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Article

The Effect of Incorporating Industrials Wastewater on Durability and Long Term Strength of Concrete

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Abstract: Concrete, as one of the essential construction materials is responsible for a vast amount of emissions. Using recycled materials and gray water can considerably contribute to the sustainability aspect of concrete production. Thus, finding a proper replacement for fresh water, in the production of concrete, is significant. The usage of industrial wastewater, instead of water in the concrete can is considered in this paper. In this study, 450 concrete samples are produced with different amounts of wastewater. The mechanical parameters such as slump, compressive strength, water absorption, tensile strength, electrical resistivity, rapid freezing, half-cell potential, and appearance are investigated. The results showed that the usage of industrial wastewater does not significantly change the main characteristics of concrete. Although, increasing the concentration of the wastewater can decrease durability and strength features nonlinearly.

Keywords: sustainable concrete; wastewater; industrial waste management; sustainable development; sustainable construction materials

1. Introduction

In the modern era, concrete is one of the most used materials in the construction industry [1-4]. Since the first-time concrete was utilized as the building material, the fresh water is used to produce and cure the concrete [5]. The performance of the concrete, which is made of wastewater had also been investigated, however, further researches are essential to examine whether using wastewater is financially resealable and could meet construction standards or not [6]. Clearly, there is still a research gap on life cycle assessment and further environmental, functional, and economic aspects of using wastewater [7]. Bearing in mind the amount of required water for construction projects, if potable water could be substituted by recycled water, it would reduce the costs, but it would also prevent wasting of an enormous amount of drinkable water resources [8]. Nowadays, there is much scarcity of drinkable water resources that would not give us economic advantages but can help us environmentally. Rivers and fountains which are not contaminated by domestic wastewaters and do not have a salty taste, are appropriate for concrete mix designs [9]. Researches also have indicated that the water of the lakes, which contain less Silt, organic materials, and impurities, has insignificant adverse effects on concrete features; however, other comprehensive studies are needed about other replacements [10]. In industrial and urban areas with limited drinkable resources and according to fast enhancement in industry, the demand for storing water is being felt more and more [11]. According to the majority of scientists, the best way to make construction materials is using the residue of materials, and one of the most prominent construction materials is concrete, which is used approximately 5 million cubic meters per year in the whole world [11]. This significant value can be counted as an excellent opportunity to use wastewater in concrete, containing 28% of the water cycle [12]. It is undeniable that one

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of the most usable basic materials in industrial towns is water, which becomes wastewater after using, and it is highly harmful to human health and the environment. Concerning the potable water crisis, especially in the Middle East, finding other water resources as a suitable replacement rather than drinkable water for producing and curing concrete has drawn significant attention, remarkably those solutions that not only economize cost and energy but also present novel methods to better productivity and burring the harmful materials so as not to have detriment influences on the environment. According to the United Nation (UN) world water development report, a series of global actions have been doing over five years, and it has costed over 25 billion dollars in order to have healthy infrastructures for water and wastewater; the Water Quality Protection and Job Creation Act of 2017 is a bipartisan bill that invests $25 billion over five years in clean water and wastewater infrastructure [12]. It is worth mentioning that the amount of produced industrial wastewater and sludge in the United States of America are 119 billion gallons and 17 million tons per year, respectively; these statistics for Europe are 123 billion gallons and 18.9 million tons, respectively [12].

Al-Ghusain and et al. [13] studied primary, secondary and tertiary treated wastewater was taken from the local wastewater plant. The water utilized by them did not change the slump; however, setting time was more increased by worsening water quality. They described that impurity in the water of concrete imposes different effects on setting time, strength and making some stains on the external surface. All impurities do not harm concrete and some reactions can be neutral or even suitable for concrete.

Shekarchi [14], carried out the use of biologically treated wastewater in concrete mixing and curing. Physical and mechanical tests were performed on mortar and concrete cube specimens. Some durability tests of concrete were also evaluated. When mixing and curing of concrete was done in primary and secondary water, the compressive strength increased up to 17% than concrete mixed and cured in tap water up-to 180 days. After 180 days a small reduction in concrete was observed which is mixed and cured in primary treated water and when secondary treated water was used as mixing or curing in concrete, compressive strengths were decreases from 9 to 18%. The water absorption of the concrete mixed in tap water and treated wastewater was identical. Curing in secondary wastewater increased water absorption of the specimen. These results showed the feasibility of biologically treated water in the concrete production industry

Asadollahfardi et al. [15] studied using concrete wash water to produce concrete. Their results indicated that concrete wash water is suitable for producing fresh concrete. This research is based compressive strength, flexural strength, abrasion resistance, chloride resistance and carbonation resistance of treated wastewater concrete (10%, 25%, 50% and 100% replacement with Tap water) and compares the results with control concrete. This research gives the feasibility of use of treated wastewater in concrete to reduce consumption of fresh water in concrete industry as well as to solve the disposal problem of the industrial wastewater

Asadollahfardi et al. [16] used the treated domestic wastewater instead of drinking water to produce and cure concrete samples. Their results indicated that the compressive strength of the samples made with treated domestic waste-water at the age of 28 days was 93–96% of the compressive strength of the control samples which made with drinking water. Also, the use of treated domestic wastewater did not have much effect (less than 4% decrease in resistance) on the tensile strength of the concrete samples; however, delayed the final setting time of cement by 15 min was observed.

Clearly, there is still a research gap in the functional and economical aspects of using wastewater. According to new developments and increasing the human population, coupled with the demand to curb expenditure in different government budget sectors, attention should be focused on the reuse of resources if possible. In the present research, different industrial wastewater concentrations were used for producing concrete specimens; subsequently, the durability and strength within 365 days were assessed. For this purpose, two types of industrial wastewater were used. First, treated wastewater itself

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and its different concentrations including diluted and concentrated treated wastewater. Second, Primary Wastewater that is non-refined; it can reveal the quality of refineries' performance and the optimum extent of refinement for concrete.

2. Materials and Methods

2.1. Method of Examination

The used wastewaters are gathered from Toos industrial town, Mashhad, Iran, and within a maximum of three hours, wastewaters were analyzed in the laboratory. The analyses were done on industrial's primary wastewater, treated wastewater, diluted treated wastewater and concentrated treated wastewaters; the control specimen was produced with drinkable water of Mashhad City which is standard water. Altogether, 450 specimens were made in ten times pouring concrete and fourteen skilled operators participated in producing specimens, which took two hours in total. The number of done tests on specimens are as follows: slump 10 samples, compressive strength 240 samples, electrical resistivity 20 samples, water absorption of thirty minutes 10 samples, mass water absorption 10 samples, capillary water absorption 30 samples, tensile strength 40 samples, rapid freezing and thawing 40 samples and half-cell 30 samples. All of the tables, results, and tests are done exclusively for this research, and no archive data is used. Technical and Vocational University (TVU), Mashhad, Iran, provided researchers with test facilities. The used standards are shown in Table 1.

Table 1. shows the assessment ways for all the experiments.

Type of testing	Method of testing
Chemical and physical properties of treated wastewater	APHA [17]
Mixing water for concrete. Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete	BS EN 1008 [18]
Standard specification for Portland cement	ASTM-C150 [19]
Standard test method for density of hydraulic cement	ASTM C188-15 [20]
Standard test method for sieve analysis of fine and coarse aggregates	ASTM-C136 [21]
Standard specifications of concrete aggregates	ASTM-C33 [22]
Standard test methods for time of setting of hydraulic cement by Vicat needle	ASTM-C191 [23]
Slump of hydraulic-cement concrete	ASTM C143 [24]
Method for determination of compressive strength of concrete cubes	BS 1881-116 [25]
Standard test method for splitting tensile strength of cylindrical concrete	ASTM-C496 [26]
Absorption of concrete water	BS1881-122 [27]
Florida method of test For Concrete resistivity as an electrical indicator of its permeability	FM-5-578 [28]
Water absorption rate by hydraulic- cement concretes	ASTM-C1585 [29]
Concrete resistance against thawing and rapid freezing	ASTM-666 [30]
Standard method for test of half-cell potentials of uncoated reinforcing steel	ASTM- C876-91 [31]
Standard test method for density, absorption, and voids in hardened concrete	ASTM C642-13 [32]
Standard test method for air content of freshly mixed concrete by the pressure method	ASTM C231/M17a [33]

In this research, ten different groups of specimens were produced with different wastewater concentrations. All groups of specimens had the same mix design, and no additive was used in order to figure out the exact effect of wastewater concentration on concrete durability and strength features. In this study, one of the targets was finding the optimum concentration of a treated wastewater that the impurity can cause 10% less compressive strength than the control sample (made with drinkable standard water). Technically, 10% compressive strength reduction still be counted as an acceptable substitution for water of concrete mix design [34]. The main control sample was made by the potable water of Mashhad city (Ctrl). The used industrial wastewaters are categorized

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into four groups. First, Treated Wastewater (TWW). Second, diluted treated wastewater which is a mixed with distilled water including (75%TW), (50%TW) and (25%TW); numbers show the percentage of treated wastewater in water of mix design. Third, concentrated treated wastewater which are the concentrated version of TWW, including (TW+20%C), (TW+25%C), (TW+30%C) (TW+35%C); number shows the percentage of concentration. Fourth, Primary Wastewater (PWW) which is totally unrefined.

In addition, all groups of concrete specimens were produced in a similar situation and cured in drinkable water, treated wastewater according to the tests standards and intended purposes. Also, the parameters like concrete density, temperature, moisture, cement type, aggregates characteristics were used in the same condition for all of the specimens.

2.2. Wastewaters

For producing concrete with wastewaters, the amount of their distilled water based on the quality of the control specimen was considered and all other extra substances were subtracted. In majority of time, there is an allowable limit for the water of mix design that within those restrictions, the impurity can be harmless and acceptable. Nevertheless, there is no limitation for organic materials in concrete and it assumes that only wastewater impurities are the reasons for negative effects on water of concrete mix design.

2.2.1 Treated Wastewater (TWW)

Treated wastewater is known for output wastewater too and goes through three steps of refinement including filters, aeration and chlorination. Treated wastewater was used as the main replacement for drinkable water and it was utilized for producing distilled and concentrated specimens as well. TWW was used for curing the specimens if they were intended to be cured by wastewater separately. The characteristics of TWW is presented in Table 2.

2.2.2. Diluted Treated Wastewater (%TW)

Diluted specimens were produced by TWW plus mixing distilled water. They contained 75% wastewater (75%TW), 50% wastewater (50%TW) and 25% wastewater (25%TW) and the rest of percentages are distilled water. These water of mix designs were selected in order to investigate existence of linear or non-linear relationships in strength and durability features by diluting treated wastewater as the water of mix design. Based on the laboratory results, the number of parameters was reduced correctly by dilution percentages. In order to get the number of parameters in diluted specimens, the characteristics of treated wastewater (Table 2) should be reduced by dilution percentages.

2.2.3. Concentrated Treated Wastewater (TW+ %C)

Concentrated specimens were produced from TWW by evaporation; concentrating percentages are 20% (TW+20%C), 25% (TW+25%C), 30% (TW+30%C), and 35% (TW+35%C), respectively. Based on laboratory results, the parameters of thickened specimens were increased almost by concentration percentages. So, concentrated specimens have the same parameters of treated wastewater (Table 2) but their characteristics are 20%, 25%, 30%, and 35% more than characteristics of Treated wastewater, respectively. According to the intended concentration, the amount of surplus treated wastewater was added and after measured time with precise warming temperature, intended concentration were achieved. However, reaching intended concentration by evaporation is almost acceptable but the sufficient accuracy for important parameters like COD, BOD, Sulfate, Chromium, Cadmium, and Salt were considered and double checked.

2.2.4. Primary wastewater (PWW)

The initial discharge of industrial wastewater is primary wastewater which is a collection of several polluting industries like pharmacy, food, Ironmaking and chemical. It

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contains lots of organic materials and caustic heavy metals like Cadmium and Chromium because it doesn't go through any refinement process and technically this is the TWW before refinement procedure. PWW has a huge amount of organic materials, microorganisms, and heavy metals which are mostly harmful and caustic for environment and concrete. Table 2 shows the characteristics of primary wastewater (PWW).

Table 2. Chemical and physical characteristics of treated wastewater and primary wastewater.

No.	Parameter	Unit	Treated wastewater	Primary wastewater	Mashhad potable water (Ctrl)
1	pH	-	7.92	7.68	7.2
2	TDS	Mg/l	1870	2541	412
3	SALT	Mg/l	2.4	2.51	40
4	EC	Mg/l	3950	4120	193
5	COD	Mg/l	150	3215	0
6	BOD	Mg/l	114	1240	3
7	TSS	Mg/l	25	451	121
8	NH4	Mg/l	2	3	0.4
9	Detergent	Mg/l	1.25	3.1	-
10	Color	-	Light brown	Black	Transparent
11	Temperature	°C	17	17-19	25
12	Sulfate	Mg/l	80	145	50
13	Chloride	Mg/l	1230	740	94
14	Chromium	Mg/l	0.9	1.89	0.1
15	Cadmium	Mg/l	0.7	2.95	-
16	Lead	Mg/l	2.85	2.85	0.02
17	Turbidity	Nephelometric Turbidity Unit	10	800	2

2.3. Concrete Preparation

For producing the control sample and curing of all groups with normal water, portable water of Mashhad, Iran, was used. Also, the Portland cement type II was chosen and its quality was tested according to the ASTM-C150 was tested. Table 3 shows the chemical and physical properties of cement. For reducing the effect of other parameters on concrete, except wastewater, the good-quality, continuous, less flaw aggregation was used. The standard of ASTM-C33 was considered and the mass of aggregates was weighted in SSD condition. Table 4 depicts the characteristics of aggregate in various specimens.

For reaching the optimum mix design, ASTM-C305 [36] was used based on the water-cement ratio of 0.42, and the good-quality aggregates were selected after several initial samples according to the details in Table 5. Mix design for all groups of specimens was the same and almost the same shape of aggregates was used for producing all specimens. Besides, the concrete specimens were molded in metal molds and cured based on ASTM-C31 [37]. The specimens were cured by drinkable water, treated wastewater.

Table 3. Chemical and physical properties of cement.

Chemical & Physical Measurands	Units	Test Method	ISIRI 389	EN 197-1: 2011	Sample Analysis
SIO_2	%	ASTM C114:2011b	> 20.00	-	21.77
AL_2O_3	%	ASTM C114:2011b	< 6.00	-	5
Fe_2O_3	%	ASTM	< 6.00	-	4.3

		C114:2011b			
CaO	%	ASTM C114:2011b	-	-	63.13
MgO	%	ASTM C114:2011b	< 5.00	< 5.00	1.78
L.I.O	%	EN 196-2:2013	< 3.00	< 5.00	1.38
SO_3	%	EN 196-2:2013	< 3.00	< 3.5	2.22
IR	%	EN 196-2:2013	-	< 5.00	0.63
Na_2O	%	EN 196-2:2013	-	-	0.32
K_2O	%	EN 196-2:2013	-	-	0.83
CI	%	EN 196-2:2013	-	< 0.10	0.010
Free CaO	%	EN 196-2:2013	-	-	1.10
Cao/ SIO_2	-		-	> 2.0	2.90
C_3S+C_2S	%		-	> 66.667	73.48
Fineness	Cm^2/gr		>2800	-	3000
Le Chatelier Expansion	mm	EN 196-3:2005	-	< 10.00	0.9
Initial Setting Time	min	EN 196-3:2005	> 45	> 75	116
Final Setting Time	min	EN 196-3:2005	< 360	-	175
3 days Com. Strength	MPa	EN 196-3:2005	-	-	16.8
7 days Com. Strength	MPa	EN 196-3:2005	-	-	23.2
28 days Com. Strength	MPa	EN 196-3:2005	-	> 32.5, < 52.5	45.3

Table 4. The characteristics of aggregates.

Sample	Free water mass	Wastewater mass	Cement mass	Sand mass
Control (Ctrl)	168 kg	-	400 kg	974 Kg
Treated wastewater (TWW)	-	168 kg	400 kg	974 Kg
Concentrated treated wastewater (TW+%C)	-	168 kg	400 kg	974 Kg
Diluted treated wastewater (%TW)		168 kg	400 kg	974 Kg

Table 5. Detail of mix design of concrete samples.

Parameter	Control (Ctrl)	Treated wastewater (TWW), Concentrated treated wastewater (TW+%C), Diluted treated wastewater (%TW)	Primary wastewater (PWW)
Free water mass	168 kg	-	-
Wastewater mass	-	168 kg	168 kg
Cement mass	400 kg	400 kg	400 kg
Sand mass	974 Kg	974 Kg	974 Kg
Fine gravel mass	185 kg	185 kg	185 kg
Coarse gravel mass	576 kg	576 kg	576 kg
Stone powder	74	74	74
Additive	-	-	-

3. Results and Discussion

3.1. Slump

The slump shall be consistent with the placement and consolidation methods, equipment, and site conditions and shall be identified by the contractor and concrete supplier prior to construction. According to achieved results, TWW had less workability than the control sample. Diluted specimens reacted like TWW, which shows existence of

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the wastewater can affect the workability even in low percentages. The concentrated specimens followed the same way of treated TWW, but TW+25%C had a reduction and stayed in next specimens too. The TWW had 13.3% lower workability than the Ctrl specimen and by 25% increasing the concentration of treated wastewater TW+25%C, the workability declined 20% than Ctrl. It blatantly showed that wastewater has a subtractive effect on workability and it is dependent on wastewater concentration. So, it is highly recommended that in the project with high required workability, the additives should be considered to increase the slump, especially while more concentrated wastewaters are used as the water of mix design. No linear relationship was observed in any specimens while their concentration was increased or decreased orderly. The concentrated specimens had more viscous and greasier and it is one of the reasons why concentrated specimens had less workability and it was obvious in PWW sample which had the highest impurities. Figure 1 shows the slump test results.

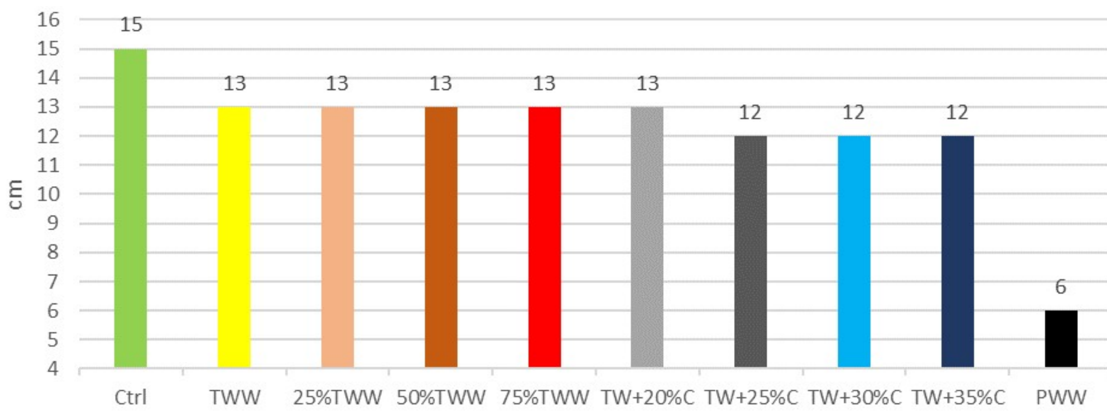

Figure 1. Slump test results

3.2. Compressive Strength

The result of compressive strength at different ages days is shown for specimens cured by drinkable water (Figure 2) and cured by treated wastewater (Figure 3). The Ctrl sample had the highest strength in all ages and it substantiated that the best result can be achieved by using drinkable water. TWW had lower strength than Ctrl, but its reduction was insignificant. So, it demonstrated that treated industrial wastewater is applicable for using in concrete. The compressive strength in wastewater specimens was better when the concentration of water for producing and curing were the same. It vividly showed the homogeneity and similarity features between the curing situation and water of the mix design. For instance, at the age of 7, 28, 90, 365 days when TWW and 75%TW were cured by treated wastewater, they had 0.54%, 1.65% 1.06%, 1.55% and 2.86%, 0%, 3.6%, 1.06% more compressive strength than cured by standard water, respectively. Besides, 25%TW which its mixed design water was roughly similar to drinkable water had 1.62%, 1.1%, 1.6%, 1.02% more compressive strength, when it was cured by standard water in different ages. The concentrated specimens in low ages had better performance when they were cured by treated wastewater but in late ages, they showed better results by drinkable water. The positive effect of curing with treated wastewater for those specimens produced by treated wastewater disappeared by increasing the specimens' concentration and got changed adversely. For example, TW+35%C cured by treated wastewater had 3%, 3.1%, 2.4%, 2.6% less compressive strength when it was cured by treated wastewater than was cured by drinkable water. PWW produced by primary wastewater and had the highest impurity, corroborated this result and it had 2.6%, 5.3%, 4.5%, 4.3 less compressive strength when it was cured by treated wastewater. Neither in diluted specimens nor

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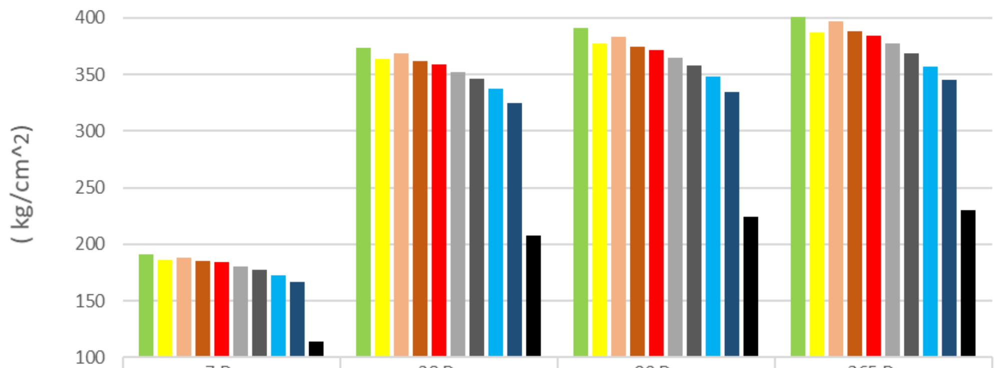
concentrated specimens, linear relationship was observed and non-linear relationship was dominant; however, the concentration of specimens was increased and decreased orderly.



	7 Days	28 Days	90 Days	365 Days
Ctrl	191	374	391	402
TWW	186	364	377	387
25%TWW	188	369	383	397
50%TWW	185	362	375	388
75%TWW	184	359	372	384
TW+20%C	180	352	365	377
TW+25%C	177	346	358	369
TW+30%C	173	337	348	357
TW+35%C	167	325	335	345
PWW	114	208	224	230

Figure 2. Compressive strength cured by drinkable water (kg/cm²) at 7, 28, 90, and 365 days.

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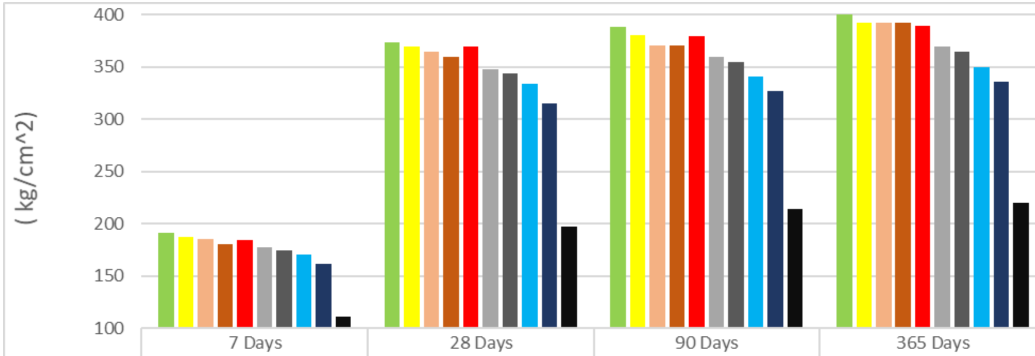


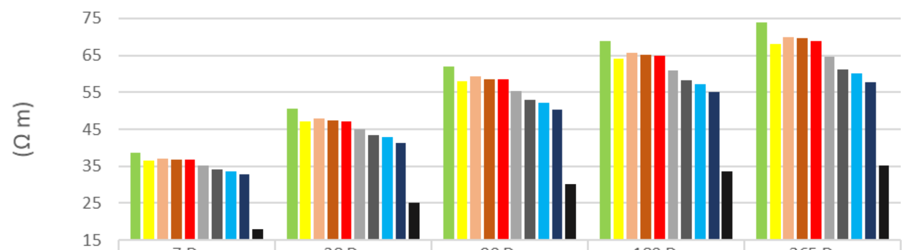
	7 Days	28 Days	90 Days	365 Days
Ctrl	191	374	389	402
TWW	187	370	381	393
25%TWW	185	365	371	393
50%TWW	180	360	371	393
75%TWW	184	370	380	390
TW+20%C	177	348	360	370
TW+25%C	175	344	355	365
TW+30%C	171	334	341	350
TW+35%C	162	315	327	336
PWW	111	197	214	220

Figure 3. Compressive strength cured by treated wastewater (kg/cm²).

By aging, concentrated specimens had less compressive strength growth than Ctrl sample and by increasing the specimens' concentration the reduction was increasing. One of the most important intentions of this study was to find the impurity and concentration of the wastewater which causes 10% reduction in compressive strength of concrete in comparison to Ctrl after 28 days. Based on Figures 2 and 3, TW+30%C cured by drinkable water and treated wastewater at the age of 28, had 9.9% and 10.7% less compressive strength than Ctrl; respectively. It clarified the worst amount of impurity in industrial treated wastewater which can be still applicable [34].

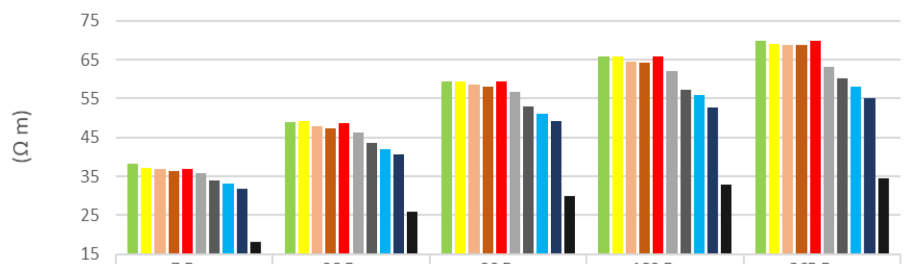
3.3. Electrical resistivity

The level of permeability of concrete has direct effect on electrical resistivity of specimens. This test indicates specimens' permeability and specifies existing voids and cracks in the concrete structure which has a significant effect on concrete durability [38]. Figures 4 and 5 present electrical resistivity of specimens. at the age of 7, 28, 90, 180 and 365 days.



	7 Days	28 Days	90 Days	180 Days	365 Days
Ctrl	38/7	50/5	62/1	68/9	73/8
TWW	36/6	47	58	64/1	68/1
25%TWW	37/1	48	59/3	65/7	70
50%TWW	36/9	47/5	58/5	65/2	69/6
75%TWW	36/7	47/2	58/5	64/8	68/8
TW+20%C	35/3	45/1	55/3	61	64/5
TW+25%C	34	43/3	53	58/2	61/3
TW+30%C	33/7	42/8	52/2	57/1	60
TW+35%C	32/8	41/3	50/4	55/1	57/8
PWW	18	25/1	30/2	33/6	35/2

Figure 4. The results of concrete electrical resistivity tests cured by standard water.



	7 Days	28 Days	90 Days	180 Days	365 Days
Ctrl	38/2	48/9	59/5	65/8	70
TWW	37/1	49/1	59/3	65/8	69/1
25%TWW	36/9	47/9	58/7	64/6	68/8
50%TWW	36/4	47/4	58/1	64/2	68/7
75%TWW	37	48/8	59/5	65/8	70
TW+20%C	35/8	46/3	56/8	62/2	63/1
TW+25%C	33/8	43/5	53	57/4	60/2
TW+30%C	33/1	42	51/1	55/8	58/2
TW+35%C	31/7	40/7	49/1	52/8	55
PWW	18	25/8	30	32/9	34/4

Figure 5. The results of concrete electrical resistivity tests cured by treated water (TWW).

Ctrl sample had better resistance when it was cured by drinkable (standard) water and a reduction was observed when cured by treated wastewater. Also, by concentrating the concentration, electrical homogeneity was decreasing. The diluted specimens' behavior was inclined toward the TWW results not Ctrl, even when insignificant treated wastewater was involved. For example, 25%TW which its producing water is 75% drinkable water, followed the TWW resistance not Ctrl, either cured by drinkable water or treated wastewater. It showed that whenever wastewater parameters are involved in the specimens, they could exceedingly influence the concrete structure and they make void and porosity in specimens. So, diluting the concentration has insignificant effect on electrical resistivity enhancement. TWW and specimens with close concentration to TWW, had better resistivity when they were cured by treated wastewater in low ages,

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however, by aging the positive effect was declining even on them; as if being cured by treated wastewater in long term have caustic effects on the concrete structure and causes more penetration ways. Nevertheless, specimens with a lower concentration at an early age, a resistance growth was observed which again supported the positive effect of homogeneity feature as well as negative effect of being cured by treated wastewater in long term.

At the age of 28 days, TW+30%C cured by drinkable and treated wastewater had %15 and %14 less electrical resistivity than Ctrl sample; respectively. It indicated that using wastewater in concrete has more negative effects on concrete's durability features than strength aspects because it had %10 reduction in compressive strength test but %15 in electrical resistivity. Therefore, it is recommended not to use treated wastewater for projects with high touch with caustic material or marine projects.

3.4. Water Absorption Mass

For the water absorption test, the specimens are dried in an oven for a specified time and temperature and then placed in a desiccator to cool. Immediately upon cooling the specimens are weighed. The material is then emerged in water at agreed upon conditions, often 23°C for 24 hours or until equilibrium. This test was done based on BS1881-122 [27]. Table 6 indicates the results of mass water absorption which has a significant relationship with concrete permeability. The less porous and crack the structure of concrete has, the less possibility exists for moving harmful parameters into the structure of concrete; consequently, the concrete corrosion is less expected. Hence, based on BS1881-122 the allowable water absorption is restricted between 2% to 5%. In this test except PWW, all other specimens were stood in the allowable limitation after 72 hours, however, TW+35%C stood at the edge of rejection. This test showed that not only using wastewater increases water absorption, but also the rate of age to age water absorption growth is more than Ctrl which is improper. For instance, Ctrl sample from 1 hour to 72 hours had %49.5 water absorption growth; but TWW and TW+30%C had 53.3%, and 63.4%, respectively. The TW+30%C had 39.5% more mass water absorption than Ctrl, which acknowledged the exactness of 30 minutes water absorption results. Table 6 shows the mass water absorption.

Table 6. Mass water absorption

	1 Hour (%)	**3 Hour (%)**	**24 Hour (%)**	**72 Hour (%)**
Ctrl	2.10	2.62	2.93	3.14
TWW	2.42	3.05	3.54	3.71
25%TW	2.30	2.78	3.05	3.2
50%TW	2.30	2.85	3.25	3.45
75%TW	2.34	2.94	3.38	3.52
TW + 20%C	2.55	3.21	3.60	3.88
TW + 25%C	2.64	3.39	3.85	4.18
TW + 30%C	2.68	3.48	4.00	4.38
TW + 35%C	2.90	3.83	4.40	4.92
PWW	8.6	11.04	12.45	13.60

3.5. Capillary water absorption

The capillary test evaluates the process of non-saturated concrete water absorption by capillary suction while it is in touch with water. Table 7 shows the results of capillary water absorption at 3, 6, 24, and 72 hours. Basically, the more moisture concrete contains, the less capillary water absorption will be measured. The capillary water absorption was increasing by using wastewater; even 25%TW which contained 75 percent distilled water had %11.19 more capillary water absorption than Ctrl at 72 hours. It showed that treated wastewater even with low concentration, influences capillarity absorption and subsequently reduces concrete durability. Using wastewater causes bigger and looser capillary pipes which are connected to each other and intensify the concrete corrosion. The more and larger capillary pores a concrete has, the more deleterious substances will go into superficial and interior layers of concrete. For instance, after 72 hours TWW samples had 25.87% more capillary water absorption growth than (Ctrl); this growth for TW+30%C was 95.30%.

Table 7. The results of capillary water absorption ($\frac{gr}{mm^2}$ or mm)

Sample	3 hour (%)	6 hour (%)	24 hour (%)	72 hour (%)
CTRL	1.35	1.72	2.00	2.86
TWW	1.66	2.14	2.54	3.70
25%TW	1.46	2.05	2.28	3.18
50%TW	1.53	2.12	2.40	3.38
75%TW	1.57	2.08	2.40	3.44
TW+20%C	1.80	2.35	2.84	4.22
TW+25%C	1.88	2.52	3.18	4.86
TW+30%C	1.94	2.62	3.40	5.22
TW+35%C	2.05	2.84	3.70	5.65
PWW	8.90	12..88	16.85	29.32

Figure 6 indicates the rate of growth during the test period. The wastewater specimens had more capillary water absorption and growth rates than the (Ctrl) sample. For example, from 24 to 72 hours, (TWW) and (TW+30%C) had 4% and 10% more growth than (Ctrl). So, based on Table 8, 9 and 10, it is highly recommended not to utilize wastewater with high concentration as the water of concrete mix design when it is going to be used in caustic environments because of the high possibility of corrosion.

Figure 6. The capillary water absorption growth hour to hour (%).

3.6. Tensile strength

The tensile strength of concrete is a prominent property when it is to be utilized in making prestressed concrete structure, roads and runways. Figures 7 and 8 illustrate the results of tensile strength on day of 7 and 28 cured by drinkable water and treated wastewater; respectively. This test illustrated that behavior of specimens in tensile strength test is approximately like compressive strength test but the situation is worse in concentrated specimens. For example, TW+30%C sample cured by drinkable water and treated wastewater at the day of 28 had almost 10% less compressive strength than Ctrl; nevertheless, in tensile strength it had 19% less tensile strength. It indicated that Interfacial Transition Zone (ITZ) area is weaker in wastewater specimens and the desire for water absorption is more in this area. Some wastewater parameters like sludge, have spongy features and they reduce available water for hydration reaction, while the water cement ratio is needed more in ITZ region [34]. In addition, some other greasy wastewater like oils cover the aggregates' surface and hamper the proper connection between cement and aggregates in ITZ region [34]. That is why the tensile strength is more affected by increasing the concentration tensile compared to pressive strength. Although, the specimens' concentration was increased and decreased in order, no linear relationship was observed between in diluted or concentrated specimens.

Not only by increasing the concentration tensile strength declined, but also the rate of tensile strength growth was lower than Ctrl sample. For instance, within day of 7 to 28, the Ctrl sample cured by drinkable water and treated wastewater had 85.3% and 84.4% growth. But TW+30%C had 78% and 77% tensile strength growth, and TW+35%C had 77%, 75%; respectively.

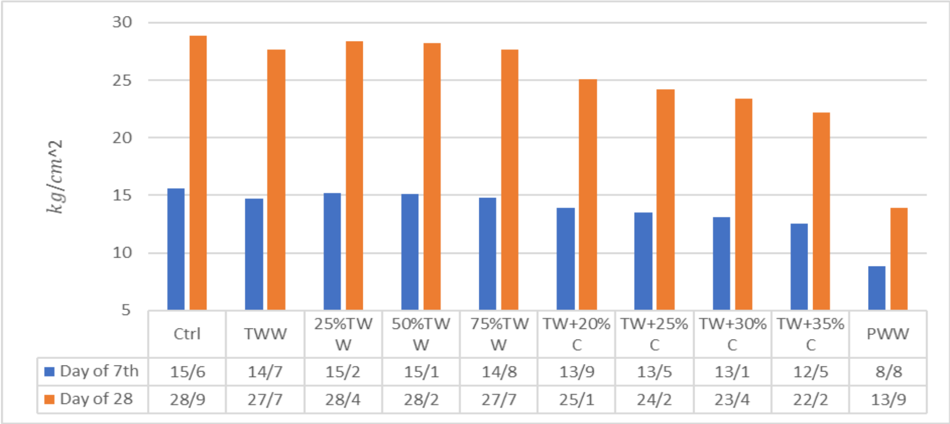

Figure 7. The results of tensile strength cured by drinkable waster $(\frac{kg}{cm^2})$.

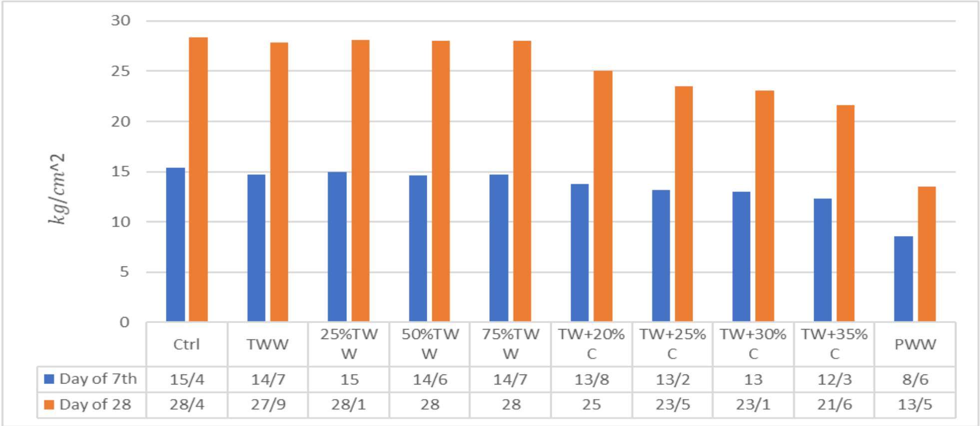

Figure 8. The results of tensile strength cured by treated wastewater $(\frac{kg}{cm^2})$.

3.7. Rapid Freezing and Thawing

Table 8 indicates the compressive strength of specimens at the age of 28 days results and the strength reduction of each cycle due to rapid freezing and thawing test Change in compressive strength: the decline of more than 10% is the sign of fail. The volume expansion is the first reason for cracking in concrete. This expansion is caused by frozen water inside of concrete. Another reason for cracking is thermal stress. Thermal stresses appear because of repeated freeze-thaw cycles. By increasing the number of fast freeze-thaw cycles, the value of the mechanical property declines. The reduction rate in the Ctrl and TWW samples was almost the same until 100 cycles, but after that TWW demonstrated different behavior and declined more than Ctrl sample. For instance, until 100 cycles in comparison to day of 28 compressive strength, Ctrl and TWW had almost 3% strength reduction; but in 150 and 200 cycles Ctrl had 4% and 5% reduction while TWW had 6% and 7.6% compressive strength reduction, respectively. Interestingly, 75%TW also had the same reaction like TWW and the rate of reduction raised after cycle 100 and no notable difference was observed in 25%TW, which is close to Ctrl specimen and it showed the negative effect of using wastewater due to making more void in concrete structure. Compare to Ctrl sample, concentrated specimens had more compressive strength reduction in all cycles, and by increasing the concentration and cycles, the rate of reduction was raising.

Table 8. The results of resistance of concrete to rapid freezing and thawing.

Samples	28-day compressive strength	50 cycles $(\frac{kg}{cm^2})$	100 cycles $(\frac{kg}{cm^2})$	150 cycles $(\frac{kg}{cm^2})$	200 cycles $(\frac{kg}{cm^2})$
Ctrl	374	364	353	339	322
TWW	358	348	337	317	293
25%tw	370	360	349	334	317
50%tw	361	351	340	326	302
75%tw	358	348	338	319	297
tw+20%C	355	342	329	306	280
tw+25%C	344	330	316	291	265
tw+30%C	335	320	304	280	253
tw+35%C	322	305	289	265	239
PWW	208	187	172	155	136

Figure 9 shows the compressive strength reduction due to rapid freezing and thawing which has direct relationship with having more void and porosity in concrete structure. Using wastewater causes more void in concrete structure and these specimens can contain water and subsequently more expected in freezing and thawing test. TW+30%C in 50, 100, 150, and 200 cycles had 12%, 13.9%, 17.4%, and 21.4% less compressive strength than Ctrl.

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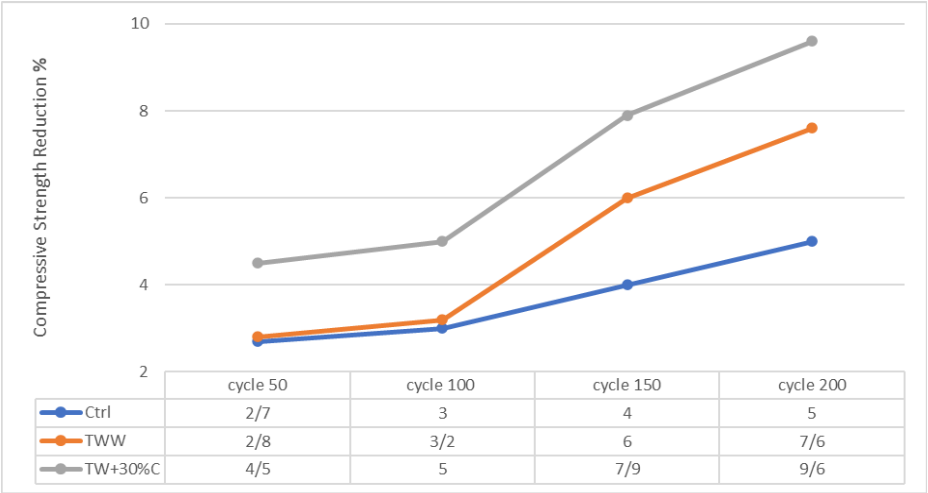

Figure 9. The compressive strength reduction in each rapid freezing and thawing cycle.

3.8. Half-cell potential

Table 9 illustrates the half-cell potential which is influenced by Chloride ion and internal Alkaline environment of concrete. Basically, increasing the wastewater concentration caused more reduction in reinforcement corrosion potential. In the other word, by aging the specimens and increasing the concentration of used wastewater as the water of mix design, the possibility of corrosion became more [34]. For instance, the corrosion in TW+30%C and PWW was started after 24 and 8 days; it is clearly because of wastewater parameters.

Table 9. The start age of armature corrosion

Sample	Age of corrosion start (day)
Ctrl	32
TWW	27
25%tw	30
50%tw	28
75%tw	28
TW+20%C	24
TW+25%C	24
TW+30%C	24
TW+35%C	22
PWW	8

3.9. Statistical Analysis

In scientific research, researchers seek to present results as quite practical and, of course, as easy as possible. One of the most important ways that other researchers can make practical use of research is to provide mathematical models for use in future experiments and research [39]. In this study, after completing the laboratory phase, the authors collected laboratory data to examine the data's relationship. Data were analyzed using SPSS statistical analysis software. In this statistical analysis, some input parameters including TDS, TSS, EC, Detergent, Sulfate, Chromium, and Cadmium to predict output parameters including Compressive Strength, Electrical Resistivity, Tensile Strength, Rapid Freezing and Thawing, Water Absorption in 30 min, Water Absorption Mass 72 hours, and Capillary Water Absorption 72 HOUR were used. The statistical indicators of all parameters are shown in Table 10.

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Table 10. Statistical characteristics of variables.

Variables	Mean	Maximum	Minimum	Kurtosis	Skewness	Variance	Std. Deviation
TDS	1879.2500	2431.00	1014.00	-1.249	-0.522	272887.933	522.38677
EC	3935.5000	3959.00	3880.00	-0.461	-1.251	1064.000	32.61901
TSS	25.6250	38.00	10.00	-1.607	-0.306	108.517	10.41713
Detergent	1.2587	1.80	0.70	-1.494	-0.206	0.152	0.39002
Sulfate	77.0000	101.00	36.00	-1.169	-0.680	596.267	24.41857
Chromium	0.8400	0.99	0.50	0.553	-1.242	0.026	0.16199
Cadmium	0.7463	0.90	0.50	0.386	-0.854	0.015	0.12099
Compressive Strength	351.2500	370.00	315.00	-0.221	-0.784	281.133	16.76703
Electrical Resistivity	45.4938	49.10	40.70	-1.340	-0.439	7.898	2.81033
Tensile Strength	25.7875	28.40	21.60	-1.625	-0.346	6.276	2.50516
Rapid Freezing and Thawing	350.3750	370.00	322.00	0.076	-0.842	245.411	15.66559
Water Absorption in 30 mins (%)	1.9137	2.30	1.72	-0.829	0.826	0.050	0.22328
Water Absorption Mass 72 hours (%)	3.9050	4.92	3.20	-0.031	0.708	0.317	0.56346
Capillary Water Absorption 72 hours (%)	4.2063	5.65	3.18	-1.504	0.491	0.874	0.93496

In the next step, the normality of the data should be checked. The normality of the data is generally determined by examining the Skewness and Kurtosis coefficients [40-42]. Achieving a situation where data distribution is perfectly normal is practically very rare, so in scientific texts, data is normal when the coefficients of Kurtosis and skewness are in the range of -2 to 2 [43]. According to the coefficients of Kurtosis and skewness in Table 19, all variables have a normal distribution. Once the normality of data is determined, it is time to determine the correlation coefficient between the variables. For normal data, the Pearson correlation test is used. Table 11 presents the results of the Pearson correlation test.

Table 11. Pearson correlation coefficients between inputs and outputs in this study.

		Inputs						
		TDS	EC	TSS	Detergent	Sulfate	Chromium	Cadmium
Outputs	Compressive Strength	-0.793	-0.525	-0.834	-0.85	-0.747	-0.678	-0.831
	Electrical Resistivity	-0.81	-0.536	-0.858	-0.856	-0.77	-0.688	-0.817
	Tensile Strength	-0.898	-0.661	-0.933	-0.934	-0.868	-0.777	-0.874
	Rapid Freezing and Thawing	-0.853	-0.658	-0.879	-0.891	-0.819	-0.796	-0.889
	Water Absorption in 30 mins	0.842	0.602	0.888	0.896	0.807	0.728	0.832
	Water Absorption Mass 72 Hour	0.896	0.697	0.927	0.942	0.869	0.831	0.902
	Capillary Water Absorption	0.906	0.673	0.942	0.942	0.876	0.807	0.886

Once the correlation coefficients have been determined it is time to determine the estimation models for research outputs. Multivariate linear regression is used for this purpose. The general form of multivariate linear regression is as follows [44-46]:

$$Y=a_0+a_1X_1+a_2X_2+a_3X_3+\ldots, \quad (1)$$

where, Y is dependent variable (output of model), Xi are independent variables (inputs of model), and ai are regression coefficients of model. The models obtained from the analysis performed with SPSS software are presented in Table 12. To measure the accuracy of the models, two criteria R2 and standard error were used.

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Table 12. Prediction models for determining characteristics of concrete.

Equations	R^2	Std. Error
$\text{Compressive Strength} = 2504.102 - 0.017\text{TDS} - 4.693\text{TSS} - 24.11\text{Detergent} + 2.869\text{Sulfate} + 93.896\text{Chromium} - 134.054\text{Cadmium} - 0.551\text{EC}$	0.964	4.37321
$\text{Electrical Resistivity} = 467.794 - 1.426\text{TSS} + 7.087\text{Detergent} + 0.522\text{Sulfate} + 15.7\text{Chromium} - 17.614\text{Cadmium} - 0.110\text{EC}$	0.960	0.76933
$\text{Tensile Strength} = 280.918 + 0.001\text{TDS} - 0.066\text{EC} - 0.758\text{TSS} + 2.536\text{Detergent} + 0.197\text{Sulfate} + 19.169\text{Chromium} - 17.064\text{Cadmium}$	0.994	0.25981
$\text{Rapid Freezing and Thawing} = 3634.478 - 0.021\text{TDS} - 0.847\text{EC} - 7.396\text{TSS} - 1.118\text{Detergent} + 4.532\text{Sulfate} - 24.176\text{Chromium} - 63.520\text{Cadmium}$	0.999	0.0001
$\text{Water Absorption in 30 min} = 0.0006092\text{TDS} + 0.011\text{EC} + 0.112\text{TSS} - 0.19\text{Detergent} - 0.051\text{Sulfate} - 0.739\text{Chromium} + 0.945\text{Cadmium} - 39.212$	0.998	0.0002
$\text{Water Absorption Mass 72 hours} = 0.02\text{EC} + 0.178\text{TSS} + 1.037\text{Detergent} - 0.104\text{Sulfate} + 0.515\text{Chromium} + 1.866\text{Cadmium} - 74.792$	0.997	0.0005
$\text{Capillary Water Absorption 72 HOUR} = 0.001\text{TDS} + 0.032\text{EC} + 0.389\text{TSS} - 1.269\text{Detergent} - 0.161\text{Sulfate} - 1.902\text{Chromium} + 2.821\text{Cadmium} - 117.984$	0.999	0.0001

The equations presented in Table 12 are very accurate, but they include an important point. These equations are constructed based on laboratory data of this study. If the number of laboratory data is increased, the coefficients of the models will may change slightly. Therefore, the authors recommend that other researchers, before applying these equations, first calibrate the models for their project or research conditions and then use them.

In sum, the achieved results were commensurate with other tests with data integrity, and no significant contradiction was observed. Negative impact of the wastewater was conspicuous in durability results and curing with wastewater is not recommended. This research indicated that using industrial wastewater could decrease the quality of produced concrete according to its concentration, but based on the results, a proper understanding of using different concentration was presented which helps reaching the economy level of refinement in industrial towns for using their wastewater in the concrete.

4. Conclusions

In this paper, ten groups of concrete specimens with different industrial wastewater concentration were produced and cured by drinkable water and treated wastewater separately according to the tests and standards. Using wastewater as water of mix design reduces the strength and durability but TWW can be good and acceptable replacement for the water of mix design and had insignificant strength and durability reduction on concrete in all tests. By concentrating the treated wastewater properties up to 30% in (TW+30%C) specimen, the compressive strength declined almost 10% after 28 days, however, concentrating had more adverse effects on durability tests which showed using wastewater causes more negative effects on durability than strength features of concrete. PWW did not have acceptable behavior in any tests, and it was rejected. Although in concentrated and diluted specimens the percentage of wastewater was increased or decreased orderly, no linear relationship in strength and durability tests was observed. Ctrl specimens showed better strength and durability when they were cured by drinkable water which proved homogeneity and similarity features, but wastewater specimens showed better strength and durability when they were cured by wastewater only in low ages, whereas the good effect disappeared in late ages; as if being in touch with treated wastewater for curing damages the specimens and causes corrosion. All of the specimens had less growth in terms of strength and durability when they were cured by treated

 doi:10.20944/preprints202102.0433.v1

wastewater in comparison to be cured by drinkable water. Using wastewater reduced the electrical resistivity and increased water absorption of and diluting the treated wastewater could not correct the negative effects on concrete durability; diluted specimens' results were closer to TWW not Ctrl and by increasing the concentration negative effects were more noticeable. In half-cell potential test, using wastewater insignificantly damaged the reinforcement, but specimens with more concentrated wastewater started to get corrosion faster. The specimens' appearances had insignificant differences except for PWW, which had more discontinuity and distinguishable lack of hydration, however, by increasing the concentration, uneven and small cracks on exterior layers were observed. Using wastewater increased water absorption and decreased workability. Therefore, it is highly recommended not to be used in those projects with caustic materials, exposed surface, or when high slump is needed.

Author Contributions: Conceptualization, E.N., D.M.S. and N.K.; methodology, E.N. and D.M.S.; software, N.K; validation, N.K. and A.M.; formal analysis, D.M.S. and N.K.; investigation, E.N.; resources, E.N. and D.M.S.; data curation, E.N. and D.M.S.; writing—original draft preparation, E.N. and D.M.S.; writing—review and editing, N.K.; visualization, A.M.; supervision, D.M.S. and N.K.; project administration, A.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

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

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