF), the morphology of samples and the chemical composition (SEM-EDS), the thermal stability and degradation of MWS (thermogravimetric analysis (TGA)/Differential Scanning Calorimetry (DSC)).

The particle size and the particle size distribution were measured with the laser light scattering method using the Mastersizer 2000 analyzer (Malvern Instruments, Malvern, UK). The particle size distribution of the powdered samples was measured using the Mastersizer Scirocco 2000 analyzer (Malvern Instruments, UK). The results obtained were presented according to three dependent parameters: the surface-weighted mean diameter (SD) (μm) or volume-weighted mean diameter (VD) (μm), the specific surface area (SSA) (m^2/g) and the span values.

The XRF analyses were performed using a Thermo Fisher Scientific (Waltham, MA, USA) Niton XL3t GOLDD+ XRF analyzer. Each sample was measured for 240 s in the Test All-Geo mode. This testing time was chosen so that limit-of-detection values could be obtained for all the elements.

The FESEM Tescan Mira 3 XMU was used for the morphological characterization of the samples. Prior to analysis, the samples were coated with Au.

The thermal stability and degradation of solidified wastewater sludge was studied at room temperatures up to 1200 °C in an air atmosphere (flow rate: 100 $cm^3\ min^{-1}$; weight accuracy: ±1%) in alumina sample cups using an SDT Q600 TGA/DSC instrument (TA Instruments, New Castle, DE, USA). The heating rate was 20 °C min^{-1}, while the used mass of the sample was 34.517 mg.

2.3.2. Mortars

The analysis of the mortars was performed using the following instrumental techniques and methods: bulk density and consistency tests; the flexural and compressive strength were tested at the ages of 2, 7 and 28 days, as an average of three measurements for all parameters. After reaching the age of 28 days, three samples per mortar mix were tested for their frost resistance. The bulk density and consistency tests were performed on the fresh mortar mixtures based on the EN 1015-3 [26] and EN 1015-7 [27] standards. The measurements of mass were performed using a scale with an accuracy of 1 g. The flexural and compressive strengths of hardened mortars were tested at the ages of 7 and 28 days, according to EN 1015-11 [28], using an Amsler testing machine with an accuracy of 0.1 kN for flexural strength and 2.5 kN for compressive strength measurements. After reaching the age of 28 days, samples were exposed to 25 freeze–thaw cycles according to the Serbian national standard SRPS U.M8.002 [29], using an FDM climatic chamber with a range between −25 °C and +70 °C. One cycle included exposing the samples to a temperature of −20 °C for 4 h and then thawing them in water with a temperature of +20 °C for 4 h. After 25 cycles, the flexural and compressive strengths of the samples were tested and compared to the reference samples that were tested after 33 days of curing in water.

2.3.3. Lightweight Concrete

The analysis of the lightweight concrete was performed using the following instrumental techniques and methods: tests for the bulk density, compressive strength (tested at the ages of 7, 21 and 28 days), water permeability and frost resistance. The lightweight concrete samples were tested in a hardened state. The bulk density and compressive strength were tested at the ages of 7, 21 and 28 days, using a scale with an accuracy of 5 g and a compression testing machine with an accuracy of 1 kN. After reaching the age of 28 days, the water permeability and frost resistance were also tested according to the EN 12390-8 [30] and SRPS U.M1 206-1, Appendix D [31], standards. The frost resistance was tested using fifty freeze–thaw cycles (one cycle was composed of 4 h at a temperature of −20 °C and 4 h in water with a temperature of +20 °C); three cycles were performed daily. After 10 days from the beginning of the test, the reference samples that were cured in water at a temperature of +20 °C were tested for their compressive strength. At the end of the test, the samples exposed to freeze–thaw cycles were also tested, and a comparison of the compressive strength of these two types of samples was performed. The process for the leaching analyses of concrete samples was based on the TCLP test (Toxicity Characteristic Leaching Procedure, USEPA method 1311, 2003) [32].

2.3.4. Human Reaction to Use of Waste Materials in Structural Materials

Besides all the engineering-based characterization methods and techniques, a part of this research was focused on the readiness of the end users to accept the application of waste materials in the production of classical building materials.

The main goal of the research and work with end users was to raise their awareness and knowledge [33] about this area of environmental problems, providing them with skills and motivation to resolve existing problems and to prevent the occurrence of new ones in future [34].

Concerning the implementation of innovative solutions in the construction industry, Song, Wang and Li [34] emphasized that decision-makers must consider not only the technical aspects and implementation costs but also residents' attitudes and willingness. Without securing end users' participation, it becomes challenging to effectively implement policies and engage producers. As shaping attitudes and willingness is a gradual and time-consuming process, it is relevant to initiate it alongside the testing of technical solutions.

The participants were recruited from a student and citizen (general population, architects and construction engineers) participant pool. A total of 348 students at the University of Belgrade (N_{female} = 245 (70%); N_{male} = 103 (30%)) with an average age of 22 (M = 21.70; SD = 2.54) completed the study. The sample included students from the Department of Psychology in the Faculty of Philosophy (SP; N = 174) and students in the Faculty of Civil Engineering (N = 174). Students in the Faculty of Civil Engineering were enrolled in the general civil engineering (SGCE; N = 108) or the hydraulic and environmental engineering (SHEE) (N = 66) study programs.

Regarding the citizen sample, the research included a total of 531 participants from both the general population and professionals working as civil engineers and architects (N_{female} = 338 (63.65%); N_{male} = 193 (33.35%)) with an average age of 30 (M = 29.95; SD = 13.56). Thus, the survey was completed by 470 (88.5%) respondents from the general population, 29 (5.5%) civil engineers and 32 (6%) architects.

The online survey was accessible to participants through 1KA and Google Forms. They provided their informed consent before answering the questions. The survey comprised demographic inquiries (gender, age, educational attainment, and occupation) as well as the main research metrics, such as 1. questions about relevant experience (with or without experience in recycling, environmental protection, flooding and construction/renovation) and 2. environmental concerns (the perceived seriousness of air, water and solid waste pollution).

Adhering to established research methodology principles, a two-phase approach was necessitated: the pilot phase (student sample) and the main phase (citizen sample).

The pilot phase was imperative due to the dearth of literature addressing the willingness to adopt construction technological solutions within the local context. A comprehensive questionnaire was created, encompassing relevant socio-demographic variables and drawing insights from questionnaires used in construction and demolition waste management research, given its relevance as a related concept (questions on attitudes, values, beliefs, social norms, knowledge, motivation, a sense of control, and the willingness to accept project solutions). As a result of the pilot phase, an initial pool of 212 items was refined based on conceptual, methodological and empirical analysis.

Accordingly, the survey in the main phase comprised demographic inquiries (gender, educational attainment, and occupation) as well as the main research variables, such as 1. questions about relevant experience (with or without experience in recycling, environmental protection, flooding and construction/renovation), 2. environmental concerns (the perceived seriousness of air, water and solid waste pollution), 3. attitudes toward project solutions and 4. the willingness to accept project solutions.

3. Results

3.1. Modified Solidified Wastewater Sludge (MWS)

3.1.1. Particle Size and Particle Size Distribution

The particle size distribution for the SWS and MWS samples (before and after modification) is presented in Figure 3.

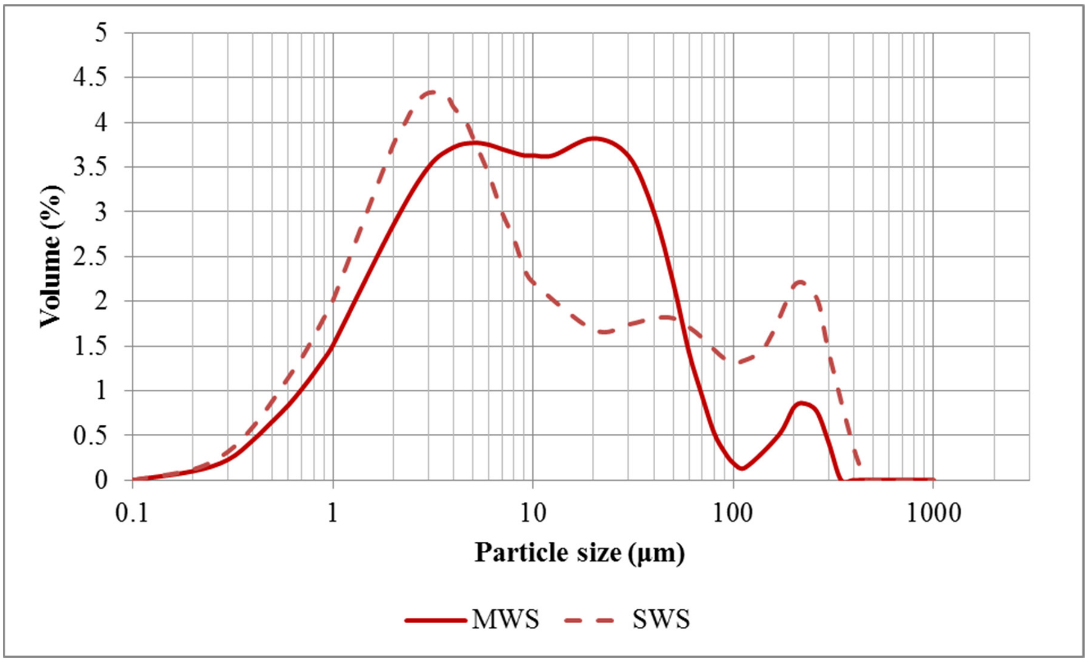

Figure 3. The particle size distribution of the SWS and the MWS samples.

The specific surface area of the sample was 1.79 m^2/g, while the surface-weighted mean of the particles was 3.35 μm. It was also discovered that 50% of the particles had a diameter lower than 8.49 μm, while 90% of particles had a diameter lower than 45.5 μm.

3.1.2. XRF

The results obtained from the XRF analysis of MWS are presented in Figure 4. As expected, after mixing SWS with aluminum oxide and magnesium silicate, the amount of CaO continued to be the most pronounced. Nevertheless, the measured values of SiO_2 and Al_2O_3 were also significant. Apart from the oxides presented in Figure 4, the sample also contained Mn_3O_4, ZnO, NiO, CrO, CuO, PbO and WO_2. It can be clearly seen that MWS is not a viable replacement for cement, at least not as far as its function is considered.

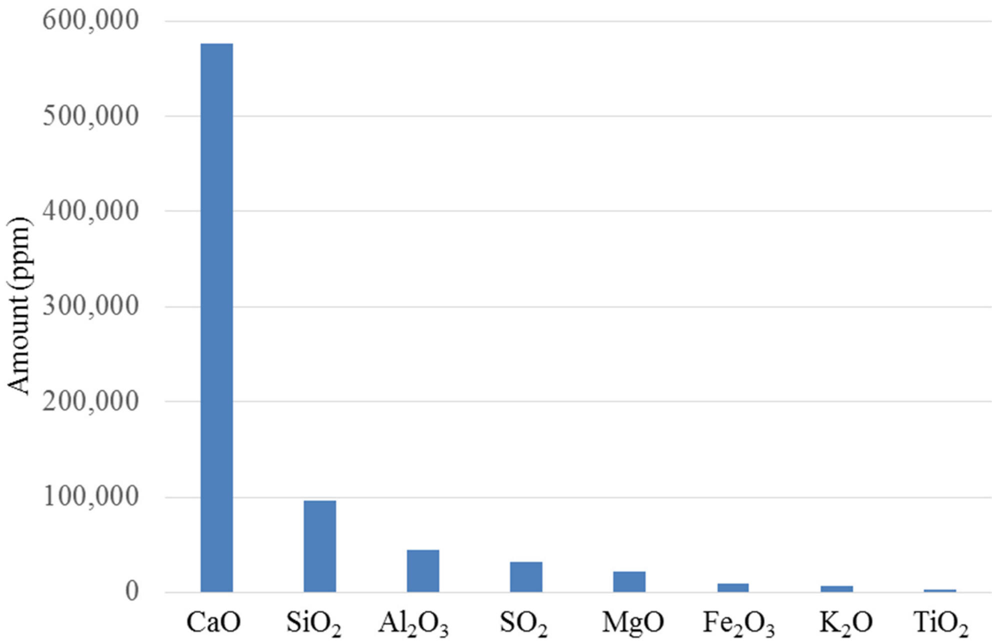

Figure 4. The chemical distribution of oxides in the MWS sample, according to XRF measurements.

3.1.3. Scanning Electron Microscopy (SEM)

From the SEM images presented in Figure 5a, complex aggregates of $Ca(OH)_2$ and $CaCO_3$ particles can be observed. At higher magnifications (Figure 5b,c), individual agglomerates can be observed, consisting of numerous, irregular, smaller particles [35]. These SEM images reveal a higher presence of the granular stone shape, which can be attributed to $Ca(OH)_2$ [36]. Additionally, multiple-layered porous hierarchical flake-like structures with relatively large grain sizes were also observed that could be related to the lower presence of $CaCO_3$ particles [37]. These results are in accordance with the chemical analysis, where a substantial amount of $Ca(OH)_2$ was detected.

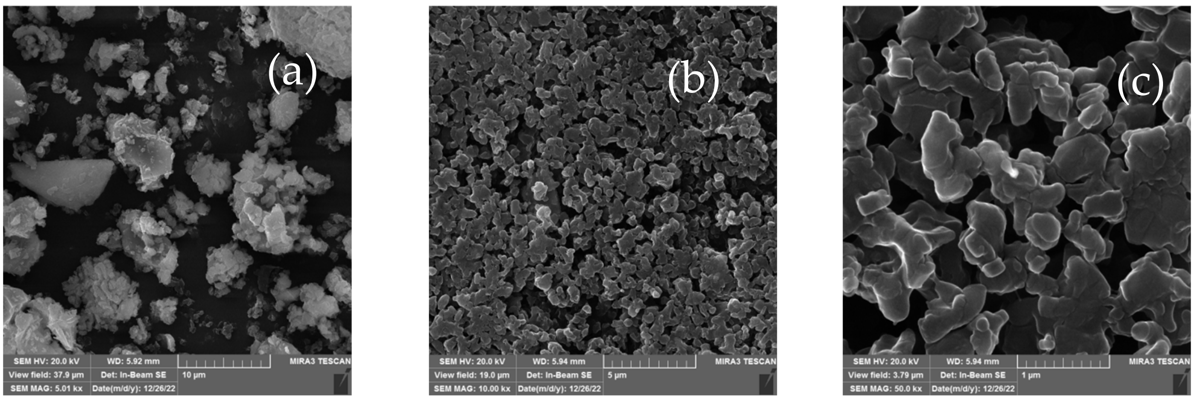

Figure 5. SEM images of the MWS sample with different magnifications: (**a**) 5000, (**b**) 10,000, (**c**) 50,000.

3.1.4. Thermal Stability and Degradation (TGA)

The thermal decomposition of MWS occurred in six steps when exposed to the air (Figure 6).

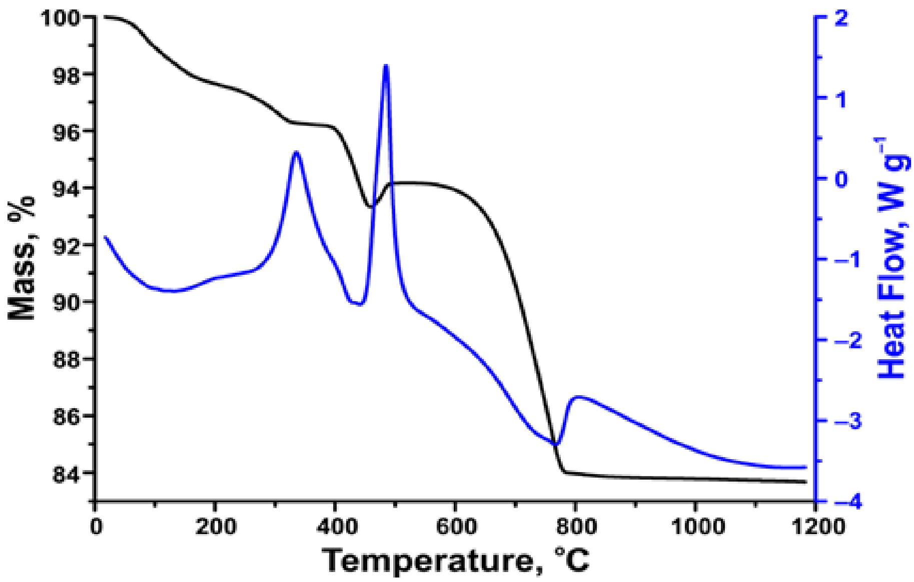

Figure 6. TGA (black) and DSC (blue) curves of the MWS in an air atmosphere.

At temperatures up to 455 °C, the TGA curve revealed a mass loss of 6.62% that happened in four overlapping steps, which were followed by one strong exothermal maximum at 336 °C in the DSC curve (Figure 7). In the next step, at temperatures up to 499 °C, a mass gain of about 0.78% was observed, followed by another strong exothermal maximum at 485 °C in the DSC curve. In the last step, a long plateau was observed in the TGA curve in the temperature range 798–1200 °C that could probably be ascribed to the formation of oxide materials. Up to the final temperature of the analysis, the total mass loss after the thermal decomposition of solidified wastewater sludge was 16.3%.

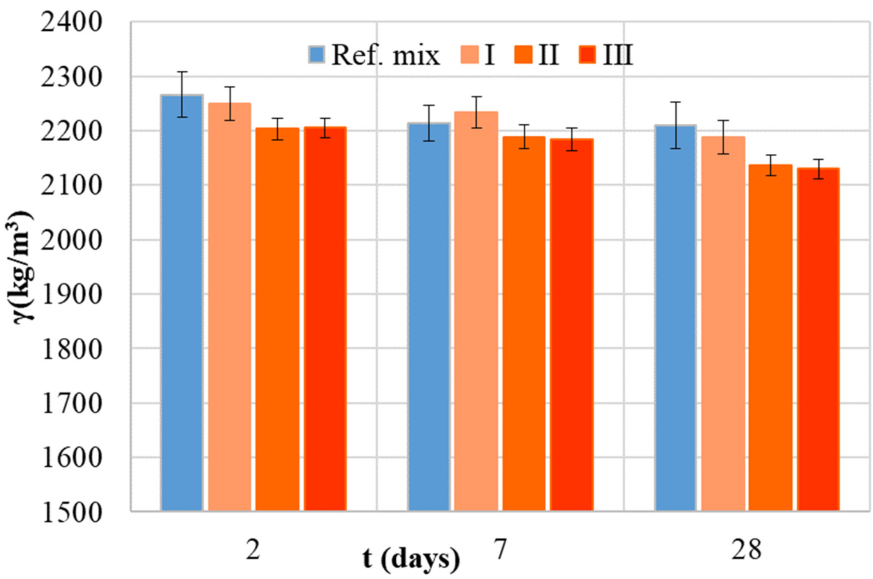

Figure 7. The bulk densities of the tested mixtures at different ages.

3.1.5. Mortar Mixtures

The bulk density and consistency (the slump flow diameter, obtained using the table method) of mortars in a fresh state are presented in Table 5.

Table 5. The fresh state properties of tested mortars.

Mixture	Bulk Density (kg/m^3)	Slump Flow Diameter (mm)
Reference	2221	150
I	2175	156
II	2174	157
III	2175	150

The bulk densities at the ages of 2, 7 and 28 days are presented in Figure 7. They are calculated as the average values of three measurements, with presented standard deviations. Although it was noticed that the mixtures with 20% and 30% cement replacement with MWS had lower values of the bulk density, these differences were not significant. The greatest decrease of 3.62% was measured at the age of 28 days.

The measured values of the flexural and compressive strength at the ages of 2, 7 and 28 days are presented in Figures 8 and 9, relative to the reference mixture values.

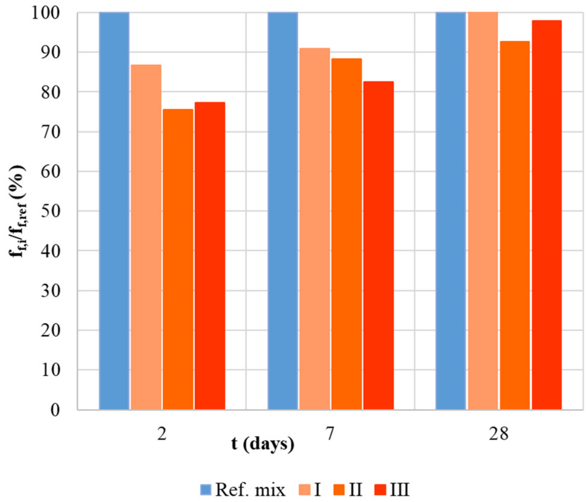

Figure 8. The relative flexural strength of mixtures at different ages.

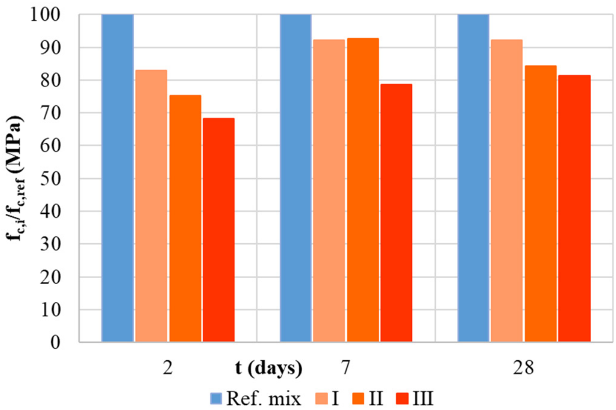

Figure 9. The relative compressive strength of mixtures at different ages.

The compressive strength of the reference mortar mixture was 33.6 MPa, 42.7 MPa and 59.6 MPa, while the flexural strength was 6.6 MPa, 7.8 MPa and 7.9 MPa, at the tested ages. The addition of MWS led to a decrease in the flexural strength, but the differences between the reference mixtures and the mixtures with MWS were the highest at the age of 2 days, reaching 24.2%. The addition of MWS also induced a greater decrease in the values for the compressive strength. At the age of 28 days, the strength of the mixture with 30% cement replacement reached 81.2% of the reference mixture strength.

The prismatic samples, after reaching the age of 28 days, were exposed to 25 freeze–thaw cycles. After the finalization of the test, the flexural (f_f) and the compressive strengths (f_c) were tested. At the same time, samples cured in water up to the age of 35 days were also tested, as reference samples. The decrease in strength (in percent) compared to the reference samples was calculated (Δf_f and Δf_c). For the flexural strength, this reduction was between 6% and 7% for all tested mixtures, except for the mixture with 20% cement replacement. For the compressive strength, the differences were even smaller. The highest reduction in strength was measured for the 10% mixture, and it was 6.4%.

3.2. Lightweight Concrete (LWC)

3.2.1. Bulk Density of LWC

The bulk density of the LWC sample was tested at the ages of 7, 21 and 28 days. The obtained results are presented in Figure 10. The differences between the LWC-R and LWC-I were negligible at all ages. According to these values, both mixtures belong to the structural lightweight concrete category.

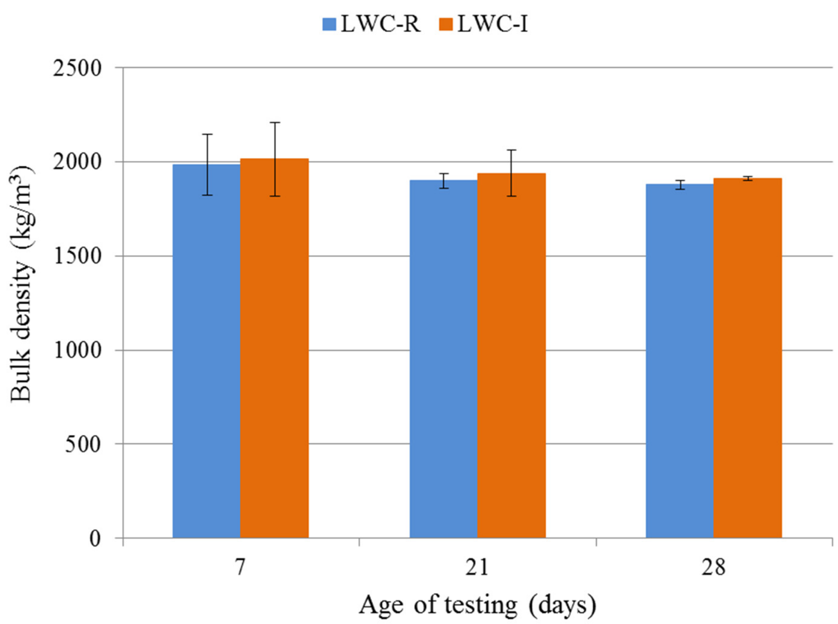

Figure 10. The results of the bulk density testing.

3.2.2. Compressive Strength

The compressive strength was tested at the same ages as the bulk density. Each of the measurements was performed on three cubic samples (dimensions of 15 cm). The results are presented in Figure 11. At the age of 28 days, the reference concrete reached a compressive strength of 35.1 MPa while the LWR-I concrete reached 33.3 MPa. The relative ratio between these two results was 0.95. According to the standard EN 206 [38], both types of lightweight concrete fulfill the conditions for the concrete class LC 25/28.

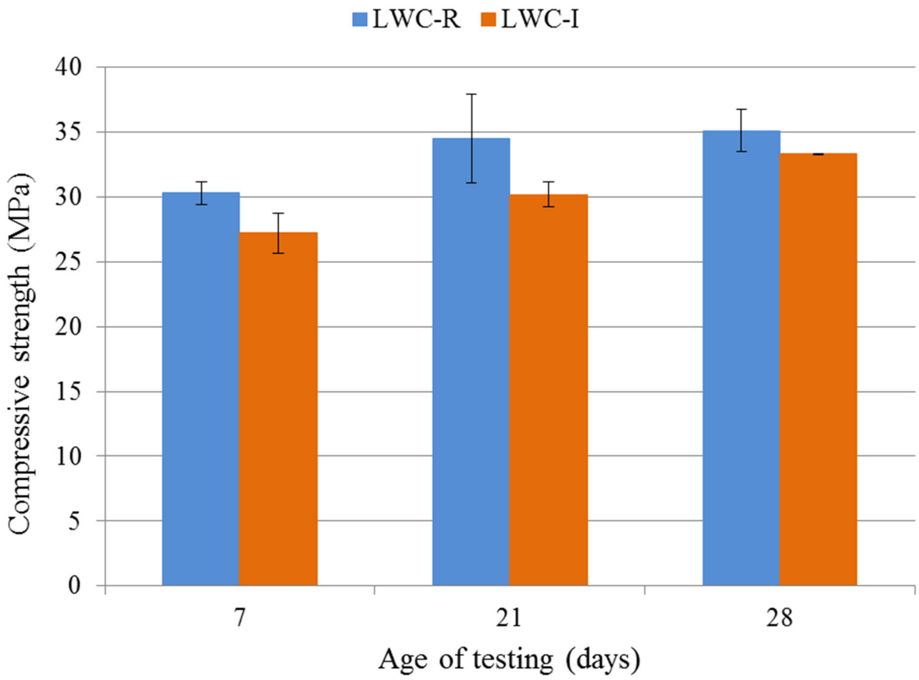

Figure 11. The results of the compressive strength testing.

3.2.3. Water Permeability Test and Frost Resistance

The water permeability was tested for both concrete mixtures at the age of 28 days (Figure 12). After the samples were exposed to a water pressure of 5 bars for 72 h; they were split in two halves, and the maximum water penetration height was measured for each sample. The obtained results are presented by photos of the samples together with the measured maximal water penetration height. The penetration depth was between 25 and 27 mm for the reference mixture and between 13 and 18 mm for the mixture containing MWS.

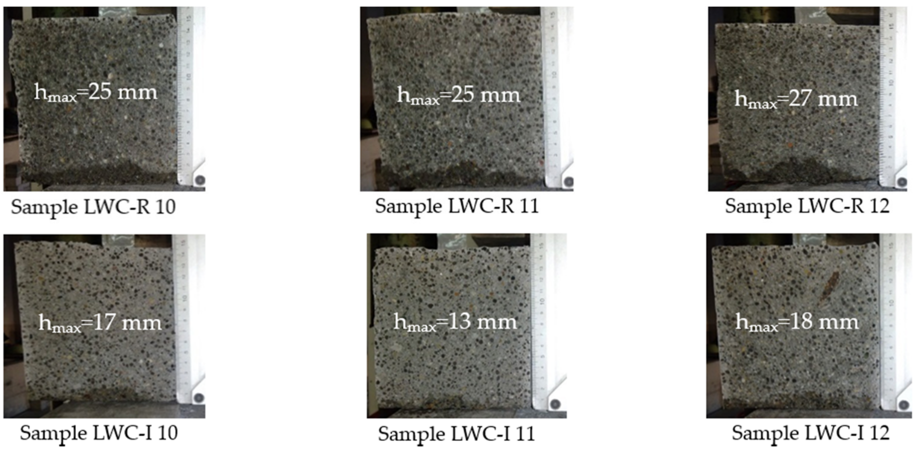

Figure 12. The photos of the LWC samples together with the measured maximal water penetration heights.

The frost resistance was tested after reaching the age of 28 days. The drop in the compressive strength was 7.6% for the LWC-R mixture and 6.1% for the LWC-I mixture.

3.2.4. Concrete Leaching Test

The TCLP leaching test results are presented in Table 6. No great differences between the values measured for the reference concrete and concrete samples containing MWS were noticed.

Table 6. Leaching test results.

No.	Parameter (mg/kg)	LWC-R	LWC-I (1)	LWC-I (2)
1.	Arsenic (As)	<0.2	<0.2	<0.2
2.	Barium (Ba)	5.3	6.8	5.3
3.	Cadmium (Cd)	<0.05	<0.05	<0.05
4.	Chromium (Cr)	<0.5	0.52	0.65
5.	Copper (Cu)	<0.5	0.5	<0.5
6.	Molybdenum (Mo)	<0.5	<0.5	<0.5
7.	Mercury (Hg)	<0.1	<0.1	<0.1
8.	Nickel (Ni)	<0.2	<0.2	<0.2
9.	Lead (Pb)	<2	<2	<2
10.	Antimony (Sb)	<0.5	<0.5	<0.5
11.	Selenium (Se)	0.39	0.47	0.44
12.	Zinc (Zn)	<1	<1	<1

Labels (1) and (2) represent the same samples (cubes with modified solidified wastewater sludge), for which the measurements were repeated.

3.3. The Role of the Human Factor

The key factors influencing the willingness to accept project solutions investigated in the main research phase—identified during the pilot phase—included socio-demographics, environmental concerns, relevant past experiences, and attitudes toward MSW in concrete, as detailed in Tables 7–11.

Table 7. Descriptive statistics and correlations between the main study variables.

Variable	M	SD	1	2	3	4	5	6	7
Age (1)	29.95	13.56	—						
Air pollution (2)	8.09	1.59	0.01						
Water pollution (3)	8.41	1.31	−0.10 *	0.69 **					
Solid waste pollution (4)	7.59	1.73	0.07	0.61 **	0.51 **				
A_{MSW}(5)	39.43	8.23	0.05	0.20 **	0.15 **	0.28 **			
W_{MSW} (6)	41.54	10.91	0.04	0.21 **	0.17 **	0.25 **	0.62 **		
Financing MSW (7)	3.30	1.07	0.02	0.15 **	0.09 *	0.14 **	0.37 **	0.48 **	—

A_{MSW}—attitudes toward use of MSW in concrete. W_{MSW}—willingness to use MSW in concrete. M—arithmetic mean. SD—standard deviation. * = $p < 0.05$. ** = $p < 0.01$.

Table 8. Mean and standard deviation of males and females regarding willingness to accept MWS in concrete.

	Male		Female	
	M	SD	M	SD
Gender	40.40	11.21	42.19	10.70

M—arithmetic mean. SD—standard deviation.

Table 9. *t*-test results comparing males and females on willingness to accept MWS in concrete.

					95% Confidence Interval of the Difference			
	t	df	*p*	Mean Difference	Lower	Upper	Cohen's d	r
Gender	−1.81	527	0.70	−1.79	−3.72	0.14	−0.16	−0.08

t—the value of the *t*-test. df—the degrees of freedom. *p*—the *p*-value. r—effect size.

Table 10. Mean and standard deviation of respondents with or without relevant experience regarding willingness to accept MWS in concrete.

	Yes		No	
	M	**SD**	**M**	**SD**
recycling	42.23	10.35	39.62	12.16
environmental activism	42.36	10.40	38.69	12.13
construction/renovation	41.76	11.86	41.42	10.39

M—arithmetic mean. SD—standard deviation.

Table 11. *t*-test results comparing respondents with or without relevant experience regarding willingness to accept MWS in concrete.

					95% Confidence Interval of the Difference			
	t	**df**	***p***	**Mean Difference**	**Lower**	**Upper**	**Cohen's d**	**r**
recycling	2.26	215.69	0.03	2.61	0.34	4.88	0.23	0.12
activism	2.98	169.47	0.00	3.66	1.24	6.09	0.32	0.16
construction	0.33	328.33	0.74	0.34	−1.71	2.39	0.03	0.02

t—the value of the *t*-test. df—the degrees of freedom. *p*—the *p*-value. r—effect size.

Table 7 contains the descriptive statistics and correlations between the main study variables.

A moderately positive correlation was observed between the perceptions of the severity of various forms of pollution (air, water and solid waste). The respondents' perceptions of the severity of the water contamination issue decreased with age (low positive correlation). Based on the correlational analysis, individuals who were more concerned about environmental pollution and favored creative environmental solutions were more receptive to these solutions and more willing to support them financially.

The subsequent step involved assessing the association between gender (Tables 8 and 9), relevant experience (Tables 10 and 11) and the willingness to accept the application of MWS in concrete.

Similarly to the results from the student sample, gender (Tables 8 and 9) did not demonstrate a relationship with the willingness to accept MWS in concrete in the citizen sample.

There is evidence both in favor of and against the influence of gender in the relevant research. The results differ according to the nature of environmental issues and their solutions (e.g., construction waste management, recycling) [39–41].

Individuals with current recycling experience or involvement in environmental protection activities demonstrated significantly greater willingness to adopt MWS in concrete (Tables 10 and 11). This finding aligns with relevant research, which shows a strong empirical relationship between attitudes toward various types of recycling and recycling behavior in different contexts [40,42].

Conversely, respondents with experience in construction/renovation did not exhibit a significant difference in willingness compared to those without such experiences.

Previous analyses [39] indicated that attitudes and willingness varied somewhat within different professional groups. Namely, students with more professional knowledge and experience tended to have more negative attitudes and were less willing to accept MWS in concrete. In particular, psychology students displayed more positive attitudes and willingness to embrace MWS's application in concrete compared to civil engineering students. Additionally, the results showed differences in the attitudes and willingness even between two groups of students within the Civil Engineering Faculty (general civil engineering and hydraulic and environmental engineering).

To assess the relative contribution of these factors in predicting the willingness to accept MSW in concrete, three linear regression models were tested: one for the general population and two for professionals—architects and civil engineers—where professional experience and knowledge might play a role (Table 12). Two professional groups were considered due to the previously observed differences in attitudes and willingness, both between psychology and construction engineering students and between two study groups within the Civil Engineering Faculty.

Table 12. Model summary and coefficients of each linear regression model.

Model	Sample	R^2	F	df1	df2	*p*
1	general population	0.374	270.365	10	458	<0.001
2	construction engineers	0.953	420.700	10	21	<0.001
3	architects	0.715	40.264	10	17	0.004

R^2—coefficient of determination. F—the value of the F test. df—the degrees of freedom. *p*—the *p*-value.

All three models were statistically significant.

In the general population sample, which did not include professionals from relevant fields such as architecture, construction or materials technology, the attitudes towards using MSW in concrete ($\beta = 0.578$, $p < 0.001$) and personal experience with flooding ($\beta = 0.114$, $p = 0.047$) showed a statistically significant relative predictive contribution (Table 12). Positive attitudes and prior flood experience were positively linked to a greater willingness to accept MSW in concrete (Tables 7–11).

For both architects and construction engineers, positive attitudes also demonstrated a statistically significant relative predictive contribution (architects: $\beta = 0.718$, $p < 0.001$; construction engineers: $\beta = 0.492$, $p < 0.001$), as did concerns about pollution caused by solid waste (architects: $\beta = 0.466$, $p = 0.034$; construction engineers: $\beta = 0.358$, $p < 0.001$) (Table 12). Positive attitudes and greater concern about solid waste pollution were positively associated with a willingness to accept the solution (Tables 7–11). However, among construction engineers, additional factors significantly contributed to their willingness to accept MSW in concrete (Table 12). These included their age ($\beta = -0.205$, $p = 0.027$), experience in recycling ($\beta = 0.256$, $p = 0.041$), environmental activism ($\beta = 0.427$, $p = 0.001$) and personal experience with flooding ($\beta = 0.147$, $p = 0.020$). Specifically, younger construction engineers with environmental concerns, exposure to flooding and favorable views on MSW in concrete expressed a greater willingness to use it (Tables 7–11).

4. Discussion of Results

4.1. Properties of MWS

If the particle size distribution of the original SWS sample, before mixing it with additional components, is compared with MWS, two pronounced peaks at 5 and 200 µm can be observed for both samples [17]. For MWS, one additional peak appears at 25 µm. More precisely, this peak is more pronounced for the modified sample. The MWS sample had particles with larger sizes than the original solidified sludge and, therefore, a lower density. Almost 90% of particles for both samples were smaller than 45.5 µm. The MWS material had granulation which was similar to or finer than ordinary Portland cement [43]. The fineness of the particles could be observed and recognized by SEM micrographs (Figure 4).

The chemical presence and quantification of oxides was determined through XRF analysis. These results were in accordance with the chemical composition of all the individual compounds. As expected, the most present and in the highest amount was CaO, which originated from SWS (mainly composed of $CaCO_3$ and $Ca(OH)_2$) [17]. Compared with the previous results obtained from XRF analysis, the original sample had a very similar amount of CaO. Nevertheless, all other oxides in the original sample were present in significantly lower quantities. The only unexpected result when the MWS sample was analyzed was the amount of SO_2 (4.0%). This oxide could have originated from the SWS or magnesium silicate.

If MWS is considered as a supplementary cementitious material, from a chemical composition perspective it resembles ordinary Portland cement (OPC), a result presented by Chang et al. [44]. The most prominent difference is the silica content, which was several times higher for the OPC sample compared to MWS. Still, it is not the chemical composition that dictates the ability of a material to behave as Portland cement, but rather the proportions of the oxides and, more specifically, a high content of SiO_2, Al_2O_3 and Fe_2O_3.

These findings were in accordance with the TGA analysis. The most pronounced peak was displayed at 485 °C, which was related to the dehydration of $Ca(OH)_2$. The long plateau in the final part of the temperature range began at a temperature of 798 °C, which can be related to the decarbonization or loss of CO_2 and $CaCO_3$ (between 600 °C and 800 °C). The peaks measured around 120 °C (probably dehydration) and 750 °C corresponded to the degradation of magnesium silicate [45].

If compared with the composition of wastewater sludge ashes (WWSAs), the differences are pronounced, especially due to the different content of CaO. The range of the CaO content varies from 2 to 4% in WWSA samples [3] to 10% in sludge ash obtained from an incinerator [44]. These differences are a consequence of the different treatment methods, and they influence the behavior of these materials in a cement matrix.

When SEM micrographs of a similar WSA are compared with the micrographs of the MWS samples, they exhibit similar, irregular particle shapes with rough open pores (Figure 5b). In another paper, the SEM micrographs of wastewater sludge ash from an incinerator were also presented [44]. The shape of these particles was the same as in this paper, though the particle size was not. Two different granulations of WWSA were analyzed, one coarser and one finer than MWS.

4.2. Properties of Mortars Containing MWS

The partial replacement of cement with MWS in the amounts of 10% and 20% led to an increase in the mortars' workability. The mortar prepared with 30% cement replacement showed the same workability as the reference mixture. The addition of MWS regardless of the amount of cement replacement influenced a small decrease in the bulk density of the fresh mortars that was almost negligible (2%). The differences in the bulk densities increased with time, still only reaching 3.6% at the age of 28 days. This was a consequence of the partial drying of the samples due to the adopted curing conditions.

The highest differences in the compressive strength were obtained for the early ages (after two days). Up to the age of 28 days, the differences were smaller and lower than 20% for all percentages of cement replacement. Still, at this age only for mixture I (with 10% cement replacement), the drop in the compressive strength was lower than 10%. The flexural strength differences at the age of 28 days were very small, lower than 10% for all the tested mixtures.

The influence of MWS on the compressive and flexural strength of mortars can be recognized through the strength activity index (SAI). This value represents the ratio between the compressive strength of the reference mixture and the mixture containing an SCM at the age of 28 days. Figure 13 presents the effects different types of WWSA have on the SAI. The SAI value ranges between 66 and 97%. In all mortar mixtures, the addition of wastewater sludge leads to the loss of compressive strength.

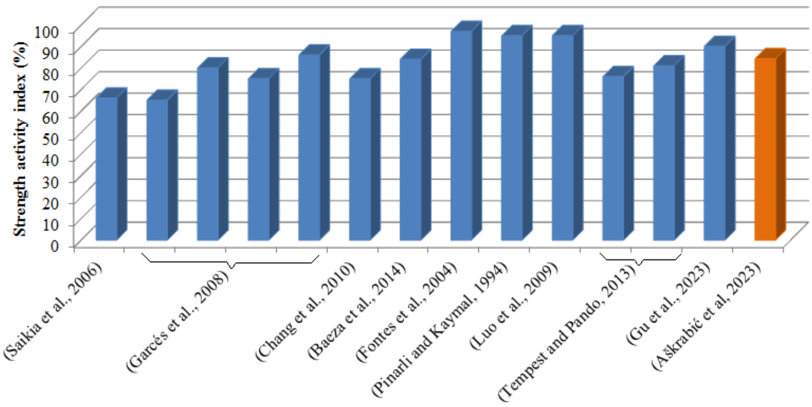

Figure 13. The strength activity index calculated for mortars prepared with wastewater sludge ashes (based on [7]), using results from [25] in orange and [46–54] in blue.

De Carvalho Gomes et al. [55] performed a detailed review of the mechanical properties of concrete and mortars prepared with wastewater sludge. The results according to their research, combined with the results obtained in this paper, are presented in Figure 14.

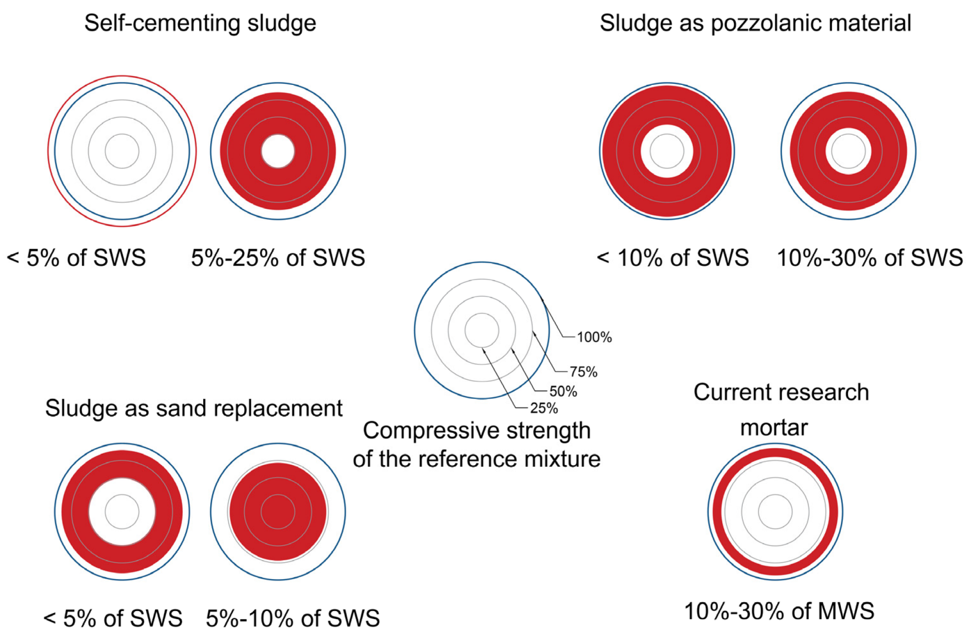

Figure 14. The ratio between compressive strength of mortar and concrete mixtures incorporating sludge and reference mixtures.

The gray circles in Figure 14 represent the values for 25%, 50% and 75% of the reference compressive strength, while the red surfaces demonstrate the differences in the compressive strength when a chosen percentage of replacement was applied. Similarly to previous findings, the addition of sludge, either as cement or a sand replacement, led to a decrease in the mechanical properties of cement composites. The only exception was the addition of sludge with self-cementing properties as a cement replacement in an amount lower than 5%. The calculated decrease in the compressive strength when MWS was used was lower than the results obtained by other researchers. The results of the modification of the SWS seem to show good potential for the improvement of sludge properties for application in cement composites.

All of the tested mortars showed good frost resistance, where the differences in strength before and after the exposure to cycles of freezing and thawing were lower than 7% for each mixture.

The obtained results show potential for the use of MWS as a cement replacement. Additional fine tuning is needed in order to define the optimum level of cement replacement. When compared to the results from the literature, it is probably recommended not to use more than 20% of this addition as a cement replacement.

4.3. Properties of Lightweight Concrete Containing MWS

The differences in the measured bulk densities of the LWC at different ages were negligible, especially if the discrepancy in the results is taken into account. Similarly to the results obtained for mortar mixtures, higher differences in the compressive strength were measured at the ages of 7 and 21 days than at the age of 28 days. At this point, the difference in the compressive strength between the reference and the mixture containing MWS was only 5%.

The LWC-I mixture showed a higher resistance to water permeability than the reference mixture and can be categorized as belonging to a V-I water permeability class (according to SRPS U.M1.206). This is probably a consequence of the water-repellent nature of the solidified sludge and the addition of the water retainer to the mix through the MWS formation.

As far as the durability test was concerned, when the compressive strength of the samples exposed to the freeze–thaw cycles was compared to the samples cured in water up to the age of testing, it was shown that both LWC-R and LWC-I had very good frost resistance. The drop in strength was even lower for the mixture containing MWS, which is a very promising result for the further application of this material.

The obtained values for the measured chemical parameters, according to the leaching test, showed very low concentrations of heavy metals in the eluate. By looking at the test results for the reference material, i.e., for the lightweight aggregate concrete that contained no recycled components, it can be seen that the results deviation in the modified materials (cubes) was extremely small. The measured concentrations of heavy metals were close to the numerical values for concrete that does not contain recycled components. The tested concrete sample was exposed to extreme conditions, and the results showed that the material is safe for use from an environmental point of view.

4.4. A Discussion on the Factors Influencing Citizens' Willingness to Use MSW in Concrete

According to the gained results, citizens who had positive attitudes toward innovative environmental solutions, whether from the general population or a project-related group of professionals, tended to be more receptive to and financially supportive of these solutions. As this was a correlational study, it could not infer causation or mediation between variables. Future research will aim to more robustly integrate theoretical frameworks, such as the Theory of Planned Behavior, to enhance our understanding of these complex relationships.

The term "citizens" was chosen based on theoretical, methodological and practical considerations. Conceptually, "citizens" aligns well with the holistic, all-encompassing methodology of contemporary social science research presented in the systemic approach [56]. This approach places a strong emphasis on viewing global issues through the eyes of the general public, making sure that the interests of the larger social community are taken into account [57]. Thus, those who have a specific stake in a certain decision or stakeholders are the subsample in this research.

Practically every resident is impacted, either directly or indirectly, by design solutions pertaining to environmental problems. To evaluate and approve project solutions, citizens must feel trusted and encouraged to participate. Through this interaction, professional and non-professional inputs are integrated and public opinion is shaped [58].

The factors identified in the pilot phase of exploration—demographics, relevant experiences and attitudes—showed distinct influence patterns across the general population, architects, and construction engineers. For citizens from the general population, positive perceptions of using MSW in concrete and direct experiences with environmental challenges, such as flooding, were the most significant drivers of acceptance for innovative project solutions. For architects and construction engineers, a positive attitude and concern about solid waste pollution were identified as common influential factors. Among construction engineers, younger males who had experience in environmental activism, recycling habits and exposure to flooding consistently showed a greater willingness to incorporate MSW into concrete.

Similarly, differences in attitudes towards MSW utilization and willingness to accept its use were observed between students from different faculties, as well as between students from different study groups within the same faculty [39]. In the student sample, the most influential factors beyond attitudes included having a close associate affected by flooding, rather than personal flooding experience. Notably, previous construction experience was a significant determinant, often leading to reluctance to embrace innovative project solutions.

In conclusion, regarding differences between the groups, the acceptance of MSW in concrete was predominantly shaped by positive attitudes across all the groups. Personal experiences and environmental concerns played varying roles, reflecting the influence of professional expertise and individual characteristics on the willingness to adopt sustainable practices. This highlights the nuanced interplay of demographic, experiential and attitudinal factors within these different citizen or stakeholder groups.

An important finding from the pilot phase merits further consideration. The responses from participants showed significantly greater consistency regarding the concrete containing WWS, which was included during the statistical and conceptual variable reduction and refinement of the assessment model [39]. Compared to solutions that included MSW in concrete, both the reliability coefficient for the scale and inter-item correlations and the correlations of individual items with the entire scale were significantly higher. This implies that the introduction of WWS contributed to response homogenization and emerged as a notably more steadfast determinant compared to other variables (socio-demographic factors, relevant experience, recycling practices). To put it differently, the research confirmed that the respondents' understanding of the technical characteristics of an innovative solution significantly influences their attitude and willingness toward that solution. This underscores the importance of educational efforts in raising citizens' awareness and acceptance of new developments in environmental protection and improvement.

Therefore, the subsequent pivotal step entails the development of a targeted educational program. In the context of this research, the educational initiative should foster the knowledge, skills and attitudes of community members in regard to utilizing recycled materials.

4.5. Recommendations

For future research concerning the utilization of sludge as a partial replacement of cement in concrete, there are still potential benefits and challenges that need further investigation. Modified solidified wastewater sludge can partially replace cement, which at the same time reduces GHG emissions. Moreover, sludge incorporated in concrete enhances waste management and provides opportunities for a sustainable solution for the disposal of this by-product. The possibility of the treated sludge's incorporation in Autoclaved Aerated Concrete should also be considered. This research partially provided insight into the influence of the MWS on the workability, strength development and durability of cement composites.

The research also still needs a deeper insight into the environmental impacts and additional durability tests, such as tests of the resistance to chloride ion penetration, sulfate attacks and alkali–silica reactions [59].

These recommendations underscore the importance of customizing educational strategies to address the unique characteristics and concerns of diverse end user groups, emphasizing the pivotal role of awareness, knowledge and proactive engagement in fostering the acceptance of innovative project solutions.

5. Conclusions

Waste and recycled materials have lately been used in the construction industry to comply with the principles of the circular economy and sustainable development.

This paper presents research on the possible application of modified solidified wastewater sludge in cement composites, specifically in lightweight concrete. This may reduce cement use and address waste disposal, offering dual environmental benefits.

Although results concerning the use of wastewater sludge as a lightweight aggregate or as a partial sand replacement, appear in the literature, research on the application of wastewater sludge as a cement replacement in lightweight concretes is still not promoted enough.

The modification of solidified wastewater sludge was accomplished by the addition of new components. The additional components were aluminum oxide, magnesium silicate and an admixture (water retainer). The additional components added to the SWS slightly increased the size of the grains in the material and lowered its specific surface area. The chemical analysis confirmed that the MWS had increased and improved the content of aluminum oxide and silicon oxide when compared to the original sample. The results obtained for the mortar samples regarding the properties in a fresh and hardened state are promising, as the addition of MWS led to an increase in the workability of mortar mixtures (when used up to the amount of 20%), a decrease in the bulk density, and a decrease in the compressive strength that was lower than 20%. Still, as other studies have indicated, 20% cement replacement is the recommended upper limit for the application of this type of material. The results also confirmed that these mortars are frost-resistant. The lightweight concrete prepared with MWS as a partial replacement for cement in the amount of 20% was tested in a hardened state. No influence on the bulk density was noticed at different ages of testing. The compressive strength for the mixture containing MWS was 5% lower than for the reference one at the age of 28 days. The water permeability was reduced with the addition of MWS, and both the reference and the concrete containing MWS exhibited good frost resistance. Also, a test that was performed showed that the proportion of recycled material in the concrete is safe for use from the perspective of leaching.

All of the obtained results show good potential for the application of this type of material in cement composites. The resistance to carbonation and chloride action still needs to be further investigated.

Developing a comprehensive educational program targeting citizens' attitude change appears feasible. The research results suggest that such a program should be tailored based on a prior assessment of the factors influencing project solution acceptance, taking into account the specific characteristics of the citizen groups targeted by the project.

Author Contributions: Conceptualization, M.Š. and V.R.-O.; methodology, M.Š. and A.S.; validation, A.R., A.S. and V.R.-O.; formal analysis, A.R. and A.S.; investigation, M.Š., Z.N., Ž.R. and S.S.; resources, V.R.-O.; writing—original draft preparation, M.Š., Ž.R. and S.S.; writing—review and editing, A.R., A.S., Z.N. and V.R.-O.; visualization, M.Š.; supervision, V.R.-O.; project administration, A.R.; funding acquisition, V.R.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Science Fund of the Republic of Serbia, 7737365, Zero-Waste Concept For Flood Resilient Cities-Ø-Waste-Water, and by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (grant number 200092).

Institutional Review Board Statement: The Ethics Committee of the Faculty of Philosophy at the University of Belgrade, Serbia, approved the research on the psychological and social determinants influencing the acceptance of project proposals (05/2-7 NO 1067/1, dated 2 October 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting the presented results, based on respondents' reports, are subject to approval by the Ethics Committee of the Faculty of Philosophy, University of Belgrade, Serbia (Approval No. 05/2-7 NO 1067/1, dated 2 October 2020). Inquiries can be directed to the co-author Snezana Svetozarevic at snezana.svetozarevic@f.bg.ac.rs.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

C&D	construction and demolition
DWS	drinking water sludge
FA	fly ash
LWA	lightweight aggregate
LWC	lightweight concrete
MWS	modified solidified wastewater sludge
SAI	strength activity index
SCM	supplementary cementitious material
SEM	scanning electron microscopy
SW	solidified wastewater sludge
TGA	thermogravimetric analysis
WWS	wastewater sludge
WWSA	wastewater sludge ash

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