EFFECT OF CONCRETE SLUDGE FROM RESIDUAL CONCRETE ON HARDENED CEMENT PASTE PROPERTIES

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Abstract: Waste is produced in great quantities in the concrete producing sector. Such garbage may be used to create goods that are more environmentally friendly and have a smaller carbon footprint. This study looked at concrete sludge, a byproduct that is difficult to use and is made by washing a concrete truck with leftover concrete. Concrete sludge is created when the leftover insoluble fine particles react with water after the aggregates from the concrete mixture are removed during washing. In the testing, both dried and wet concrete sludge were employed. With cement, superplasticizer, dry and wet concrete sludge, and tap water, samples of various compositions were created. By substituting dry concrete sludge for a portion of the cement, seven cement pastes with various compositions (0%, 5%, 10%, 15%, 20%, 25%, and 30%) were created. Cement was substituted in compositions including wet concrete sludge in the same proportions as dried concrete sludge. For new cement pastes, the slump, setting time, and variations to these parameters with varying quantities of concrete sludge were determined. It was discovered that as the kind of concrete sludge changes, so do the technological characteristics of the mixes and the setting time. SEM and XRD studies validated the density and compressive and flexural strength values. The findings of the study demonstrate that cement stone's mechanical qualities are worsened by dry concrete sludge while they are enhanced by wet concrete sludge. The qualities of hardened cement stone were found to be unaffected by substituting dry concrete sludge for 5% of the cement, though. Because bigger amounts have a significant impact on the mixture's technical qualities, 10% of replacement cement is advised in mixes containing wet concrete sludge.

Keywords: concrete sludge; residual concrete; cement paste

1. Introduction

Current hot topics include ecology, the environment, and sustainability [1]. Sustainability is defined as addressing existing needs without compromising the capacity of future generations to address their own needs [2] by the United Nations Commission on Global Application and Development. Sustainable development is a universal requirement. The production of concrete is one such sector. Due to its relative great durability, low cost, and accessibility of its raw ingredients, concrete is one of the primary building materials, and its use in the future is unavoidable [3]. The concrete industry is also growing internationally. Annual manufacturing quantities of concrete rise. A recent research estimates that approximately 30,000 concrete manufacturers generated 915 million cubic metres of ready-mixed concrete in 2018. According to the same survey, conducted by the European Ready-Mixed Concrete Organisation, 260 million tonnes of cement were consumed by makers of ready-mixed concrete in the organization's member nations [4]. Because of the massive amount of cement used and the fact that the cement business is one of the most polluting and carbon-intensive sectors, our environment has been badly harmed [5]. About 1 tonne of carbon dioxide is released for every tonne of Portland cement produced [6–14]. Additionally, 5% of the 30 gigatons of carbon dioxide that are emitted globally, according to scientists' calculations, are produced by the cement sector [15].

The quest for natural materials substitutes for concrete manufacturing is now underway. Natural resources may be replaced by byproducts produced from other industrial sectors throughout the production process. Utilising such materials benefits both the environment and the economy [16–18]. The principal cement substitutes that are now being studied by researchers include fly ash, ground-granulated blast furnace slag, silicon dust, and rice husks, all of which are by-products of different industrial sectors [19–23]. The mechanical strength and durability of cement stone can be increased by employing these components and their mixtures [24,25]. The concrete manufacturing business also produces waste, but it is feasible to utilise these waste byproducts to create a variety of greener, lower-carbon goods [26]. Despite the harm caused by Portland cement consumption, higher production levels also result in more trash being produced. One such waste is concrete sludge. Each 9 m3 concrete mixer truck returns 200 to 400 kg or more of freshly mixed concrete to the facility at the conclusion of each workday [27,28]. Additionally, it has been calculated that 1% to 4% of the concrete mix is wasted as concrete sludge [29]. The washout water produced after flushing the chutes of ready-mixed concrete trucks at the construction site is the main source of concrete sludge. Another source, which is more frequent in big cities, is concrete mix that was overbooked and had to be returned to the mixing facility [31]. Concrete manufacturers need to take further steps to address this issue because these practises cause enormous amounts of trash to accumulate and become very expensive to dispose of [32]. One of the possibilities is to use residual concrete recycling devices that can extract cement from concrete aggregates. The creation of ready-mixed concrete can then be done using washed aggregates [33]. Press filters can be used to filter silt out of washout water so that dry concrete sludge can be produced. Without filtering the washout water, wet concrete sludge is produced.

While little study has been done on particles smaller than 5 mm, recycled aggregates and their usage in the creation of ready-mixed concrete have received the majority of attention [34]. The utilisation of washed sand from residual concrete recycling systems was investigated by several researchers [35]. They discovered that washed sand included tiny cement particles, which had an impact on the sand's bulk density and particle size distribution. Such sand is usable in concrete mixtures, although more superplasticizer additions are necessary. By utilising concrete that had been returned to the batch facility as an aggregate, other researchers had successful outcomes [36]. To maintain the layers of the road foundation, researchers have also experimented using concrete sludge rather than cement [39]. They transformed a combination of unhardened concrete into granulated material by adding non-toxic chemical additives, which was then utilised as concrete aggregate. Other researchers have attempted to produce precast concrete blocks using concrete sludge. They created a composite cementitious material using dry concrete sludge, washed sand, and residual concrete manufacturing equipment. They then hardened the resulting material in a CO2 atmosphere. Tests revealed that the wall blocks manufactured from this mixture were sustainable and carbon-neutral. There have been attempts to produce cement using concrete sludge from batching facilities as a raw source [37]. The studies showed that concrete sludge cannot be used as a raw material to make cement.

Additionally, concrete sludge was tested as a mortar microfiller by researchers [38]. They discovered that dried concrete sludge affected the mortars' ability to be worked and necessitated significantly greater levels of superplasticizers. Another downside was a wide range of compressive strength across the specimens, ranging from 30% to +17% less than the control specimen. Concrete sludge has been used successfully to strengthen foundations, according to reports [40]. In comparison to the same amount of ordinary Portland cement, the results demonstrated that it was able to obtain 38% of the stabilising effect in terms of compressive strength. Concrete sludge obtained from nearby batching factories was thoroughly investigated by researchers [41]. In concrete sludge, they discovered that cement particles and a little quantity of sand fines predominated. The concrete sludge under examination contains 11.6% limestone filler, 49.7% cement particles, and 38.7% sand fines. In this study, the impacts of wet and dry concrete sludge on the characteristics of hardened cement paste are analysed. The sludge's chemical and mineral constituents were examined. The material's thermal stability and the percentage of volatile components were assessed using thermogravimetric analysis. The cement paste's slump flow and setting time were determined, and the cured cement paste's density, compressive, and flexural strengths were as well.

2. Materials and Methods

2.1. Raw Materials

The experiments were conducted using cement CEM I 42.5 R that complies with LST EN 197-1 [42] and concrete sludge that was collected from residual concrete processing systems following the separation of coarse particles. Concrete sludge that was examined was both wet and dry. Wet concrete sludge was dried to a consistent mass for dry concrete sludge testing at a temperature of 120 5 °C. Table 1 shows the chemical make-up of dry concrete sludge, while Table 2 shows the sludge's physical characteristics.

Table 1. Chemical composition of dry concrete sludge.

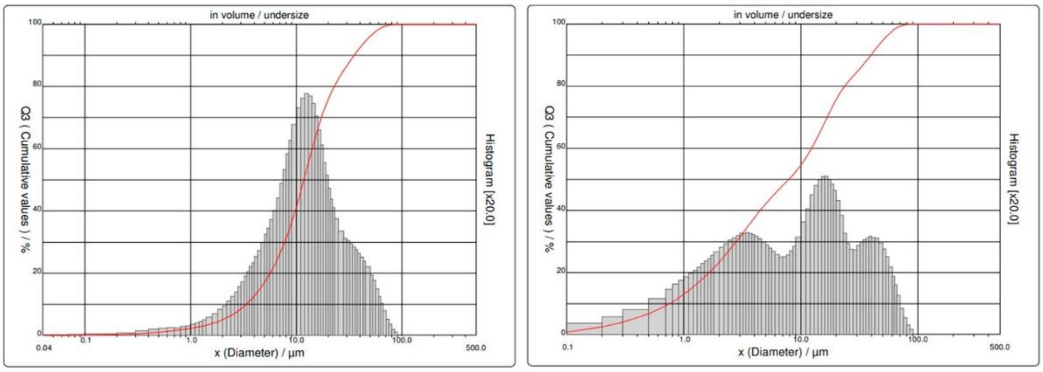
Chemical Composition of Concrete Sludge, %

CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	K_2O	P_2O_5	TiO_2	SrO	MnO	Cl
40.9	14.9	3.14	2.40	2.37	2.26	0.89	0.38	0.21	0.06	0.04	0.03

Table 2. Properties of dry concrete sludge.

Properties	**Dry Concrete Sludge**
Specific surface area, cm^2/g	316
Particle density, kg/m^3	2774
Bulk density, kg/m^3	826

Wet concrete sludge's density and dry solids content were calculated. This was done in compliance with LST EN 1008-2005 [43]. The concrete sludge used for the testing had a density of 1220 kg/m3. The sludge's dry solids concentration was 500 kg/m3. According to LST ISO 4316:1997 [44], the pH of the wet sludge was 11.4, and the pH of the cement paste was 14. When the w/c ratio in the cement paste was 0.35, the pH of the cement paste was 14. Particles with an average size of 15.85 m predominated in the tested sludge, according to an examination of the particle size distribution of dry concrete sludge. The particles had a diameter of 3.35 m at 10%, 10.18 m at 50%, and 12.88 m at 90%. Particles from CEM I 42.5 R varied in size from 0.1 to 70 m. At 10%, 7.88 m, and 90%, the particle diameter was 0.75 m, 39.66 m, and 39.66 m, respectively. 14.21 m was the average particle diameter. The particle distributions of the dried concrete sludge and utilised cement are shown in Figure 1. According to our findings, Portland cement has more fine particles than dry concrete sludge, and the particles are dispersed more uniformly when compared to those of used Portland cement.



(**a**) (**b**)

Figure 1. Particle distributions of (**a**) dried concrete sludge and (**b**) cement.

2.2. Paste Design and Sample Preparation

The mix design in Table 3 was used to make the cement pastes. They created two separate mixtures. The first mixture was created to investigate how freshly made and solidified cement pastes would react to dried concrete muck. Dried concrete sludge was used in place of cement in the initial mix at percentages of 0%, 5%, 10%, 15%, 20%, 25%, and 30%. Wet concrete sludge replaced some of the cement in the second mixture. Due to the fact that wet concrete sludge has a two-fold lower dry solids content than dried concrete sludge, the amount of wet concrete sludge injected was two times greater than that of dried concrete sludge. Dried concrete sludge was used in lieu of cement in the same proportions as in the first mix (5%, 10%, 15%, 20%, 25%.

Table 3. Mixing proportion of hardened cement paste.

With Dried Concrete Sludge							
Batches	0	I	II	III	IV	V	VI
Cement, %	100	95	90	85	80	75	70
Water, %				100			
Chemical admixture, %				0.40			
Dry concrete sludge, %	0	5	10	15	20	25	30
w/c				0.35			
With Wet Concrete Sludge							
Cement, %	100	95	90	85	80	75	70
Water, %	100	95	90	85	80	75	70
Chemical admixture, %				0.40			
Wet concrete sludge, %	0	10	20	30 430	40	50	60
w/c				0.35			

Following mixing, the new pastes were crushed for 20 seconds on a vibrating table before being cast in 160 40 40 mm steel moulds. After compacting, all specimens were kept at a temperature of 20 2 C for 12 hours before being demoulded and submerged in water for the same amount of time. For 28 days, all specimens were submerged in water to cure.

2.3. Test Methods

Using the Cilas 1090 LD particle size analyser and air as a carrier, the dry technique was employed to measure the specific surface area and particle size distribution of dry concrete sludge particles. Up to a 12% dispersion of the substance in the medium was attained, the particles were spread out using ultrasound. The measuring period was 60 seconds. The operating system was a typical one (Fraunhöfer). An X-ray diffractometer (BRUKER AXS D8 ADVANCE, Bruker Corporation, Rheinstetten, Germany) was used for the XRD investigation. CuK radiation, a Ni filter, a detector step of 0.02, an intensity measurement span of 0.5 s, anode voltage Ua = 40 kV, and current I = 40 mA were the XRD parameters employed. The XRD measurements have a precision of 2 = 0.01. Using a spectrometer (Bruker X-ray S8 Tiger WD), X-ray fluorescence spectroscopy was carried out. With an anode voltage of up to 60 kV and a current (I) of up to 130 mA, a Rh target X-ray tube was employed. In a helium atmosphere, the specimens were measured. For the measurements, the SPECTRA Plus QUANT EXPRESS technique was employed. SEM equipment (SEM JEOL JSM-7600F, JEOL (Germany) GmbH, Freising, Germany) was used to examine the microstructures of the materials. Table 3 provides the compositions of hardened cement pastes. The quantity of cement and tap water was decreased in the test mixes with wet sludge by substituting wet concrete sludge, but the amount of cement was decreased in the test combinations with dry concrete sludge by substituting concrete sludge. LST EN 12350-5:2019 for slump flow [45], LST EN 12390-7:2019 for hardened cement paste density [46], LST EN 12390-3:2019 for compressive strength [47], and

LST EN 12390-5:2019 for flexural strength [48] were used to determine the key characteristics of concrete.

3. Results and Discussion

3.1. Parameters of Concrete Sludge

The XRD spectra of dry concrete sludge revealed the presence of the following substances: 36% calcite, 16% portlandite, 14% dolomite, 11% quartz, 7.6% kuzelite, and 3.8% ettringite.

The XRD picture of dry concrete sludge is shown in Figure 2.

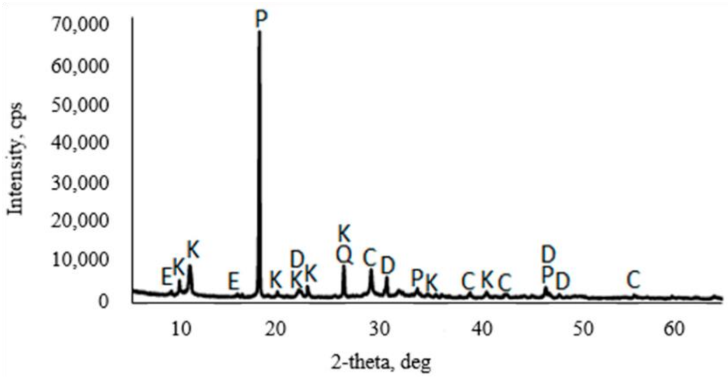
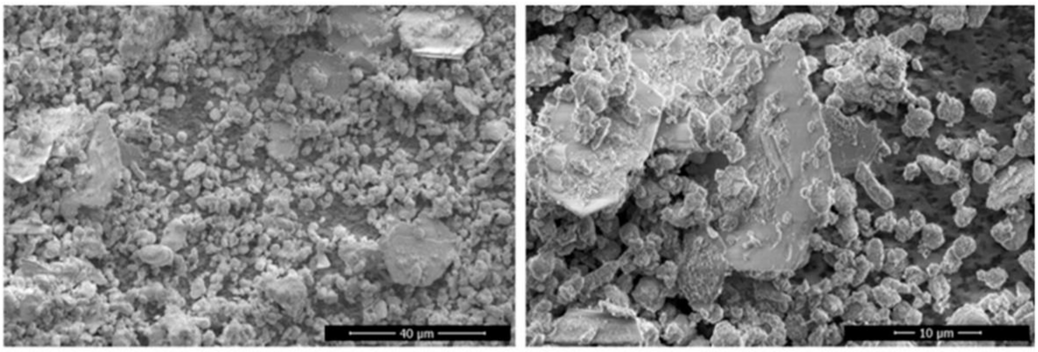


Figure 2. XRD image of dry concrete sludge: C—calcite; P—portlandite; D—dolomite; Q—quartz; E—ettringite; K—kuzelite.

The Helios NanoLab 650 SEM was used to examine the microstructure of concrete sludge. Table 2 displays the results for the dry concrete sludge's physical properties. The dried concrete sludge is formed of spherical crystals that are in calcite and hexagonal plates, according to the microstructure photographs. Portlandite crystals, which measure 60 to 100 m in size, are hexagonal in shape. According to certain studies [49–51], portlandite crystals can grow to a size of up to 100 microns in cement pastes with a high water–cement ratio. Portlandite crystals form in nanometric dimensions and are disseminated in the C-S-H gel when the water-to-cement ratio is less than 0.25. SEM research shows that a lot of water in wet concrete sludge results in A thermogravimetric study of dry concrete sludge was performed. The analysis's findings showed that at temperatures between 100°C and 200°C, there was a significant endothermic impact and a mass loss of roughly 13%. Ettringite and monocarboaluminate breakdown, as well as the loss of hydrated water in cement minerals, can be blamed for these outcomes. Ettringite breakdown has an endothermic action between 100 and 140 °C and results in a weight loss of roughly 9%. These findings support the XRD data (Figure 3) that show ettringite and kuzelite to be present. However, the dry concrete sludge sample was dried at a temperature of 120°C, which would account for why no ettringite was visible in the SEM picture (Figure 4).

Monocarboaluminate decomposition is responsible for a second minor endothermic impact that causes a weight loss of roughly 3% between 158 and 175 C [52]. It is noted that portlandite decomposes between 450 and 550 degrees Celsius. The breakdown of calcite takes place at the temperature range between 690 C and 790 C, which is where the third endothermic action takes place. The sample has had a 29.5% overall mass reduction.



(A) ×1000 (B) ×2500

Figure 3. Microstructure of dry concrete sludge: (**A**) ×1000 magnification and (**B**) ×2500 magnification.

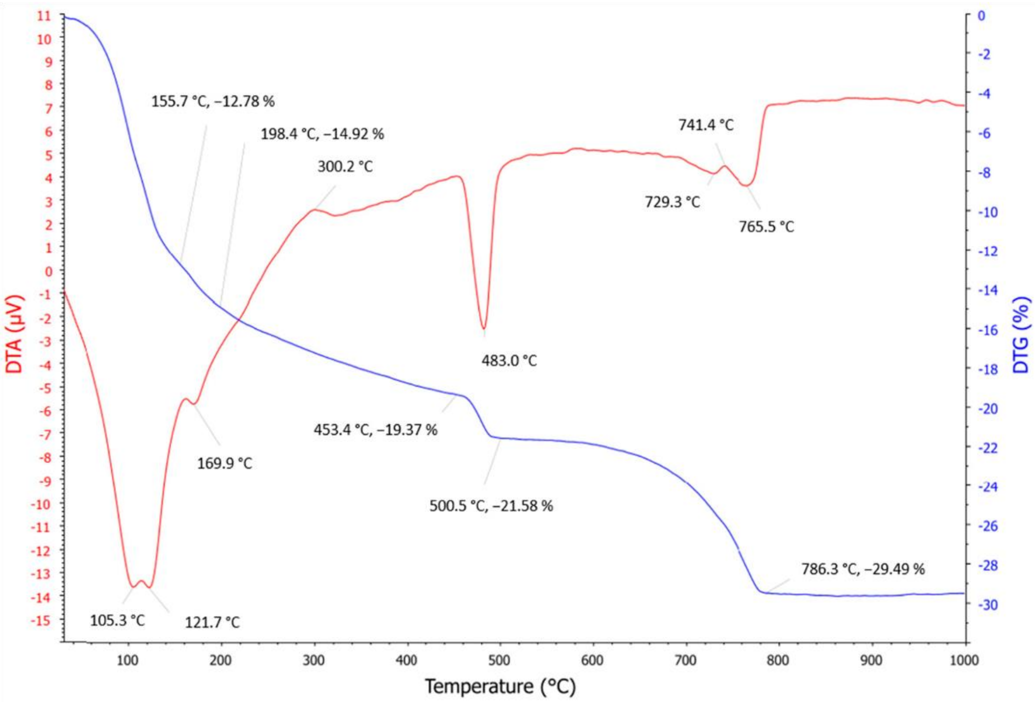


Figure 4. TGA graph of dry concrete sludge.

3.2. Properties of Fresh Cement Paste

Figure 5 shows the results of the cement paste slump flow experiments, which demonstrate that the slump rises when dry concrete sludge is used in place of cement. The slump flow increases when more cement is substituted with dry concrete sludge. In comparison to the control specimen, the slump flow of the specimens with dry concrete sludge replacing 30% of the cement rose by 56.7%. The specimens containing wet concrete sludge showed the opposite pattern. Wet concrete sludge replaced more cement, causing the paste's viscosity to rise and the slump flow to decrease because the density of wet sludge is higher than that of water. When wet concrete replaces a certain amount of cement.

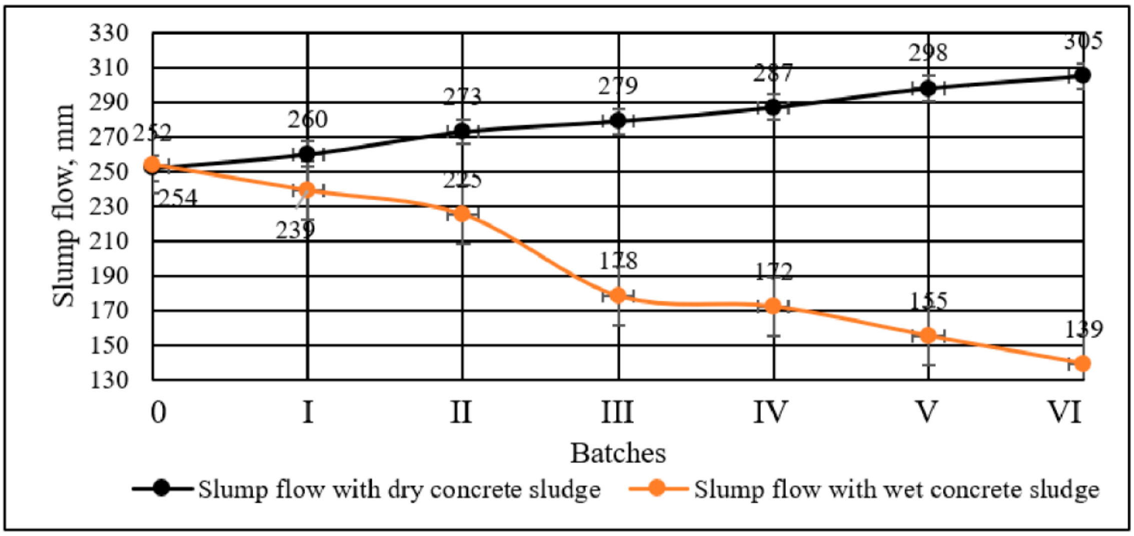


Figure 5. Slump flow of cement paste with different amounts of cement replaced with wet and dry concrete sludge.

With a larger sludge load in the specimens, the first setting time of the specimens with both dry and wet concrete sludge reduced. It was found that regardless of the kind of concrete sludge added to the combinations, the change in the first setting time was very consistent. This can be explained by the fact that the sludge contains a sizable quantity of calcite, which is known to shorten the setting time [53]. Calcium hydroxide and ettringite, which were discovered in concrete sludge, can also be used to explain a reduction in setting time. Figure 6 shows the outcomes of the initial setup period.

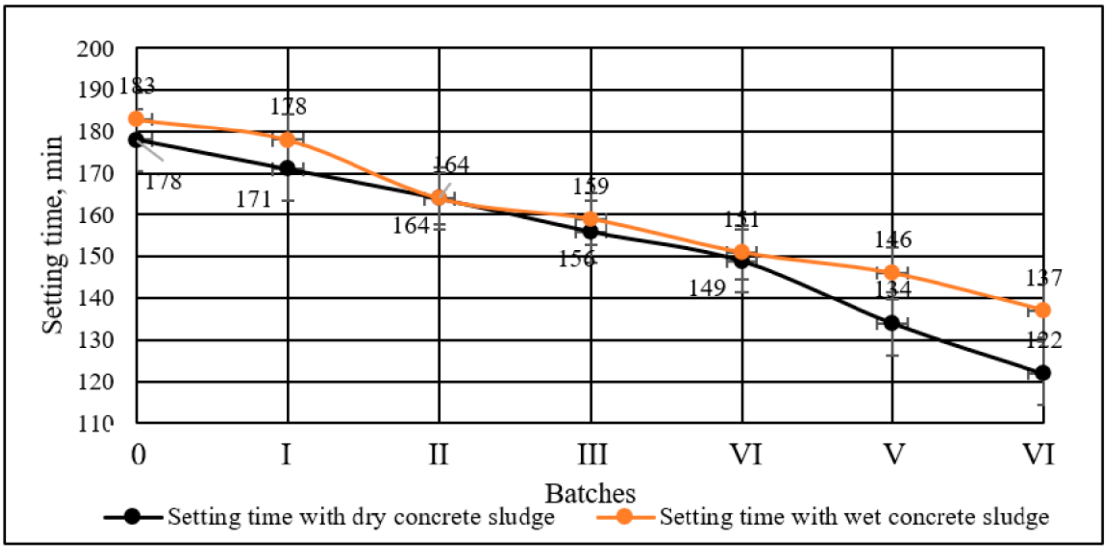


Figure 6. Initial setting time of cement paste with different amounts of cement replaced with wet and dry concrete sludge.

3.3. Hardened Cement Pastes' Properties

XRD analysis was used to compare the chemical compositions of samples with and without concrete sludge as well as samples with dried and wet concrete sludge. Test samples included those with no addition, 10% dry concrete sludge, and 10% wet concrete sludge. The testing revealed that portlandite, calcite, dolomite, ettringite, and CSH are present in every sample. Only the concentrations of these substances in the samples vary. The outcomes are displayed in Figure 7.

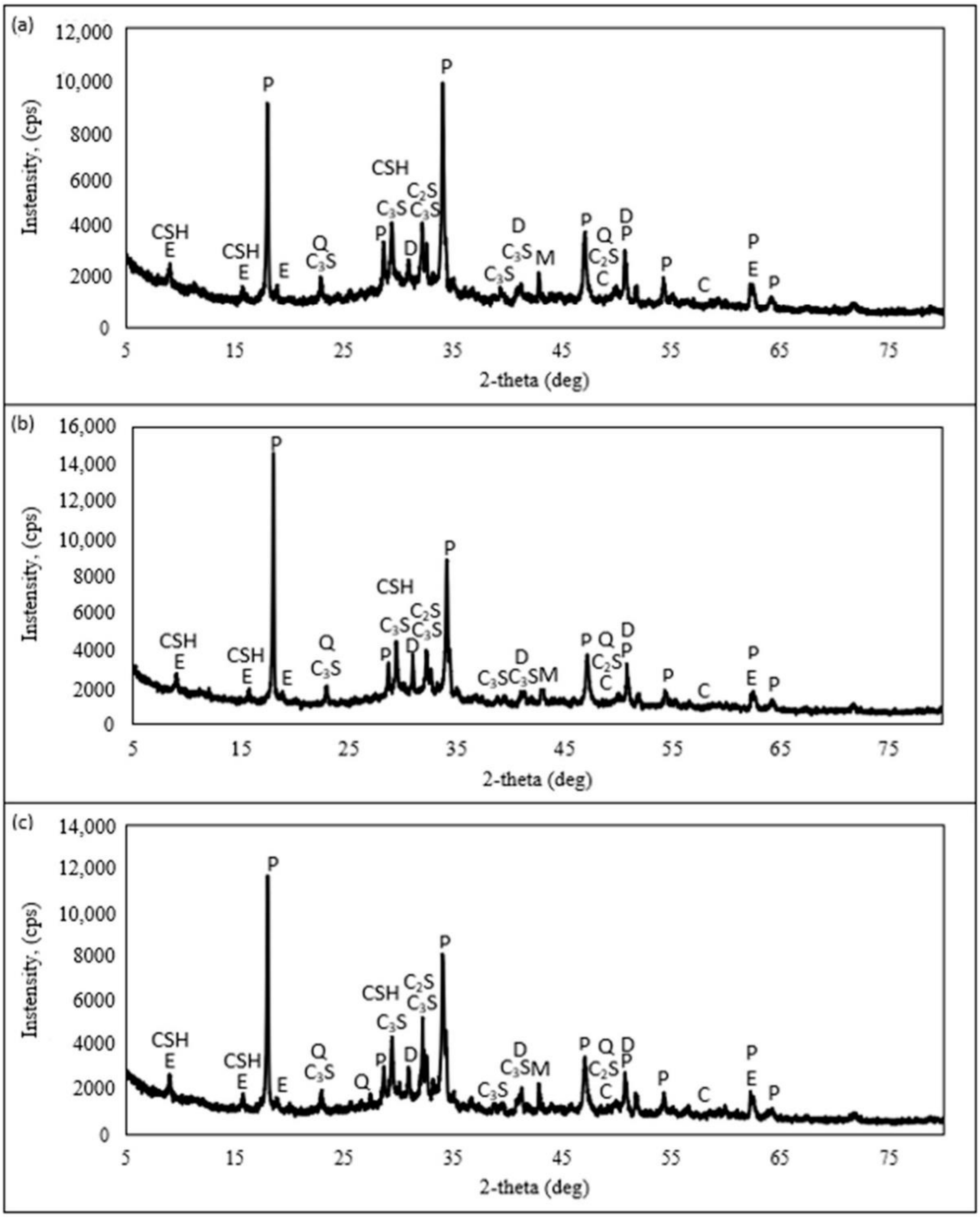


Figure 7. XRD image of hardened cement paste: (**a**) without sludge, (**b**) with 10% cement replaced with dry concrete sludge, (**c**) with 10% cement replaced with wet concrete sludge; C—calcite; P—portlandite; D—dolomite; E—ettringite; C_3S—tricalcium silicate; C_2S—dicalcium silicate; CHS—calcium silicate hydrate; Q—quartz.

Despite having varying cement amounts, all of the samples had roughly the same percentage of portlandite, which ranges from 41–45% but tends to be higher in compositions containing sludge. This might imply that portlandite from sludge can also add to the quantity of portlandite in a sample. But given that 16% of portlandite was found in the dry sludge, as shown by X-ray analysis calculations (Figure 3), the sludge (dry or wet) enhanced cement mineral hydration.

Similar levels of calcite were discovered in all samples: 23.0% in the control sample, 18.1% in the wet concrete sludge sample, and 20.3% in the dry concrete sludge sample. These findings demonstrate that more calcium ions are involved in the crystallisation of the hydration products in the sample containing wet concrete sludge. Non-reacted C3S and C2S were found in varying amounts: 15.4% in the first sample without concrete sludge, 9.5% in the second sample with dried concrete sludge, and 5.6% in the third sample with wet concrete sludge. Because there was less cement in the samples with sludge, the drop in C2S and C3S is noticeable. Unreacted C2S and C3S are, however, approximately 1.7 times lower in the sample with wet concrete sludge than in the sample with dry concrete sludge. This outcome demonstrates how much more aggressively cement minerals hydrate when moist sludge is present. Ettringite concentrations vary as well. Ettringite quantities for CSH-type minerals present at the same time in the samples containing concrete sludge vary: 3.2% in the control sample, 5.9% in the sample containing wet concrete sludge, and 2.7% in the sample containing dry concrete sludge. This might imply that wet concrete sludge encourages the crystallisation of minerals of the CSH type. It appears that the presence of moisture in the wet sludge encourages more active cement mineral hydration, which may be explained by the presence of a distinct layer of water on top of the sludge particles. The control sample doesn't yield any quartz. The samples that included sludge had some quartz. All three samples include dolomite, although the quantity is nearly three times more in the sludge-containing samples than it is in the control sample.

Images of the samples' microstructure at various magnifications are shown in Figure 8. It is clear that concrete sludge, whether wet or dry, thickens the sample's microstructure, possibly as a result of the higher concentrations of hydration products. The opposite trend was seen in density tests performed on specimens containing both dry and wet cement sludge (Figure 9). The density of the specimens in which dry concrete sludge was used in lieu of cement steadily declined, but the density of the specimens in which wet concrete sludge was used in place of cement rose. The density of hardened cement paste may decrease because the bulk density of dry concrete sludge is smaller than the density of cement. In contrast to the control specimen, the density of the specimens with dry concrete sludge replaced at 30% fell by 90 kg/m3, whereas the density of the specimens with wet concrete sludge replaced at 30% rose by 88 kg/m3. This could have occurred because of the wet concrete sludge's higher density (1220 kg/m3) compared to the utilised water, which causes specimen microstructures to become denser when the slump flow is lower.

Additionally, it is apparent that specimens with wet sludge contain less ettringite than those with dry concrete sludge. Similar to the density data, the strength values in the moulded specimens containing wet and dry concrete sludge showed various tendencies. These patterns may be seen in Figure 10. The larger percentage of dry concrete sludge replacing cement in the specimens at 28 days coincided with a drop in compressive strength.

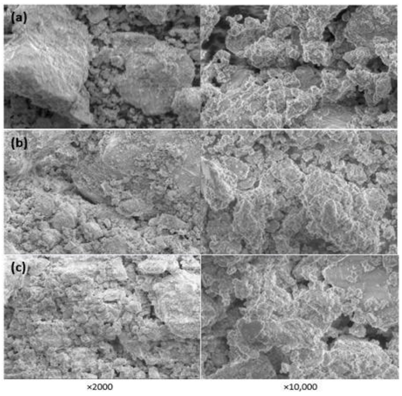


Figure 8. SEM images of cement stone: (**a**) with no concrete sludge, (**b**) with 10% cement replaced with dry concrete sludge, (**c**) with 10% cement replaced with wet concrete sludge.

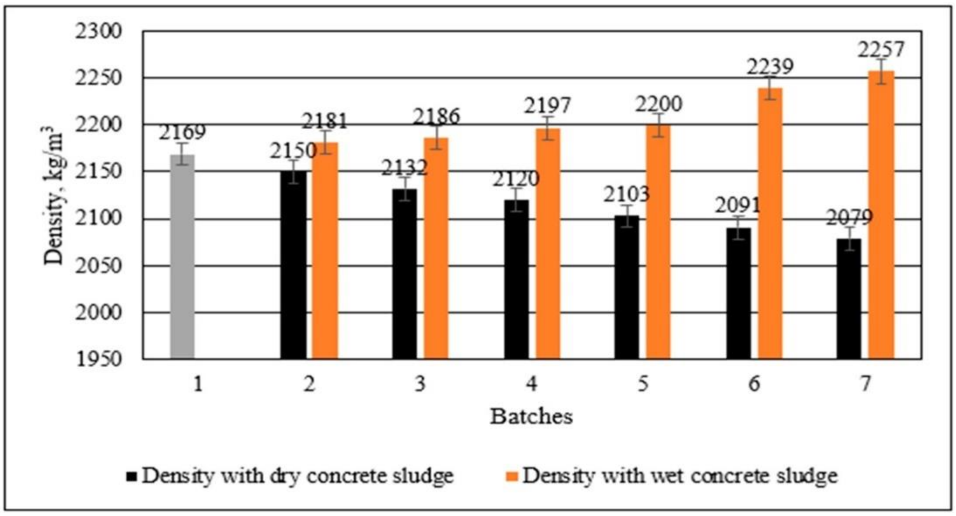


Figure 9. Density of concrete with different amounts of cement replaced with wet and dry concrete sludge.

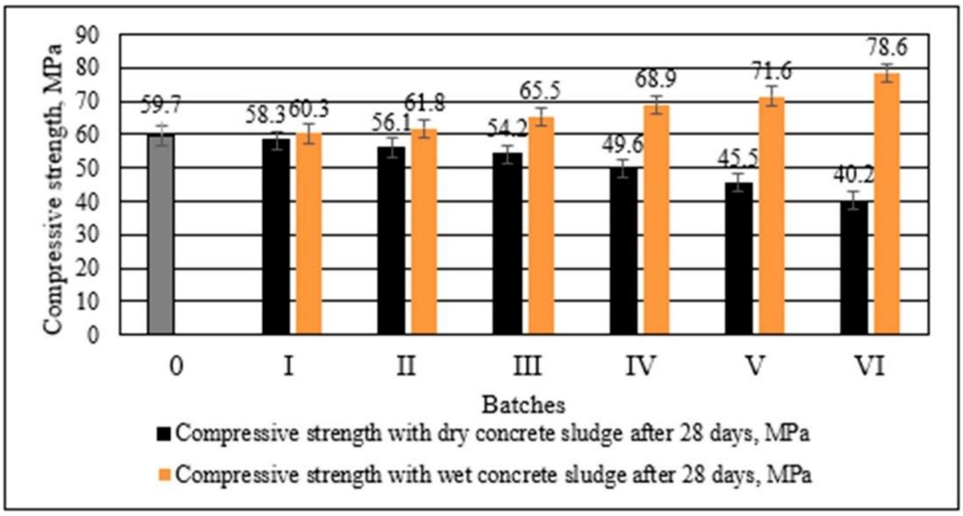


Figure 10. Compressive strength of concrete with different amounts of cement replaced with wet and dry concrete sludge after 28 days.

When dried concrete sludge was used to replace 10% of the cement, the compressive strength decreased somewhat. The compressive strength was lower by 3.6 MPa compared to the control specimen. The compressive strength of the specimens decreased by 19.5 MPa when dry concrete sludge replaced 30% of the cement. On the other hand, the compressive strength rose in the specimens where wet concrete sludge took the place of various quantities of cement. In comparison to the control specimen, the compressive strength rose by 19.7 MPa when 60% of wet concrete sludge (or 30% of dry matter) was applied.

The test results shown in Figure 11 show the similar pattern for the flexural strength. Flexural strength decreased by 34.3% when 30% of the cement was replaced with dry concrete sludge compared to the control specimen, but only by 4.4% when just 10% of the cement was substituted. When 60% of wet concrete sludge (or 30% of dry matter) was employed, the flexural strength rose by 31.8%.

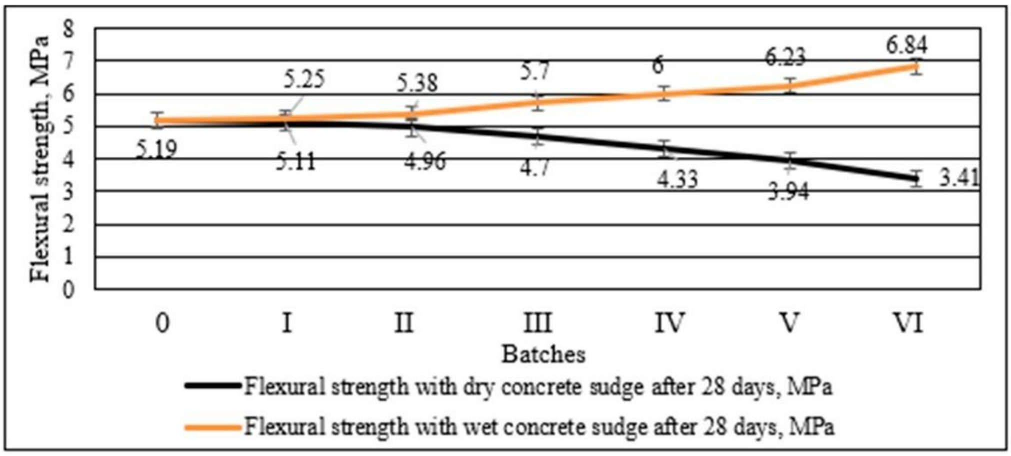


Figure 11. Flexural strength of concrete with different amounts of cement replacement with wet and dry concrete sludge after 28 days.

Due to the dilution effect [54] and more porous structure, when the density of the sample falls, both the compressive strength and the flexural strength of the specimens containing dry concrete sludge dramatically reduced. When cement is swapped out for dry concrete sludge, portlandite crystals, some of which might be rather big, develop a more porous framework around themselves. Additionally, this specimen also produces trace quantities of CSH-like chemicals. Due to the wet conditions of the sludge, the layer of water covering sludge particles speeds up the hydration of cement minerals and specimens, achieving greater strength. The strength of the specimens with wet concrete sludge increased significantly, most likely as a result of the denser structure and increased density of the specimens. Additionally, XRD research (Figure 7).

4. Conclusions

This study looked into the idea of using dry and wet concrete sludge to replace some of the cement. Analysis has been done on cement stone's slump flow, setting time, produced structure, and physical-mechanical characteristics. After performing the research, the following results were drawn. The amount of dry concrete sludge used to substitute cement resulted in an increase in the cement paste's flowability. The flow rate rose by 56.7% when dry concrete sludge was used to replace 30% of the cement. On the other hand, the cement paste's flowability deteriorated when it was mixed with wet concrete sludge. Concrete lost 45.3% of its flowability when wet concrete sludge made up 30% of the cement.

The setting time in the pastes including both dry and wet concrete sludge was reduced, according to the findings of the experiment. The setting time decreases with increasing concrete sludge addition. The setting times of the specimens changed with dry concrete sludge and wet concrete sludge were both reduced as compared to the control specimens, each by 56 and 46 minutes, respectively.

Portlandite from sludge enhanced the amount of portlandite in the specimens and took part in the hydration processes, according to an XRD study. Unreacted C2S and C3S levels were 1.7 times lower in the sample where wet concrete sludge was used in place of cement than they were in the sample where dry concrete sludge was used, while CSH-type compounds were twice as abundant. This finding demonstrates that wet concrete sludge increases cement hydration and the crystallisation of minerals of the CSH type. When 30% of the cement was replaced with dry concrete sludge instead of the control specimen, the density declined by 4.1%; however, when 30% of the cement was replaced with wet concrete sludge instead of the control specimen, the density of the specimen increased by 4% as a result of the greater sludge density. Increased cement replacement with dry concrete sludge reduced the specimen's compressive strength by up to 32.7% in comparison to the control specimen, whereas increased cement replacement with wet concrete sludge increased the specimen's compressive strength by up to 1.32 times. Due to their denser structure and accelerated cement hydration, the specimens with wet concrete sludge had greater strength. The flexural strength values show a similar tendency to what was shown for the compressive strength. It was discovered that just a small percentage of cement, up to 5%, could be substituted with dry concrete sludge, but 10% was shown to be the ideal percentage.

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