

Article

Mechanical Performance of Concrete Exposed to Sewage—The Influence of Time and pH

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Abstract: Contact of concrete with aggressive factors, technological structures, reduces their durability through microstructural changes. This work presents the results of research on determining the influence of post grit chamber sewage and sewage from the active sludge chamber in three different environments, i.e., acidic, neutral, and alkaline, on the structure and compressive strength of concrete. Compressive strength tests were carried out after 11.5 months of concrete cubes being submerged in the solutions and compared. To complete the studies, the photos of the microstructure were done. This made it possible to accentuate the relationship between the microstructure and performance characteristics of concrete. The time of storing the cubes in both acidic environments (sewage from post grit chamber and active sludge chamber) has a negative influence on their compressive strength. The compressive strength of cubes decreases along with the time. Compressive strength of cubes increases with increasing pH of the environment.



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Keywords: sewage; durability; acids; sulfate attack; concrete strength; compressive strength test

1. Introduction

The destructive effects of sewage and active sludge on concrete elements of the technological structures of wastewater treatment plants were observed in the middle of the past century [1]. The main source of acidic aggressive media is municipal sewage (biogenic H₂SO₄) [2]. Flow of sewage and its composition lead to detrimental phenomena of abrasion, causing damage to the surface of the concrete structures and shortening their service life [2–4]. Another significant aspect which ought to be taken into account when discussing the influence of sewage on concrete structures is its chemical composition, which underwent distinct changes over the course of the past two decades; the various types of organic compounds found in sewage during the course of the treatment process are becoming highly aggressive [4–6].

Processes taking place during sewage treatment result in the decomposition of organic matter contained in sewage, among others by anaerobic bacteria, which leads to the formation of high quantities of hydrogen sulfide. Next, the aerobic bacteria living above the water table oxidize the hydrogen sulfide to sulfuric acid, which creates a highly aggressive environment when settling on the concrete elements, characterized by a pH = 2. Such a highly aggressive environment is the cause of concrete corrosion as well as that of steel bars in reinforced concrete elements [5,7].

The concentration of compounds of hydrogen sulfide in sewage in the discussed period increased suddenly from a level of 10 ppm to as much as 300 ppm [8], and in the case of bioreactors, even to a level of 1000 ppm. The growth tendency of the concentration of sulfuric acid is a consequence of aerobic bacteria multiplying in the sewage, which is the reason behind the lowering of pH to as little as 1 [9,10]. This phenomenon is long-lasting and accelerates the corrosion of concrete, reinforced concrete, and steel elements. The

majority of studies pertaining to the corrosion of concrete, however, come down to determining the physical and mechanical characteristics according to European standards. In the aim of finding long-lasting methods of protecting concrete structures or reinforced concrete tanks for sewage treatment plants, carrying out studies, and especially laboratory studies, is an essential step [9,11]. This is necessary, seeing as how treatment tanks characterized by a low class of exposure aggressiveness XA2 [12,13] are still operational in sewage treatment plants, which is a significant problem when it comes to their use in light of the gathered studies and facts.

The basic reaction of an aggressive acidic environment with concrete is calcium hydroxide neutralization according to [2,14]:



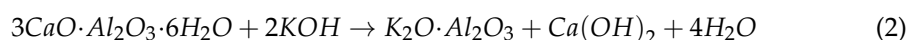
As a result of this reaction, calcium salts are formed, which are easily or hardly soluble in water. The easily soluble salts are washed out of the cement matrix, which increases the porosity and permeability of the outer layers of the concrete [15]. The pH of the concrete is also lowered, which is related to the reduction of the amount of alkaline $\text{Ca}(\text{OH})_2$ [2,12,16].

An aggressive environment characterized by an acidic pH poses a large problem for concrete structures [17]. Sulfate attack is one of the most dangerous corrosive phenomena during the life cycle of a concrete structure. It occurs most frequently in structures exposed to sewage. Fertilizers and industrial wastewater can be sources of sulfate. External corrosion occurs when the concrete is exposed to sulfate solutions. The main reaction with concrete taking place in such an environment are exchange reactions between the calcium hydroxide and the acidic environment. Calcium salts are formed in two different sequences (as a result of chemical reaction) which cause damage to concrete elements. Firstly, salts which display minimal strength and minimal binding properties can be formed, thus resulting in decreased concrete properties. In the second variant, compounds with a higher volume than the actual reaction substrates are created. Sulfate ions from the environment react with the cement matrix to form gypsum and/or ettringite [18]. During the formation of both compounds, the volume increases. This leads to microcracks, desquamation, decrease in strength, and finally—the destruction of the concrete element [8,9,19].

As a result of the effects of an acidic environment on concrete structures, the mechanism of leaching salts from the cement matrix may also occur, thus resulting in the increased porosity and permeability of the outside layer of concrete. The reduction of the amount of alkaline $\text{Ca}(\text{OH})_2$ in concrete consequently results in the lowering of pH at the pore solution of the hardened cement matrix [15,17,20–24].

As acid corrosion progresses, it is also possible to decompose the C-S-H phase. First, the C-S-H phase is decalcified because it acts as a buffer for the pore liquid. In order to temporarily raise the pH of the concrete, Ca^{2+} ions pass from the C-S-H phase to the pore liquid. Then, the depleted C-S-H phase reacts with the acid, resulting in the formation of amorphous silica gel (ASR gel), which is devoid of binding and strength properties [21,25]. This leads to a reduction in the strength of concrete [17].

Alkaline corrosion may also result in changes in the concrete structures. Alkaline corrosion is the gradual degradation of concrete as a result of a strongly alkaline outside environment along with its components. Although concrete is resistant to an alkaline pH, strong solutions, especially in an increased temperature, lead to its gradual degradation. This is caused by the creation of soluble sodium or potassium silicates and aluminates as a result of chemical reactions [19].



The aim of the present study is to describe the influence of an aquatic environment with the use of grit chamber sewage as well as sewage from an active sludge chamber at different pH values (in an acidic, neutral, and alkaline environment) on the compressive strength of concrete cubes.

2. Study Methodology

2.1. Materials and Specimen Preparation

The studies were carried out on a concrete mixture composition characterized by a compressive strength class of C40/50, the value of the water to cement ratio $\frac{w}{c} = 0.5$. Portland CEM I Class 42.5 R cement was used to prepare the mixture.

A CHRYSO Optima 185 free flow additive (plasticizer) [26,27] in the amount of 1.5% of the cement mass was also added [12]. The designed concrete mixture ratio is presented in Table 1.

Table 1. Concrete mixture ratio.

Component		Amount per 1 m ³ [kg]
Cement		380
Water		190
Aggregate	fraction	
	0.0–0.125	55
	0.125–0.25	36
	0.25–0.5	91
	0.5–1.0	219
	1.0–2.0	200
	2.0–4.0	182
	4.0–8.0	492
	8.0–16.0	547
Additive		5.7

Concrete cubes (standard dimension 10 cm) were prepared in accordance with PN-EN 206: 2016 [12,17,28] and were kept 28 d in water.

2.2. Exposure Conditions

Sewage used in the studies is derived from a grit chamber as well as an active sludge chamber obtained from the area of the sewage treatment plant in Piaseczno (Poland). The samples were respectively collected following the grit chamber as well as from the active sludge chamber.

The quality characteristics of post grit chamber sewage and sewage from the active sludge chamber are presented in Table 2.

Table 2. Characteristics of selected indicators in post grit chamber sewage and sewage from the active sludge chamber.

No.	Type of Indication	Units	Active Sludge	Grit Chamber
1	pH	pH	7.56	7.75
2	salinification	mg/dm ³	580	849
3	alkalinity	mval/dm ³	6.51	15.18
4	acidity	mval/dm ³	0.24	0.48
5	hardness	mgCaCO ₃ /dm ³	267.67	277.67
6	ammonium	mgNH ₄ ⁺ /dm ³	1.16	46.27
7	chlorides	mgCl [−] /dm ³	137.86	153.600
8	calcium	mgCa ²⁺ /dm ³	91.71	90.86
9	magnesium	mgMg ²⁺ /dm ³	8.74	11.14

Prepared cubes were weighed and measured and then placed for 345 d in post grit chamber sewage and sewage from the active sludge chamber. Cubes were entirely submerged in the given environment with limited access to air. In addition to the neutral environment (natural, without modifications to pH in accordance with Table 2), each of the environments were modified creating an acidic (pH ~ 3–4) or alkaline (pH ~ 11–12) environment. Corrections were made to the pH when necessary in order to maintain an appropriate character in acidic and alkaline environments. For this purpose, a measured amount of sulfuric acid (VI) [H₂SO₄] was added to acidic environments, as well as sodium hydroxide [NaOH] to alkaline environments. The temperature of the environment in which the studies were carried out was equal to 20–25 °C.

Over the course of the samples being in the research environment, the pH was measured by means of the potentiometric method, using a Sension 4 pH meter with an IJ44A gel electrode manufacture by Ionode (Elmetron, Poland, as well as the total dissolved solids (TDS) using the conductometric method with the use of a multi-parameter Sension 156 4-electrode conductometric gauge produced by Hach (Hach, Poland), with a built-in temperature sensor. Cubes were under conditions of limited access to oxygen, which, especially in the case of sewage from the active sludge chamber, caused the initiation of wet decomposition processes of organic matter.

After the assumed time of exposure, the test samples were cleaned of free raids by rinse and then dried. Then, they were weighted, measured, and photographed. The observed surface has natural fractures resulting from crushing the sample. The samples were not ground.

The assessment of the analyzed surface of a sample can be carried out by measuring roughness, as well as determining the roughness line. During the course of the study process, the concrete samples were exposed to contact with various environments, including liquids that have a destructive effect on the concrete. The analysis of the surface involved the observation and measurement of the size of the damage areas. The measurement of the depth of cavities was carried out by choosing two points or a line on the screen displaying the surface sample. Microscopic pictures were taken in the presented studies following the period (345 d) of the experiment.

The number of replicates was 10 for each environment and 12 for the reference sample.

2.3. Compressive Strength Study

Compressive strength tests were made using a Matest Class 1 durometer according to Norm PN EN 12390-4 [29]. The value of the breaking force was read with a precision of up to 0.1 kN.

2.4. Microscopic Analysis of Sample Surfaces

Concrete samples were subjected to microscopic studies of the surface using a VHX-6000 series Keyence optic microscope with digital imaging (Keyence, Poland), with a universal VH-Z20R/Z20T power zoom lens using 20, 100, 150, 200 magnification with a 1/2-inch CCD camera on a 15-inch monitor (Keyence, Poland). Testing of the microstructure of the concrete cubes was done using an SEM scanning electron microscope FEI Quanta 200 ESEM type JOEL 5500 with 14–30 kV acceleration voltage in deep and low vacuum (SEI environment) [30–33].

2.5. Statistical Analysis

The work involved the method of statistical assessment of the strength of concrete for determining the confidence intervals, carrying out the statistical analysis of an n-element set of results, numbering $n \leq 30$ [34,35]. Statistical analysis covers a compilation of the results of strength tests on the basis of which, using point estimation, the following are determined [28]:

- average value of the strength of a given concrete,
- standard deviation (root mean squares) of concrete strength,

- indicator of the variability of concrete strength as a relative measure of standard deviation,
- left quantile of order “p” determines the limit value of the random variable,
- t-Student distribution,
- confidence level.

Moreover, the results of the studies were analyzed using multifactor analysis of variance (ANOVA) with the use of the Statgraphics Centurion XVI (16.2 software and presented in Tables 6 and 7. The level of significance “p” for the analysis was assumed at 0.05. A value of the “p” parameter below 0.05 signifies that the analyzed factor has a significant influence of the compressive strength of concrete and ought to be accounted for when designing concrete using the DEO function of Statgraphics Centurion XVI (16.2 software).

3. Results and Discussion

3.1. Exposure Conditions and Mechanical Test Results

The results of compressive strength tests of concrete are presented in Figure 1. All carried out studies were divided into environments depending on their nature.

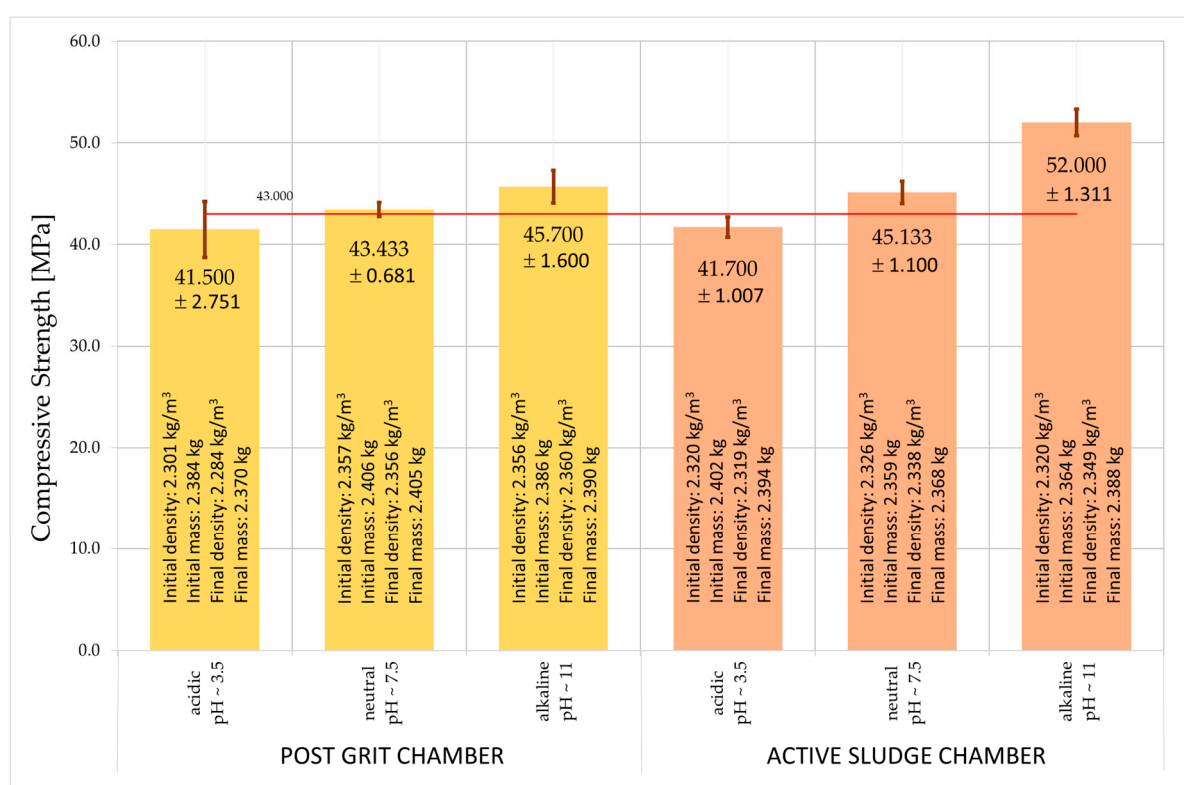


Figure 1. Relationship between compressive strength and the density of the analyzed sample stored in the post grit chamber and active sludge chamber.

The decrease in strength took place in the case of cubes stored in both acidic environments (post grit chamber sewage and active sludge chamber sewage), which is illustrated in Figure 1. It was about 3.5% in the post grid chamber and 3.0% in the active sludge chamber. A significant decrease in compressive strength along with a drop in pH were also observed in studies by Xie et al. [36]. This is most certainly caused by the strong effect of the aggressive chemical compounds formed as a result of the microorganisms present in the sewage, the effect of which was magnified by the additional acidification of the environment with sulfuric acid (IV) [H₂SO₄]. Carbonic acid as well as aggressive carbon dioxide CO₂, created during chemical processes taking place, react with dissolved products of cement hydration, especially with portlandite CaOH₂ [19]. Formed as a result of this

process are calcite CaCO_3 and water. Under conditions of decreased pH, the amount of calcite created increases [37].

If the samples are immersed in an acidic environment, the concrete's compressive strength decreases with a slight decrease in mass and a simultaneous decrease in density (Figure 1). As confirmed in the works by Zivica and Bajza [15,20], this may be caused by the crystallization of sparingly soluble salts in the process of sulfuric corrosion. The most frequently occurring type of corrosion of concrete is that caused by the effects of sodium and magnesium sulfate [38]. In the process of sulfate corrosion, in which chemical reactions between active components of concrete and sulfate ions take place, highly expansive crystals of hydrated calcium sulfoaluminate (ettringite) may form [16].

Due to the decrease in the mass of samples as well as the presence of pitting on the surface of the samples, which can be seen in Figure 2, the occurrence of the phenomena of sulfate attack can be confirmed.



Figure 2. (a) Concrete samples found in post grit chamber sewage with an acidic pH; (b) concrete samples found in active sludge with an acidic pH.

The change in color of the sample surface was noted in all the cases where the samples were kept in acidic environment (Figure 2). Figure 2b reveals a black residue. It is caused by the formation of a layer of biofilm on the surface of the concrete cube [36,39].

In the case of an alkaline environment, an increase in the compressive strength occurred both in the case of samples found in post sand grit chamber sewage, as well as that from the active sludge chamber (Figure 1). It was about 6.3% in the post grid chamber and 20.9% in the active sludge chamber. The compressive strength was maintained at a relatively high level due to the elimination of acids formed in an oxygen-deprived environment as well as thanks to the presence of CaO , which is characterized by high alkalinity.

In Figure 1, an increase in mass as well as density can be observed in the case of an alkaline environment. This is most likely caused by the crystallization of newly-formed chemical compounds [18].

Among samples stored in a neutral environment, a slight increase in strength was noted in the case of those found in sewage from the post grid chamber and active sludge chamber (Figure 1). It was about 1.0% in the post grid chamber and 0.3% in the active sludge chamber. The mass and density in this case did not change significantly.

Samples surface submerged in a neutral environment can be observed in Figure 3. Here, we observe a small amount of damage, pitting, and mineral deposits on the surface of the analyzed samples.

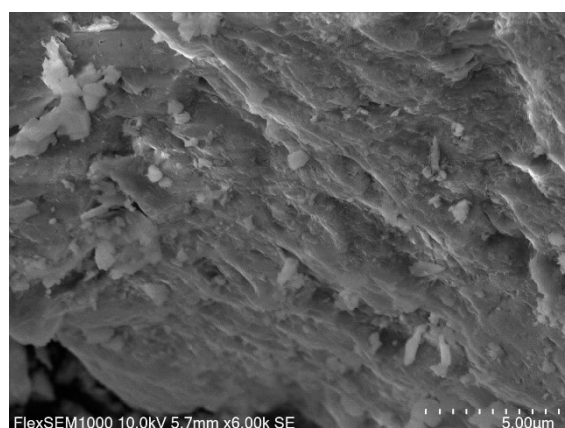


Figure 3. Concrete samples found in active sludge with a neutral pH following 345 d of the experiment.

Table 3 presents the results of pH and TDS analysis of the liquid in which the cubes were submerged, i.e., in a neutral, alkaline, and acidic environment (respectively: post grit chamber sewage and sewage from the active sludge chamber).

Table 3. Results of pH and TDS of the liquid in which the cubes were submerged.

Chamber	Post Grit Chamber						Active Sludge Chamber					
	Acid Environment pH ~ 3.5		Neutral Environment pH ~ 7.5		Alkaline Environment pH ~ 11		Acid Environment pH ~ 3.5		Neutral Environment pH ~ 7.5		Alkaline Environment pH ~ 11	
Day of Experiment	pH [–]	TDS [mg/dm ³]	pH [–]	TDS [mg/dm ³]	pH [–]	TDS [mg/dm ³]	pH [–]	TDS [mg/dm ³]	pH [–]	TDS [mg/dm ³]	pH [–]	TDS [mg/dm ³]
0	3.03	1047	7.61	731	11.13	1026	3.64	836	7.21	623	11.00	919
6	3.16	1400	7.91	762	10.89	977	4.00	1218	7.50	678	10.77	1145
14	3.33	1676	8.35	837	10.97	1255	3.56	1543	7.67	728	10.55	1355
20	2.71	2040	8.55	848	10.87	1541	3.42	1717	7.80	779	10.00	1437
28	3.57	1726	8.81	842	10.15	1589	3.55	1834	8.09	830	10.53	1514
35	4.66	1684	8.77	848	10.96	1616	3.52	1967	8.18	854	10.35	1548
42	3.20	2040	8.75	852	10.99	1625	3.41	2130	8.21	877	10.30	1564
49	3.53	1969	8.78	847	10.97	1632	4.69	1920	8.28	890	10.36	1568
55	3.61	2065	8.83	847	10.94	1643	3.67	2240	8.27	899	10.31	1580
69	3.75	2110	8.73	840	10.01	1876	2.87	2460	8.23	898	10.26	1592
76	3.28	2310	8.76	829	10.21	2445	4.11	2300	8.21	890	10.26	1587
83	2.92	2520	8.99	886	11.43	2840	2.75	2470	8.16	875	11.31	2590
90	3.05	2100	8.74	806	11.05	2770	4.27	2200	8.18	860	10.36	2540
111	3.09	2120	8.63	789	12.69	3900	3.13	2200	8.05	832	12.24	4050
118	3.01	2110	8.68	773	12.67	3940	3.07	2250	8.07	804	12.41	4620
125	4.60	1854	8.93	763	12.58	3940	4.06	2110	8.01	779	11.07	4960
140	3.52	2013	8.88	767	12.02	4130	4.79	2060	7.99	753	10.29	4910
145	3.00	2130	9.02	820	11.28	3960	3.59	2210	8.51	744	11.18	6850
152	3.24	2050	8.95	823	11.03	3800	3.36	2350	8.56	745	10.99	6990
166	3.17	2130	8.95	817	10.83	3870	3.47	2250	8.57	747	10.63	6960
187	3.44	1938	8.97	821	10.71	3860	3.52	2170	8.59	750	10.43	6950
194	3.45	2056	8.95	817	10.56	3866	3.48	2222	8.56	748	10.55	6960
229	3.44	2020	9.07	831	11.17	4300	3.27	2340	8.65	758	11.00	7860
252	3.17	2040	9.03	839	10.87	4290	3.33	2190	8.70	753	10.76	8050
278	3.30	2080	9.01	905	12.44	6180	3.56	2200	8.69	795	11.25	9190
308	3.20	1994	9.04	930	12.10	5930	3.49	2370	8.73	798	11.08	9830
345	4.51	1687	9.10	949	11.63	5750	4.56	2130	8.73	787	10.57	10,100

Table 3 illustrates the increase in salinity, which confirms that components of the concrete made their way into the environment. In the case of samples found in neutral pH in both sewage environments, a slight increase of TDS was observed. The growth tendency of salinification signifies the mineralization of organic compounds found in the sewage as a result of microbial activity [16]. In opposite, the TDS in acidic and alkaline environments significantly increase. In this case, it was due to the addition of the amount of sulfuric acid (VI) $[H_2SO_4]$ and sodium hydroxide $[NaOH]$ to maintain an appropriate pH.

3.2. Results of Microscopic Studies of Sample Surfaces

In the case of samples stored in active sludge with an alkaline character (Figures 4a–c and 5a–c), in active sludge with an acidic character (Figures 6 and 8), as well as post grit chamber sewage with an acidic (Figure 7) and alkaline pH (Figure 11), crystals are visible in the cracks and cavities and on the surface. Probably this results from the effects of monoaluminium sulfate $[3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O]$ or tricalcium aluminate $[3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O]$, which is Candlot's salt [18,22], created as a result of sulfate corrosion.

Only in the presence of water/liquid can these aggregates react with the alkali present in the pores of the concrete. As a result of this reaction, an alkaline ASR gel is formed [25] (Figure 4), which, absorbing water, swells practically without restrictions and is deposited in the pores of the concrete. Gel shells up to 2 μm thick are formed around the active grains. As the gel is bounded by hardened cement paste, internal stresses arise inside these pores which cause the concrete to crack. Figure 4a,b shows a photo taken with the Keyenes optical microscope at a magnification of 20×200 .

Figure 5 shows a photo of C-S-H found on samples stored in the active sludge chamber with an alkaline pH after 345 d of the experiment.

Figure 6 presents calcium hydroxide $Ca(OH)_2$ being washed out in the process of acidic corrosion. In this experiment, we are dealing with calcium hydroxide $Ca(OH)_2$ being washed out in the process of acidic corrosion. Cavities can be observed on the surface of the sample, caused by the leaching of highly soluble salts created as a result of acidic corrosion. Figure 6a,b shows strongly scratched aggregate grains at magnification $\times 100$ and $\times 20$, and Figure 6c shows the 3D profiling of the tested surface.

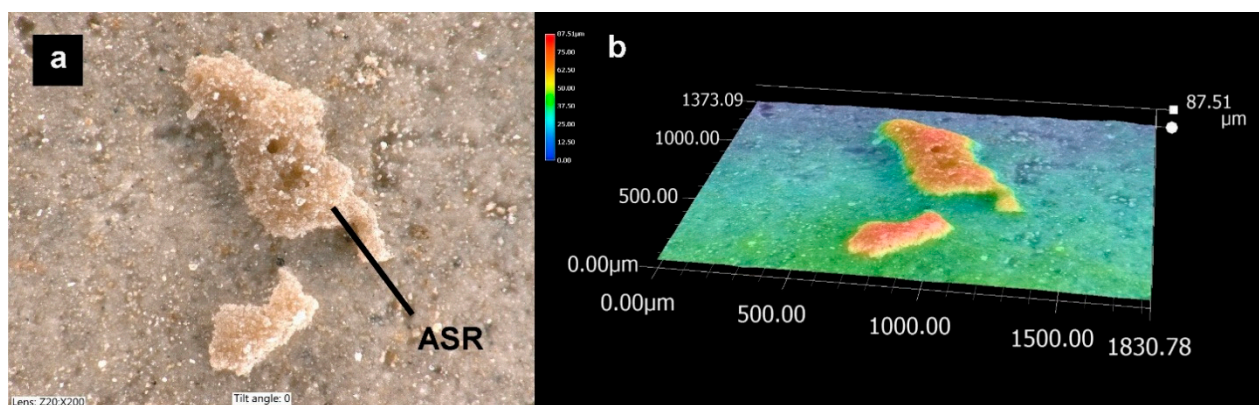


Figure 4. ASR gel found on samples stored in the active sludge with an alkaline pH after 345 d of the experiment: (a) fragment of the edge of the test sample under magnification $\times 200$ magnification; (b) the surface of the sample made with an optical microscope in the 3D technique with a clearly marked area of the damaged surface of the concrete top layer.

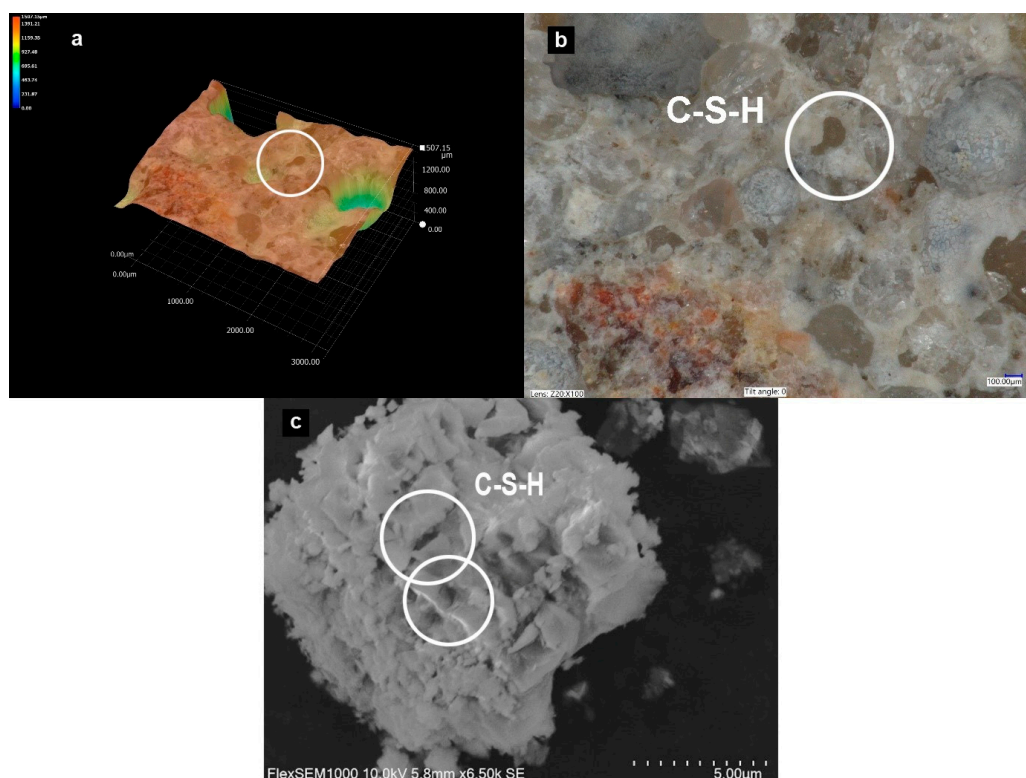


Figure 5. C-S-H found on samples stored in active sludge with an alkaline pH after 345 d of the experiment [SEM]: (a) the surface of the sample made with an optical microscope in the 3D technique with a clearly marked area of the damaged surface of the concrete top layer; (b) fragment of the edge of the test sample under magnification $\times 100$ magnification; (c) enlargement of the SEM sample $\times 1000$.

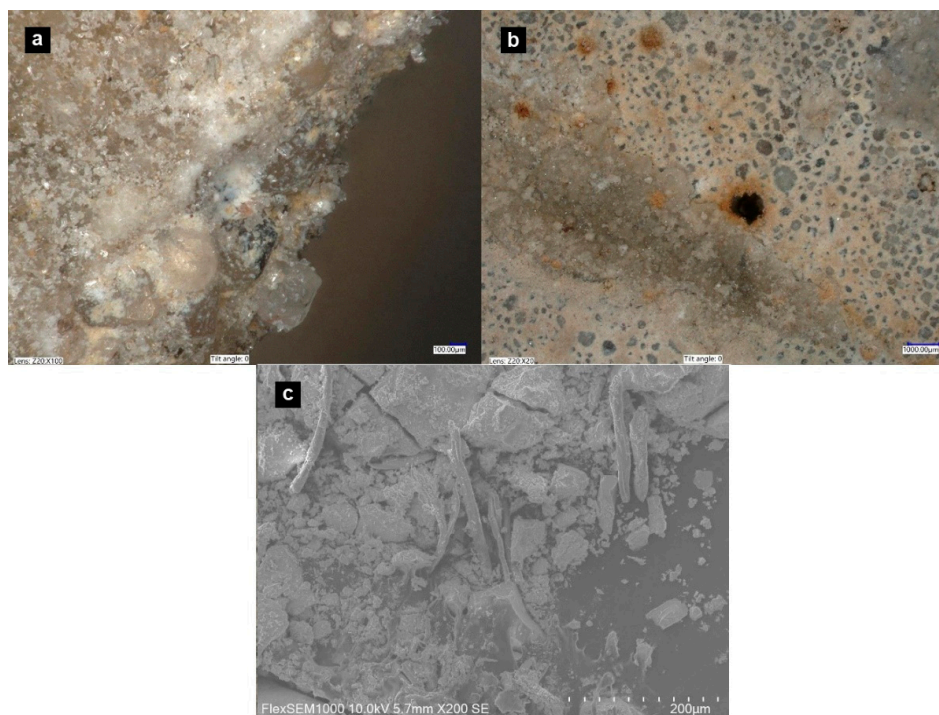


Figure 6. Concrete samples found in post grit chamber sewage with an acidic pH following 345 d of the experiment: (a) excerpt of the edge of the test sample under magnification $\times 100$ magnification; (b) magnification $\times 20$ samples from losses and color change; (c) enlargement of the SEM sample $\times 1000$.

Figure 6c is a photo of the microstructure in the central area of the cross-section. Zonal changes in the phase composition related to the decreasing concentration of sulfate ions and the type of corrosive solution were found. In the case of samples exposed to the acidic environment, there was gypsum in the surface layer.

As in the cases where the samples were kept in sewage from the post grit chamber with acidic environment, the decomposition of the C-S-H phase as a result of acid corrosion is also possible in the case of sewage from the active sludge chamber (Figure 7). The C-S-H phase is also decalcified first. Then, the depleted C-S-H phase reacts with the acid, as a result of which the strength of the concrete is lowered [2].



Figure 7. Concrete samples found in active sludge with an acidic pH following 345 d of the experiment.

By observing the processes taking place in the cubes in a neutral environment in the post grit chamber sludge in Figure 8, we are dealing with the leaching of calcium hydroxide CaOH_2 . The surface of the samples is found, revealing missing areas caused by the washing away of soluble salts created as a result of acidic corrosion, as well as the emergence of a dark residue in areas of damage.

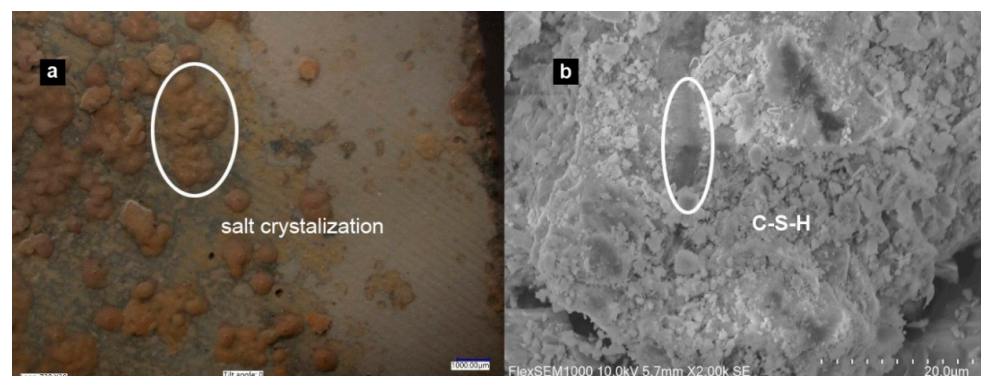


Figure 8. Concrete samples found in post grit chamber sewage with a neutral pH following 345 d of the experiment: (a) the surface of the concrete sample with visible crystallized salt compounds from the liquid made with an optical microscope at $\times 20$ magnification; (b) enlargement of the SEM sample $\times 1000$.

Figure 8a shows photos of the surface of a concrete sample with visible crystallized salt compounds from the liquid taken with an optical microscope at $\times 20$ magnification. Figure 8b shows the SEM photos. It shows salt compounds in the form of compact flakes [3].

In Figure 9, we can observe cavities, with a residue and crystals of newly formed minerals, mineral amendment compounds appearing in other areas. Figure 9a,b shows $\times 100$ and $\times 20$ magnification of the surface of the concrete sample from the grit cham-

ber with a neutral environment. Figure 9c shows the sample made in a SEM scanning microscope with a clearly marked C-S-H colloidal gel.

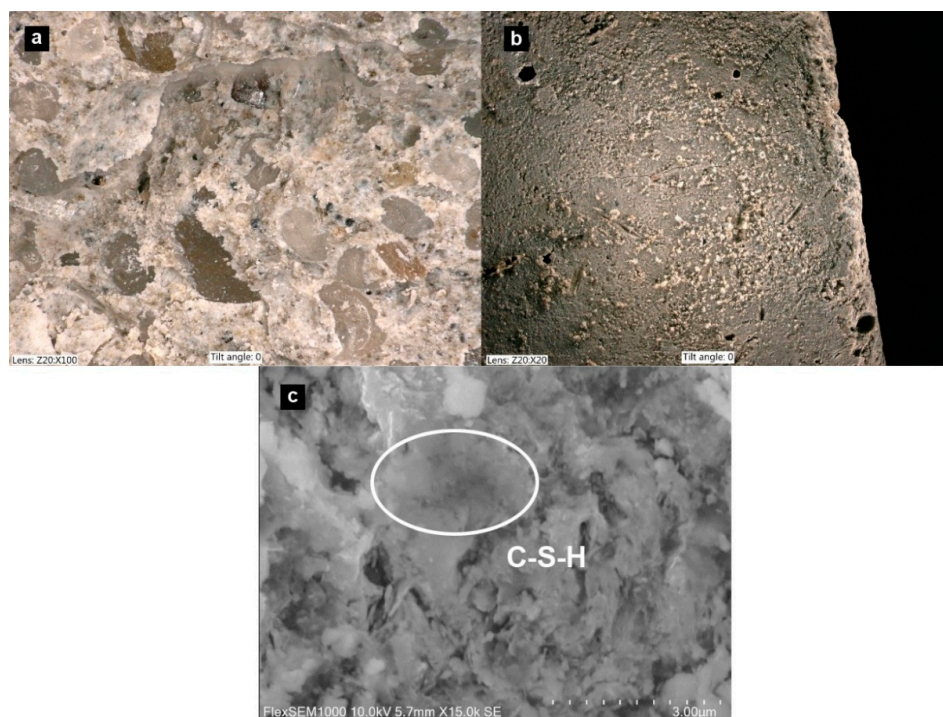


Figure 9. Concrete samples found in post grit chamber sewage with an alkaline pH following 345 d of the experiment: (a) $\times 100$ magnification; (b) $\times 20$ magnification; (c) $\times 1000$ magnification SEM.

3.3. Results of Statistical Analyses

Calculation of Individual Statistical Parameters

The calculation algorithm of individual parameters in statistical analyses for cubes stored in sewage for 345 d is presented in Tables 4 and 5 in order to assess the compressive strength of concrete and the homogeneity of these studies [38,39].

Table 4. Estimating the expanded calculation uncertainty for the value of the average compressive strength of concrete in the analyzed population of samples of standard cubes of ready-mix concrete after 345 d of storage in the post grit chamber sewage.

Testing after 345 d	Post Grit Chamber		
	Alkaline pH	Neutral pH	Acidic pH
standard deviation [MPa]	1.600	0.681	2.751
arithmetic mean [MPa]	45.700	43.433	41.500
indicator of variability of material strength, as a relative measure of standard deviation [MPa]	0.035	0.0157	0.066
left-side quantile of the order p determines the limit value of the random variable [MPa]	43.080	42.317	36.990
average value of breaking force of sample [kN]	1028.25	977.25	933.75
compound standard uncertainty [MPa]	0.961	0.466	1.606
effective number of degrees of freedom	1.710	1.004	1.911
total expanded uncertainty [MPa]	1.58	0.766	2.63
the average value of material strength in the analyzed series of samples falls in the range [MPa]	44.120–47.300	42.670–44.200	38.870–44.130

Table 5. Estimated expanded calculation uncertainty of the average value of compressive strength of concrete in the analyzed population of standard cube samples of ready-mix concrete after 345 d of storage in sewage from the active sludge chamber.

Testing after 345 d	Active Sludge		
	Alkaline pH	Neutral pH	Acidic pH
standard deviation [MPa]	1.311	1.100	1.006
arithmetic mean [MPa]	52.000	41.700	45.133
indicator of variability of material strength, as a relative measure of standard deviation	0.0252	0.0263	0.0223
left-side quantile of order p determines the limit value of the random variable [MPa]	49.849	39.900	43.482
average value of breaking force of sample [kN]	1170.00	938.25	1015.50
combined standard uncertainty [MPa]	0.815	0.51	0.637
effective number of degree of freedom	1.489	1.20	1.382
total expanded uncertainty [MPa]	1.336	0.84	1.045
the average value of material strength in the analyzed series of samples falls in the range [MPa]	50.660–53.340	40.860–42.540	44.090–46.180

The results of ANOVA 2-Factor Interactions analysis of variance for the influence of the pH of the environment as well as time of storing the post grit chamber sewage on the compressive strength of concrete samples are presented in Table 6, and in sewage from the active sludge chamber in Table 7.

Table 6. The results of ANOVA analysis of variance for the influence of individual factors on the compressive strength of concrete cubes stored in post grit chamber sewage.

Source	Sum of Squares	Df	Mean Square	p Value	F Ratio
A:time [days]	4.4595	1	4.4595	0.0650	3.52
B:pH [–]	52.6555	1	52.6555	0.0000	41.53
AB	52.6555	1	52.6555	0.0000	41.53
Total error	86.2179	68	1.26791		
Total (corr.)	196.864	71			

R-squared = 56.20 percent; R-squared (adjusted for d.f.) = 54.27 percent; Standard Error of Est. = 1.12; Mean absolute error = 0.66.

Table 7. Results of ANOVA analysis of variance for the influence of individual factors on the compressive strength of concrete cubes stored in sewage from the active sludge chamber.

Source	Sum of Squares	Df	Mean Square	p Value	F Ratio
A:time [days]	180.103	1	180.103	0.0000	185.10
B:pH [–]	313.108	1	313.108	0.0000	321.79
AB	313.108	1	313.108	0.0000	321.79
Total error	66.1652	68	0.973018		
Total (corr.)	885.771	71			

R-squared = 92.53 percent; R-squared (adjusted for d.f.) = 92.2 percent; Standard Error of Est. = 0.98; Mean absolute error = 0.63.

In both cases (cubes storing in post grit chamber sewage and in sewage from the active sludge chamber), the pH and multiplication time and pH (AB) turned out to be the most statistically significant factor. Time is a statistically significant factor only in the case of cubes stored in sewage from the active sludge chamber. However, all factors and their

interaction were taken into account in order to compare the differences in the impact of this factor on the value of compressive strength for cubes kept in the sewage from the post grit chamber and in the sewage from the activated sludge chamber.

The assessment of the influence of variables (time of storing the samples and pH of the environment) on the compressive strength of concrete samples—concrete cubes stored in post grit chamber sewage as well as sewage from the active sludge chamber, has been presented in Figure 10. Judging by the slope shown in Figure 10, the positive or negative influence of a given factor on the compressive strength can be assessed. In both cases (post grit chamber sewage and sewage from the active sludge chamber), the increasing time of storing the cubes and increasing pH of the environment have a positive influence on their compressive strength. This means that the compressive strength of cubes generally increases along with the extension of the time they are in contact with a given environment. The greater slope, the greater the influence of the given factor on compressive strength. It turns out that the pH of the environment has a greater influence on the drop in compressive strength (slope is steeper) than time of storing the samples. It is worth noting here that the compressive strength of the reference samples was at the level of 43 MPa, and for pH 3.5, it is lower, which proves that the acidic environment contributed to the reduction of the compressive strength.

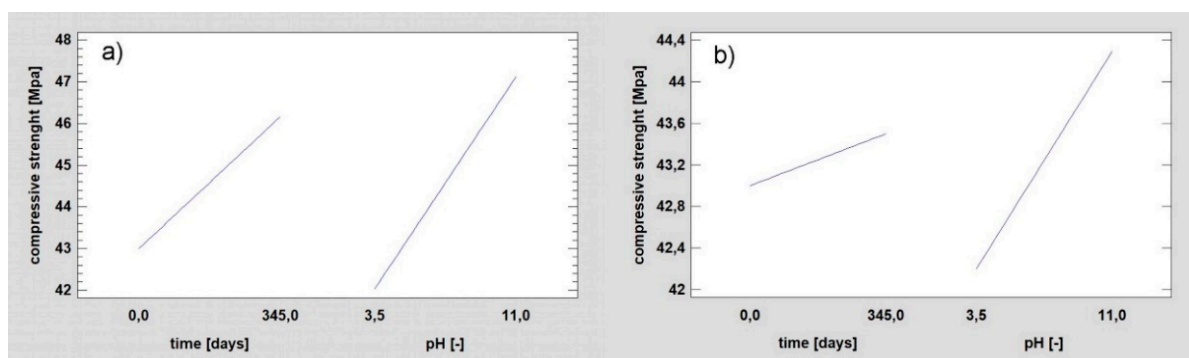


Figure 10. Influence of the time of storage as well as pH of the environment for cubes stored in post grit chamber sewage (a) as well as sewage from an active sludge chamber (b). (source: Statgraphics Centurion XVI).

The analysis of results of 11.5 months of studies made it possible to indicate a nomogram. It is possible that to read the potential compressive strength of cubes can be assessed in post grit chamber sewage and sewage from an active sludge chamber during the first 345 d of contact and for any pH in the range of 3.5 to 11 (Figure 11).

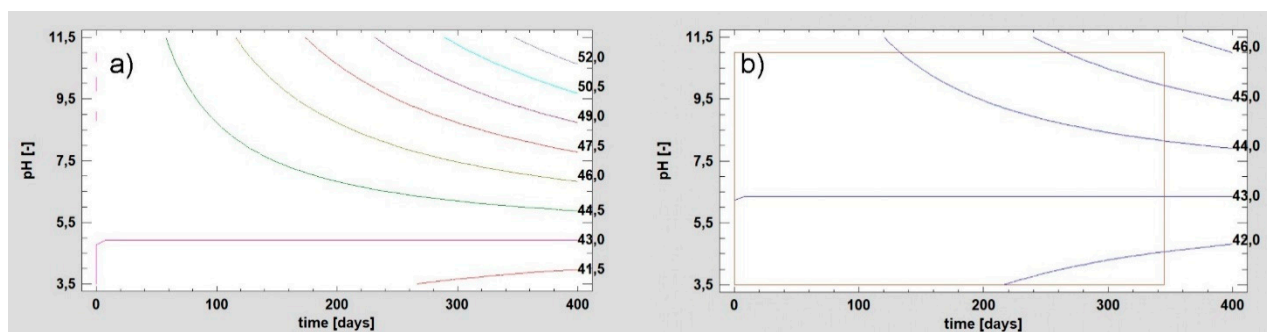


Figure 11. Nomogram for indicating compressive strength in samples stored in post grit chamber sewage (a) and in sewage from an active sludge chamber (b). (source: Statgraphics Centurion XVI).

4. Conclusions

The laboratory studies were carried out with the aim of determining the influence of sewage derived from a post grit chamber and an active sludge chamber in various environments (acidic, neutral, alkaline) on the compressive strength of concrete cubes. The greatest decrease in compressive strength was observed in the case of sewage from the post grit chamber with an acidic pH. The greatest increase in compressive strength was observed in the case of sewage from the active sludge chamber in alkaline pH.

Due to the decrease in the mass of samples as well as presence of visible pitting on the surface of the samples in acidic environment, the effects of acidic corrosion were confirmed. An insignificant drop in compressive strength occurred along with an decrease in mass.

Due to the increase in the mass of the sample stored in alkaline pH, the increase of compressive strength was observed.

The carried out studies as well as topic-related literature prove that the phenomena of corrosion caused by municipal sewage pose a serious threat. Despite the relatively short time that the samples were exposed to the aggressive factors (345 d), negative effects are observable. Laboratory studies were carried out, confirming the negative effects of environmental factors on the durability of concrete structure components. Conclusions from the conducted research may be of innovative importance in the context of the preparation of environmental impact reports necessary for obtaining a building permit and the use of facilities exposed to contact with sewage as well as their subsequent impact on the environment and surface and deep water resources.

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