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Waste Wash-Water Recycling in Ready Mix Concrete Plants

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Abstract: The management of waste wash-water (WWW) is one of the most significant environmental problems associated with ready-mix concrete production worldwide. The problems are exacerbated should it be disposed of in an inappropriate manner. This study evaluated the potential of WWW recycling in ready mix concrete plants in Jordan. A representative waste wash-water sample (400 L) was collected from a basin in a ready-mix concrete company. A pilot plant on the lab scale was fabricated and installed. The treatment system consisted of a concrete washout reclaimer, wedgebed slurry settling pond, slow sand filtration unit, and a neutralization unit. Water samples were collected from all stages of the pilot plant and analyzed. The collected waste wash-water samples were utilized for replacement of well water (mixing water) at various ratios. Fourteen concrete mixtures were produced and cast, as well as tested at various curing ages (7, 28, and 90 days). The results show that the raw WWW was not acceptable as mixing water even after dilution as it led to significant reductions in concrete compressive strength and low workability. However, the WWW from the settling pond, the filtered WWW and the filtered-neutralized WWW at dilution ratios up to 75% were shown to be potential alternatives to fresh water for ready-mixed concrete. Therefore, the current guidelines for mixing water quality should be revised to encourage the reuse of the WWW.

Keywords: concrete; wash waste water; recycling; mixing water; compressive strength; slump; workability; water quality

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1. Introduction and Literature Review

Jordan is one of the most arid countries in the Middle East and is facing severe water shortages. The mean annual rainfall in more than 90% of the country is less than 200 mm. However, the average rainfall in the mountain areas reaches up to 600 mm [1]. The current per capita water supply is 200 m^3/year for all purposes which is almost one-third of the global average. The problem of water scarcity is magnified by high population growth rates and influx of refugees from the surrounding countries. It is expected that Jordan's population will cause a drastic decline in per capita water availability to 91 m^3. Water shortage has significantly increased stress on water resources. Groundwater resources account for 54% of Jordan's total water supply. Aquifers in Jordan are being used at twice the recharge rate and are being threatened by pollution due to over-pumping, seepage from landfill sites, and improper disposal of dangerous chemicals. A key factor of water supply management is utilizing alternative sources of water such as treated waste water [2].

Currently the concrete industry can be considered as one of the largest water consumers in Jordan. Each cubic metre of ready-mix concrete consumes around 175 L as mixing water and an additional 70 L of water to later wash the mixer trucks, concrete pumps, and equipment. Following washing, the waste wash-water (WWW) contains a high suspended solid content, extremely high dissolved solids ≥ 9000 mg/L, heavy metals and is extremely alkaline with pH ≥ 12. Its disposal can be considered one of the major environmental problems with ready-mix concrete production around the world. If inappropriately disposed of it can pollute local water sources due to its high pH value [3] and can allow heavy metals to enter the surrounding environment. The toxicity of heavy metals has been proven as a major threat for human health [4], but concrete has been shown to effectively immobilize any heavy metals within it [5]. The global concrete production is 11 billion tonnes annually. This requires approximately 1.87 billion m^3 of fresh water as mixing water and generates 748 Million m^3 of WWW. For instance, in Jordan, there are 10 ready mix concrete companies with around 36 plants which generate around 1.5 million m^3 of WWW per year. While in some countries, like the UK and South Africa, almost all WWW is recycled [6]. The current practices in developing countries is illegal dumping in the city boundaries due to deficiency of government legislative and low care of concrete waste recycling. In many construction sites the construction and demolition waste are mixed together which leads to disallowing of recycling of these parts ([7,8]).

However, the common practice in Jordan is to send this WWW to a landfill or in some cases, illegally discharge this near the construction sites. This is a serious threat to the environment and water resources. Ready mix concrete plants are facing an actual challenge due to the water shortage, and high cost of fresh water, and waste water disposal. Therefore, a novel innovation which inspires new solutions to this challenge will have a direct positive impact on the environment in Jordan and worldwide. In addition, proof of concept of a pilot plant for WWW treatment using efficient, simple and feasible technologies, cost effective and applicable to scale up will lead to produce low cost ready-mix concrete.

This work adds to the existing knowledge around WWW use in concrete. This is because the situation in Jordan is different to many other countries that already use WWW in concrete in that the Hellenic standards used for water quality in Jordan are stricter than the EN (EU) or ASTM (USA) standards used elsewhere (see later), and also because the arid conditions in Jordan can result in higher salinity in soils which can be concentrated in WWW and other recycled water [2].

In this study, the optimum goal was to produce zero waste from the ready-mix concrete industry by filtering and treating WWW for reuse as a mixing water in ready mix concrete plants. In addition, the separated solid powder could be collected and recycled in cement clinker or asphalt mixtures. According to the United States Environmental Protection Agency [9], the filtered wash-water after pretreatment to remove metals and reduce its pH, it can be reused for several applications or it can be delivered to a municipal waste water network. In addition, cementitious solids can be recycled (Table 1). In the UK, according to the Environment Agency [10], it is permissible to treat and reuse concrete wash-waters, and cement fines and silt separated from wash-waters without an environmental permit as long as the activities do not threaten the environment (water, air, soil, plants or animals) and human health or cause noise or odours that affect the countryside.

Previous studies have shown promising results regarding the recycling of ready-mixed concrete waste water in several ratios with fresh water for concrete production [11,12]. Klus et al. [13] reported that recycling the waste water from concrete plant as partial replacement of mixing water (20%, 50%) in mortar production is possible without harmfully affecting the mechanical properties. The results revealed that using WWW led to a 15 min reduction in the setting time and increased the flexural strength as well as the compressive strength at 28 days of age.

Table 1. Reusing of concrete washout waste materials (after EPA, [9]).

Uses of Recycled Materials	Concrete Washout Materials		
	Wash-water	Cement Fines	Fine and Coarse Aggregates
Reused to washout additional mixer truck chutes or drums	X		
Reused as a ready mixed concrete ingredient	X	X [a]	X
Reused as an ingredient of precast concrete products, e.g., highway barriers, retaining wall blocks, rip-rap construction	X	X	X
Reused as crushed concrete products, e.g., road base or filler		X	X
Reused to pave the yards of ready mixed concrete plants			
Returned back to a surface water, e.g., river, lake, or estuary	X [b]		

[a] If allowed by the concrete quality specifications. [b] after neutralization the pH and remove heavy metals, it can be disposed to a municipal waste water network.

Tsimas and Zervaki [14] carried out research on the recycling of waste water from ready-mixed concrete plants. The results revealed that all WWW samples exceed the pH value of 11.5 and they were all classified as hazardous waste and should not be disposed according to European and US legislation. It was observed that all water samples fulfill with the ASTM and EN standard specifications for mixing water used in the production of concrete concerning their chemical properties, but none of them meet with the Hellenic Standards very strict specifications. According to the present study—and in other studies where WWW has been compared to the Hellenic standard [14]—the use of appropriately processed WWW does not harm concrete performance even though it does not fit with the Hellenic Standard. It is in some ways ironic that arid countries such as Jordan have standards that limit the use of recycled water as mix water in concrete without extensive treatment, while less arid countries such as the UK permit the use of WWW without the extensive pre-treatment.

Xuan et al. [15] carried out a review study that focused on all relevant processing of waste from concrete plants and their potential re-use. Currently, washing-out systems have been implemented at many ready-mix concrete plants, and furthermore, reclaiming systems that produce reclaimed aggregates and concrete slurry waste are sometimes used. Even though the potential to re-utilize these forms of waste has attracted a wide range of interest, the methods and principles of the mechanisms of treatments have only been reported in discrete and inconclusive manners. Management challenges associated with poor product performance, low re-utilization rate, high cost and strict regulations continue to limit their sustainable utilization.

The work described in this paper was carried out to characterize WWW from ready-mix concrete plants in Jordan and to evaluate and investigate the potential of reusing the treated WWW in ready-mix concrete using efficient, simple and feasible technologies. A pilot plant for the treatment of WWW was designed and installed in a ready mix concrete plant. Raw and treated WWW samples were collected and analyzed at the Royal Scientific Society (RSS) laboratories. Collected water samples were evaluated for their physical, chemical and biological properties. Concrete mixes using treated water were produced and tested at 7, 28, and 90 days.

The expected outcomes of this study are that a novel innovation, which inspires new solutions to this challenge, will directly impact the environment in Jordan and developing countries. In addition, this research will provide proof of concept of a pilot plant for WWW treatment using efficient, simple and feasible technologies, in a cost effective and up-scalable manner. In addition, it will provide a new water resource to sustain the concrete industry's activities in Jordan and give a clear idea about the potential of WWW reusing for ready mix concrete industry in Jordan.

2. Materials and Methods

2.1. Water

A representative waste wash-water (WWW) sample (400 L) was collected from a basin in a major ready-mix concrete producer in Jordan, which contained 25 m^3 of fresh concrete wash out from the plant, mixer trucks and pumps. It represented a composite sample which accumulated during two working days. In order to prevent sedimentation, waste water was stirred for four minutes every 15 min. 100 L of raw sample were filtered through slow sand filtration system which consisted of four layers of silica sand, and limestone aggregates (fine, medium and coarse). The aggregate was graded where the fine silica sandstone (the smallest particle size) and the coarse aggregates on the bottom of the basin which act as a drainage system. This simple slow sand filter separated all the suspended solids at the top layer and only permitted the water to pass through the backed layers of aggregates. Finally, the separated sediments were removed and scraped from the top layer. At the laboratory scale, sediments can be removed manually by a simple metal tool. However, on a large scale the design allowed a small loader to scrape the sediments from the top layer of sandstone. Figure 1 represents a schematic diagram of recycling process of concrete wash-water. A total of 60 L of the filtered WWW were collected from the laboratory prototype filtration system and stored in a plastic container. A total of 20 L of the filtered water was neutralized to pH 7 using CO_2 gas and stored in a plastic container. Laboratory samples were collected from raw, settling pond, filtered, and neutralized waste wash-water and sent for analyses at RSS laboratories. The samples were tested for physical and chemical properties. The pH value, the total suspended solids (TSS) and the total dissolved salts (TDS) were tested according to SM 2540-C [16]. The evaporation residue represents the summation of TDS plus TSS in water. The chemical oxygen demand (COD) represents all chemicals in water that can be oxidized. It was measured according to SM5220-B [17]. The Biological Oxygen Demand (BOD) represents the consumed oxygen to decompose or oxidize the organic matter by microorganisms. It was measured according to SM5210-B [18]. The total chlorides (Cl^-), sulfates (SO_4^{2-}), and nitrates (NO_3^-) were measured according to SM 4110-B [19].

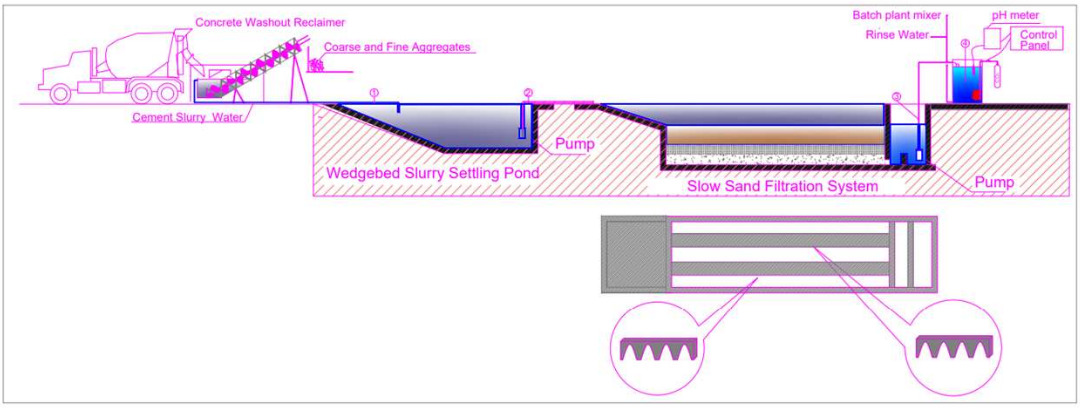

Figure 1. Schematic diagram of recycling process of concrete washout water. As represented in the diagram, the water samples that used in this study were collected from the following points: 1—Raw waste wash-water (WWW), 2—Settling pond WWW, 3—Filtered WWW, and 4—Filtered-Neutralized WWW.

2.2. Aggregates

Three fractions of aggregates (coarse (9.5–19.0 mm), medium (4.8–9.5 mm), and fine aggregates (<4.8 mm)) were used for concrete mixes. The physical properties of the used material were tested according to international standards (ASTM C136-14 [20]) (Table 2). Moreover, the fineness modulus and the recommended proportion of each aggregate type to be used in concrete mixtures were calculated from sieve analyses data.

2.3. Cement

Portland cement (OPC Type I, 52.5 N) manufactured by Qatrana Cement in Jordan was used for preparing concrete mixtures. The physical and chemical properties of the cement are presented in Table 3.

Table 2. The physical properties of the used aggregates.

Aggregate Type	Median Particle Size (mm)	Bulk Specific Gravity (SSD)	Absorption (%)	Fineness Modulus	Recommended Proportioning in Concrete Mixture (wt.%)
Coarse aggregate	14.25	2.68	0.8	6.92	24.0
Medium aggregate	8.96	2.68	1.1	6.36	29.0
Fine aggregate I (crushed limestone)	4.75	2.68	0.9	5.34	12.0
Fine aggregate II (Silica sand)	0.44	2.63	0.2	1.98	35.0

Table 3. The Cement chemical and physical properties. BS EN 196, parts 1, 2, 3, and 6 were used as cement test method [21].

Chemical Properties			Physical Properties		
Parameter	Average Results (%)	Specific Limit	Parameter	Average Results	Specific Limit
SiO_2	21.21		Blaine fineness (cm^2/g)	3430	
Al_2O_3	5.29	≤6.0	Initial setting time (min)	185	≥45
FeO_3	3.92	≤6.0	Final setting time (hour)	3.67	≤6
CaO	62.53		Compressive strength 2 days (N/mm^2)	27.6	≥20
MgO	2.21	≤6.0	Compressive strength 7 days (N/mm^2)	45.39	
K_2O	0.63		Compressive strength 28 days (N/mm^2)	61.1	≥52.5
Na_2O	0.50				
SO_3	2.70	≤4.5%			
Cl	0.06	≤0.1%			
Loss on Ignition	2.93	≤5.0%			
insoluble residue		≤5.0%			

2.4. Concrete Mixes

Based on the mix design, grading of combined aggregates (coarse, medium, and fine aggregate I of crushed limestone, as well as fine aggregate II of silica sand) were chosen to obtain the best grading mix in order to achieve the best workability of fresh concrete. In accordance with BS EN 12350-2: [22], various slump tests were conducted for the fresh concrete and the concretes were designed for a slump of 200 ± 30 mm and compressive strength of 25 MPa (Table 4).

A control mix of concrete was performed using the standard mix design which used at a major ready-mix concrete producer in Jordan (Table 4). The control mix was prepared by well water as mixing water, as used for normal production at the plant.

After the preparation of concrete control mix, well water was replaced by four types of mixing water (raw WWW, settling pond WWW, filtered WWW, and filtered-neutralized WWW) at different percentages (100%, 75% and 25%) in separate mixes. The total number of concrete mixtures was 14, as presented in Table 5. Concrete mixing was performed by using a tilting drum mixer. For each concrete mix, and after the completion of mixing, concrete fresh properties including temperature, and slump were tested according to fresh concrete testing standards EN12350-2 [22] and ASTM C 403 [23], respectively. In order to test the hardened concrete strength, twelve cubes (150 × 150 × 150) mm were cast from each mixture in three layers in the moulds and compacted with the tamping rod. Moulds were covered with plastic sheets and kept in standard conditions (21 ± 2 °C and 100% R.H.) till the next day and cured according to the Jordan standard JS 1652-2 [24], at 21 ± 2 °C and relative humidity of 100%. The samples were taken out from molds and stored for curing in water tank under standard temperature (21 ± 2) °C until testing date. For compressive strength test, specimens were tested at 7, 28, 90, and 180 days age. The average strength of three specimens at each age was calculated in order to compare the results of the different mixtures that were prepared. All strength tests were performed according to JS 1652 parts 3, 5, and 6 [24].

Table 4. Mix designation contents.

Mix Contents	Aggregate Size (mm)	Volume (L/m^3)	Dry Mass (kg/m^3)
Coarse aggregate "Fouliyah"	9.5–19.0	174.9	469.0
Medium aggregate "Adaseyeh"	4.8–9.5	211.4	565.0
Fine aggregate I "Semsmeyeh"	0.0–4.8	87.5	234.2
Fine aggregate II (Silca sand) "Sweileh sand"	0.0–4.8	255.1	688.0
Cement OPC 52.5 N (W/C = 0.56)		88.9	280.0
Total Water		156.8	170.4
Superplasticizer "AdCon SP 500"		5.5	Zero
Air voids		20.0	n.a.
Total		1000.0	2413.2

n.a.: not applicable. Names between " " represent the local names of aggregates.

Table 5. Concrete mixtures names using different mixing water.

Mix No.	Mix Name	Description
1	W100 (control)	Well water 100%
2	F100	Filtered 100%
3	F75W25	Filtered 75% + Well water 25%
4	F25W75	Filtered 25% + Well water 75%
5	FN100	Filtered-Neutralized 100%
6	FN75W25	Filtered-Neutralized 75% + Well water 25%
7	FN25W75	Filtered-Neutralized 25% + Well water 75%
8	A-R100	A * 100% Raw WWW
9	B-R100	B * 100% Raw WWW
10	R75W25	75% Raw WWW A * + 25% well water
11	R25W75	25% Raw WWW A * + 75% Well water
12	S100	Settling basin100%
13	S75W25	75% Settling pond + 25% Well water
14	S25W75	25% Settling pond + 75% Well water

A *: Part of the raw WWW weight is solid content (11.36 wt.%) which was replaced by water to fit the water cement ratio. B *: All the weight of raw WWW considered as water and the suspended solid weight was ignored.

2.5. Data Analysis

All data were statistically analysed using IBM SPSS Statistic Data Editor (Version 19.0). Each data point was measured in triplicate. All parameters were fixed and only the type of mixing water was changed. Statistical significance was evaluated by a general liner model multivariate—Tukey homogeneous subsets multivariate and multiple comparison test at $p \leq 0.05$.

3. Results and Discussion

3.1. Chemical and Physical Properties

The chemical and physical properties of the five used water samples are presented in Table 6. The results show that the raw WWW was caustic with pH value up to 12.6 (hydroxide alkalinity). Based on the raw WWW electrical conductivity (Ec) (11,854 µS/cm) and the total dissolved salts (TDS) (7097 mg/L), it can be classified as high saline brackish waste water. Klus et al. [13] reported that the raw waste water from a ready mix concrete plant has a pH value of 12.5 and Ec of 13,390 µS/cm, indicating the results presented here were consistent with previous research. The high pH was mainly attributed to the dissolved alkali hydroxides such as $Ca(OH)_2$, $Mg(OH)_2$, NaOH, and KOH. According to Tsimas and Zervaki [14], the sludge of the concrete washout waste water consisted of a large amount of $CaCO_3$, small amount of SiO_2 and portlantite $Ca(OH)_2$. The high Ec could be contributed to the dissolved salts and hydroxides as well as the chemical superplasticizer (polyelectrolytes). Tests were conducted to assess whether the superplasticizer affects the mixing water Ec or not. The results revealed that addition of superplasticizer to distilled water at a ratio of 35 mL/L led to an increase in the Ec up to 4400 µS/cm. Moreover, the raw WWW has a high TSS content up to 123 g/L which exceeded the ASTM, EN and Hellenic standard maximum limits of mixing water by a large margin. Moreover, it has a high heavy metals content where the Cr, Ni, Hg, and Pb concentrations were 5.28, 3.50, 5.02, and 0.98 mg/L, respectively. The COD and BOD concentrations were 3216 and 714 mg/L, respectively. The COD and BOD values indirectly represent the organic content in the waste water. One possible explanation of this high content of organic load in the raw WWW was from the chemical superplasticizer as water reducer and retardant. BREINS [25] reported that the superplasticizer consists of a combination of organic and inorganic polyelectrolytes. It is clear that the raw (unfiltered) WWW does not meet the concentrations limits for mixing water from the ASTM, EN or Hellenic standards. However, the Filtered WWW and the filtered–neutralized WWW meet the European and American standards for mixing water (ASTM C 1602/C and M, [26]; EN 1008, [27]; Hellenic Standard 345, [28]).

Table 6. The chemical and physical properties of the used water samples and the standard maximum concentration limits for mixing water as well as the Jordanian standard specifications limits of industrial reclaimed waste water in the event effluent water is discharged into valleys and streams.

Parameter	Well Water	Raw WWW	Filtered WWW	Filtered and Neutralized WWW	ASTM and EN Limits	Hellenic Standard Limits	JS202: 07 Maxi. Limits
Average pH	7.3	12.6	12.7	7.2	<4	6–9	6–9
Ec (µS/cm)	709	11,854	10,190	1533			
Total Suspension Solids (TSS) (g/L)	0	123.4	0	0	>50	>0.8	0.06
Total Dissolved Salts (TDS) (mg/L)	454	7097	2420	1493			2000
Average evaporation residue (g/L)	-	130.5		0.1493			
Alkalies (Na_2O + $0.658K_2O$) (mg/L)	-	481.8	497.3	468.4	>600		
Na (mg/L)		273.8	276.5	283.5	>1000		
K (mg/L)		316.1	335.5	281.0			
Ca (mg/L)		1428.6	188.5	201.0			
Mg (mg/L)		<2.00	<2.00	<2.00			
Chemical Oxygen Demand (COD) (mg/L)	-	3216	48.7	39.5			150
Biological Oxygen Demand (BOD) (mg/L)	-	714	13.4	10.9			60
Sulphate (SO_4) (mg/L)	117	<5.0		14.7	>2000	>270	300
Chloride (Cl) (mg/L)	106	49.7		77.7	>500	>240	350
Nitrate (NO_3) (mg/L)		9.91		10.4			80
Heavy metals							
Cr mg/L	<0.001	5.25	<0.001	<0.001			0.1
Ni mg/L	<0.001	3.55	<0.001	<0.001			0.2
Hg mg/L	<0.001	<0.001	<0.001	<0.001			0.002
Pb mg/L	<0.001	0.98	<0.001	<0.001	0.100		0.2
V mg/L	<0.001	7.57	<0.001	<0.001			

Moreover, the raw and the filtered WWW are classified as hazardous wastes due to their high pH values (<9) and are not permitted to be disposed in the rain fall drain, valleys, river or on soil according to European, USA, and Jordanian legislation ([14]; JS 202, [29]).

The slow sand filtration system using compacted layers of sand stone and limestone aggregates led to a significant reduction in the total suspension solids (TSS), total dissolved salts (TDS), chemical oxygen demand (COD), biological oxygen demand up to 100%, 66%, 98.5%, and 98.1%, respectively. In addition, it led to significant reduction in the heavy metal concentrations of Cr, Ni, Hg, and Pb by 100%, 100%, 97%, and 100%, respectively. The slow sand filtration system had a high efficiency for removing the solid sediments and the organic—as well as heavy metals—content in one step. These results are in agreement with previous published articles. Logsdon et al. [30] and Visscher et al. [31] reported that slow sand filters were able to physically, biologically and chemically treat water. However, the slow sand filter was not capable of reducing the filtered WWW pH value. Although, the filtered WWW meets the EU and ASTM limits for mixing water, it does not meet Hellenic Standard.

The water quality results in Table 6 show that the Filtered–Neutralized WWW using CO_2 gas meets EN, ASTM and Hellenic Standard limits for mixing water. Moreover, it meets all the maximum limits of the Jordanian Standard Specification for industrial reclaimed waste water that effluent water is discharged into valleys and streams [29] except the maximum limit of Hg. Therefore, this reclaimed WWW should be recycled as mixing water and should not be discharged into the environment.

3.2. Fresh Concrete Properties

Figure 2 shows the slump of each fresh concrete sample. The slump value of the concrete mixtures using filtered WWW (F100, F75W25, and F25W75) or filtered–neutralized WWW (FN100, FN75W25, and FN25W75) at various concentrations (100%, 75%, and 25% of total weight of mixing water) show a slight reduction in comparison with the control mixture (W100). In addition, use of WWW from the settling pond (S100, S75W25, and S25W75) showed no significant differences in comparison with the control mixture. Moreover, it is clear that using the raw WWW at various concentrations (A-R100, B-R100, R75W25, and R25W75) led to a significant reduction in the slump. Consistently, the workability dramatically decreased. The dilution of the raw WWW with well water at ratios 3:1 and 1:3 was not enough to meet the slump value and workability of the control mixture. One possible explanation is that the added water (raw WWW) includes solid suspension (TSS) and the dissolved solid (TDS) content that led to a decrease in the actual water/cement ratio [32]. In addition, the total solid content in the raw WWW was 123.4 g/L. This amount represented 1.9% by mass of the total amount of aggregates in the mixture. According to EN 1008 [27], solid material added through mixing water should not exceed 1% by mass of the total amount of aggregates. Although admixture was used in all mixtures (fixed factor), the results revealed that the concrete slump value and its workability were affected by the water quality. This result is consistent with previous studies ([33–35]). However, this disagrees with Tsimas and Zervaki [14] who reported that the slump was not affected by water quality and only affected by using admixtures. In the previous study, waste wash-water samples were only collected from a point after the first settling tank and no real raw waste wash-water samples were used in the experiment. The waste wash-water sample that was used met the standard specification. The admixture in this previous experiment was a variable parameter and not a fixed factor therefore the effect of admixtures on the slump value was investigated rather than the effect of water quality on the slump and workability of concrete mixtures. In the current experiment all parameters were fixed and the only variable parameter was the mixing water quality and quantity.

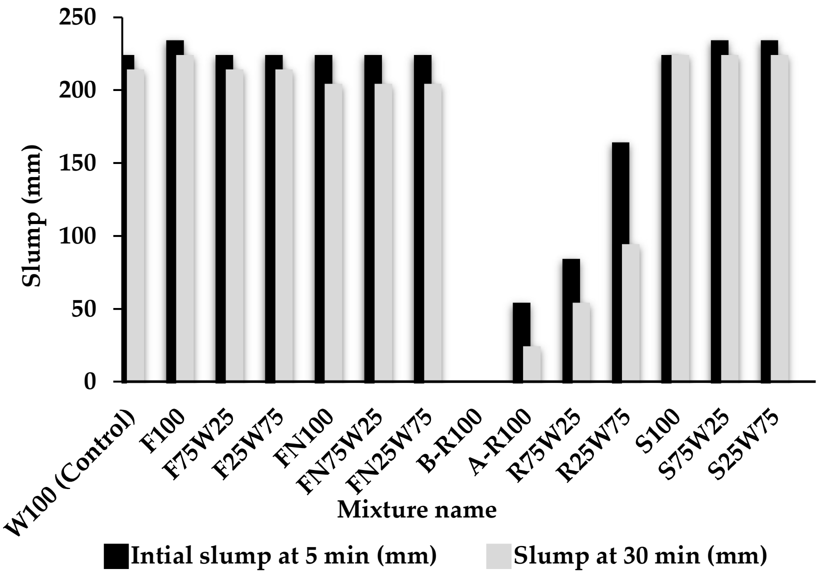

Figure 2. Average concrete mix slump using different mixing water at 5 min and 30 min after mixing. Well water was used as mixing water in control specimen. Mixtures (A-R100, B-R100, R75W25, and R25W75) contain more than 25% raw WWW. Each data point was measured in triplicate.

3.3. Hardened Concrete Properties

The results of concrete compressive strength using raw, settled, filtered, and filtered–neutralized WWW, as well as well water (control) at curing times of 7, 28, and 90 days are presented in Figure 3. It can be seen that there is a trend towards an increase in the compressive strength in the time interval from 7 to 90 days for all mixtures. Ghrair and Al-Mashaqbeh [36] reported that regardless of the type of recycling mixing water there is continuous increase in the concrete compressive strength. Moreover, the compressive strength growth rate is water type dependent.

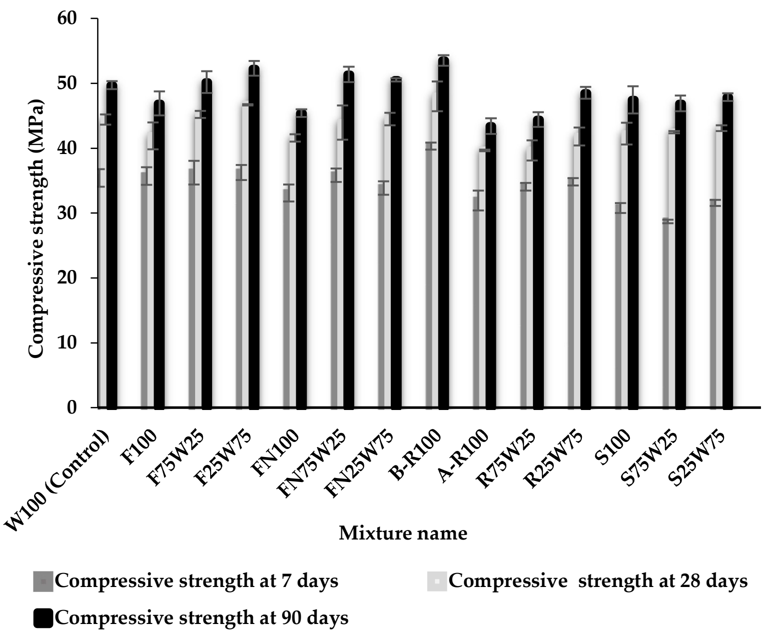

Figure 3. Compressive strength of concrete specimens at 7, 28, and 90 days curing time. Well water was used as mixing water in control specimen. Each data point was measured in triplicate and the error bar stand for standard deviation.

The statistical significance differences in compressive strength at 7, 28 and 90 days were evaluated by a general liner model multivariate—Tukey homogeneous subsets (Tables 7–9). At a curing time of 7 days, the compressive strength values were presented in six homogeneous subsets while at curing time 28 days and 90 days, the compressive strength values were presented in five and nine homogeneous subsets, respectively. The mean compressive strength that are listed under each subset represent a set of mean values that are not significantly different from each other.

Table 7. Statistical significance of concrete compressive strength at 7 days was evaluated by general liner model multivariate—Tukey homogeneous subsets.

Mix Name	Homogenous Subset						Concrete Relative Strength Index (%)
	1	2	3	4	5	6	Control
S75W25	28.700						−18.9
S100	30.767	30.767					−13.1
S25W75	31.567	31.567	31.567				−10.8
A-R100	31.933	31.933	31.933	31.933			
FN100		33.100	33.100	33.100	33.100		
FN25W75		33.867	33.867	33.867	33.867		
R75W25		34.067	34.067	34.067	34.067		
R25W75			34.833	34.833	34.833		
W100 (Control)				35.400	35.400		
F100					35.700		
FN75W25					35.8333		
F75W25					36.2333		
F25W75					36.2333		
B-R100						40.3333	+13.9
Sig.	0.088	0.075	0.081	0.050	0.110	1.000	

Table 8. Statistical significance of concrete compressive strength at 28 days was evaluated by general liner model multivariate—Tukey homogeneous subsets.

Mix Name	Homogenous Subset					Concrete Relative Strength Index (%)
	1	2	3	4	5	Control 2
R75W25	39.667					−10.7
A-R100	39.667					−10.7
FN100	41.567	41.567				
R25W75	41.800	41.800				
F100	41.900	41.900				
S100	42.233	42.233				
S75W25	42.467	42.467				
S25W75	43.067	43.067	43.067			
FN75W25		43.933	43.933	43.933		
W100 (Control)		44.400	44.400	44.400	44.400	
FN25W75		44.467	44.467	44.467	44.467	
F75W25		45.200	45.200	45.200	45.200	
F25W75			46.700	46.700	46.700	
B-R100				48.000	48.000	
Sig.	0.182	0.120	0.120	0.051	0.067	

Table 9. Statistical significance of concrete compressive strength at 90 days was evaluated by general liner model multivariate—Tukey homogeneous subsets.

Mix Name	Homogenous Subset									Concrete Relative Strength Index (%)
	1	2	3	4	5	6	7	8	9	Control
A-R100	43.40									−12.7
R75W25	44.40	44.40								−10.7
FN100	45.40	45.40	45.40							−8.7
S75W25	46.90	46.90	46.90	46.90						
F100	46.90	46.90	46.90	46.90						
S100		47.43	47.43	47.43	47.43					
S25W75		47.87	47.87	47.87	47.87	47.87				
R25W75			48.53	48.53	48.53	48.53				
W100 (Control)				49.70	49.70	49.70	49.70			
F75W25				50.20	50.20	50.20	50.20	50.20		
FN25W75					50.53	50.53	50.53	50.53		
FN75W25						51.37	51.37	51.37		
F25W75							52.30	52.30		
B-R100								53.53		+7.7
Sig.	0.05	0.06	0.12	0.08	0.13	0.05	0.34	0.08	1.00	

The results of statistical significance differences of concrete compressive strength revealed that in comparison with the control (W100) which was prepared by well water, there were no significant differences with all mixtures except S100, S75W25, S25W75, and B-R100. Moreover, S100, S75W25, S25W75 show a reduction in the relative strength index by −13.1%, −18.9%, and −10.8%, respectively. In addition, B-R100 show an increase in relative strength index by +13.9%.

The results of statistical significance differences of compressive strength at 28 days revealed that there were no significant differences between the compressive strength of the control specimens (W100) and all mixtures except mix (A-R100) and mix (R75W25). The mix (A-R100) and mix (R75W25) showed the same reduction in relative strength index by −10.66% (Table 8).

Mixtures A-R100, B-R100, R75W25, R25W75 were made with raw WWW. The only difference between mix (A-R100) and mix (B-R100) is that in mix (A-R100) part of the raw WWW weight was solid content (11.4 wt.%) which was replaced by water to fit the water cement ratio while in B-R100 all the mass of raw WWW was considered as water and the suspended solid mass was ignored. In comparison to A-R100, B-R100 had less free water and more fine powder. Although, using raw WWW in B-R100 led to a significant increase in the concrete compressive strength, it was less workable and had a slump of zero. In comparison with A-R100 at curing time 7, 28, and 90 days, dilution of the raw WWW with well water at ratios of 3:1 (R75W25) and 1:3 (R25W75) led to no significant differences in compressive strength. In addition, the slump increased with an increase in the dilution ratio, but the workability remained low in comparison with the control mixture. One possible explanation is that the mixing water sample used for B-R100 mixture contained more suspension solids (fine powder) and less free water than that required to meet the water cement ratio. Subsequently, B-R100 had zero slump and very low workability. Furthermore, the suspended solids may have acted as a nucleation point for rapid growth of C-S-H as recognized by Cheng and Wang [37].

Statistical significance of compressive strength at 90 days was evaluated by general liner model multivariate—Tukey homogeneous subsets (Table 9). The results showed that there were significant differences in compressive strength between the control specimen (W100) and the following specimens, FN100, A-R100, B-R100 and R75W25, with concrete relative strength indexes of −8.7%, −12.7%, +7.7%, and −10.7%, respectively.

The statistical significance differences of concrete compressive strength at 90 days curing time was evaluated by the Tukey multiple comparison test at $p \leq 0.05$ (Table 10). It revealed that there were no significant differences in compressive strength between control specimens (W100) and the following specimens: F100, F75W25, F25W75, FN75W25, FN25W75, R25W75, S100, S75W25, and S25W75. In addition, there were significant differences with specimens FN100, A-R100, B-R100, R75W25. The significant mean difference ranged from −3.8 to 6.3 MPa. It was clear that there was a full agreement between the statistical results as evaluated by the general linear model multivariate—Tukey homogeneous subsets and that evaluated by the Tukey multiple comparison test at $p \leq 0.05$.

Table 10. Statistical significance differences of concrete compressive strength at 90 days curing time was evaluated by general liner model multivariate—Tukey multiple comparisons test at $p \leq 0.05$.

Dependent Variable		(I) Mix. Name	(J) Mix Name	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Compressive strength at 28 days	Tukey HSD	W100 (Control)	R75W25	5.300	0.956	0.000	1.775	8.825
			R25W75	1.167	0.956	0.994	−2.358	4.691
			S100	2.267	0.956	0.552	−1.258	5.791
			S75W25	2.800	0.956	0.240	−0.725	6.325
			S25W75	1.833	0.956	0.827	−1.691	5.358
			F100	2.800	0.956	0.240	−0.725	6.325
			F75W25	−0.500	0.956	1.000	−4.025	3.025
			F25W75	−2.600	0.956	0.341	−6.125	0.925
			FN100	4.300	0.956	0.007	0.775	7.825
			FN75W25	−1.667	0.956	0.902	−5.191	1.858
			FN25W75	−0.833	0.956	1.000	−4.358	2.691
			A-R100	6.300	0.956	0.000	2.775	9.825
			B-R100	−3.833	0.956	0.023	−7.358	−0.309

HSD: Means for groups in homogeneous subsets are displayed based on observed means. The error term is mean square (Error) = 1.922.

In comparison with control specimens, the statistical results of the compressive strength of mixtures which were prepared with WWW from the settling pond at various dilution factors showed that there was significant reduction in compressive strength: with reductions for S100, S75W25 and S25W100 of −13.1%, −18.9% and −10.8% at a curing time of 7 days. However, there were no significant differences at 28, and 90 days curing time. According to IS 456 [38] and Kucche et al. [39], water is suitable for concrete production if the concrete made with it has a compressive strength reduction of less than 15% in the mean compressive strength of concrete specimens prepared with drinkable water or distilled water. Therefore, the raw WWW and its dilution at a 3:1 ratio are not accepted as mixing water due to the high reduction in compressive strength and the low workability of concrete made by it. It is clear that dilution of the raw WWW is also not a solution.

The current results are not in disagreement with AbdolChini and Mbwambo [40] who reported that the properties of the concrete are not affected by the use of recycled water from the ready-mixed concrete plant. However, this study shows that the quality of recycled water may influence the properties of the concrete. The present results are in harmony with Ghrair et al. [33] and Ghrair and Al-Mashaqbeh [36] who reported that reusing the primary and secondary treated domestic waste water in concrete led to a significant strength reduction of 19.6% and 10%, respectively. In addition, reusing raw grey water and treated grey water in concrete led to a significant reduction in compressive strength up to 13.9% and 2.4% at curing times up to 200 days, respectively. They concluded that treated waste water and grey water can be suitable for concrete production.

4. Conclusions

This study has shown that raw waste wash-water (WWW as it comes from a mixer vehicle) does not meet the current standard maximum concentration limits for concrete mixing water according to EN, ASTM or the Hellenic standard used in Jordan. Test results have shown that this raw WWW also leads to significant compressive strength and slump value reductions as well as poor workability, even after dilution. Moreover, this raw WWW meets the classification for being considered a hazardous waste in Jordan. When the WWW had larger particles removed in a settling pond, it still did not meet the water quality standards. However, when it was used to replace 75% of the mix water it did not result in statistically significant strength reductions at the 95% confidence level, and there were no major implications for workability. Consequently, this indicates that the EN and ASTM standards for mix water may have a degree of conservatism built into them since water outside their boundaries appears to be at least partially suitable as mix water.

When the water was passed through the settling pond was filtered, the quality did improve to the point where it met the EN and ASTM standards for mix water, but still did not meet the Hellenic standard, mainly because the pH was still too high. As with the water in the settling pond, there was no significant strength reduction or workability concerns when it was used as mix water.

In order to meet the Hellenic standard, as well as the Jordanian Standard Specification for industrial reclaimed waste water (JS 202, 2007), the pH was reduced through carbonation by the addition of CO_2. However, the additional cost of carbonation is difficult to justify because the results showed no benefit to concrete properties in meeting this stricter standard when compared to the EN and ASTM standards.

In conclusion, WWW is a potential new water resource to sustain the ready-mix concrete industry activities in Jordan. Moreover, this research will provide proof of concept of a pilot plant for WWW treatment using efficient, simple and feasible technologies, in a cost effective and up-scalable manner. This will directly impact the environment in Jordan and worldwide as well as for millions of people around the world. In addition, the option of developing a Jordanian standard based on further scientific studies using local materials should also be considered.

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