FRESH AND HARDENED PROPERTIES OF FIVE NON-POTABLE WATER MIXED AND CURED CONCRETE: A COMPREHENSIVE REVIEW

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Abstract

Potable water is an essential component of concrete as it is actively involved in the hydration and setting of concrete. Due to overpopulation, urbanization, and lack of proper water resource management, the available freshwater does not meet the demand resulting in water scarcity. Globally half of the world’s population is expected to suffer from a lack of access to proper water by 2025. The cumulative water consumption for concrete production was 16.6 km^3 annually. This review paper emphasizes the effects of mixing and curing of five alternate non-potable water such as seawater, wash water from ready mix concrete (RMC) plants, greywater, wastewater from the sewage treatment plants, and magnetized water on the fresh and hardened properties of concrete to enhance the sustainability in concrete industry. Based on the globally published (75 research articles until 2021), the effects of replacing potable water for mixing and curing of concrete with other sources are discussed in detail. The fresh and hardened properties of concrete mixed and/or cured with five non-potable water depends greatly on the salt concentration, total solids, treatment type and magnetization level.

Keywords*:* Non-potable water sources, Compressive strength, Seawater, Magnetized water, Durability.

Highlights

- Effects of non-potable water on mixing, curing and fresh properties of concrete were reviewed.

- Detailed discussion on the compressive strength and durability properties of concrete mixed and cured with non-potable water.
- Microstructural analysis using Scanning Electron Microscope (SEM) of cement paste/concrete by non-potable water sources was studied.
- Future recommendations are suggested to use non-potable water for concrete production.

1. Introduction

Water is aptly called an elixir of life. About 71% of the Earth's hydrosphere is water-covered, and only 3% of the available water are considered to be "freshwater". Furthermore, about 80% of this freshwater is trapped as ice in the polar caps and cannot be accessed by humans. This leaves us with roughly 0.5% of the earth's water is usable and drinkable [1]. In the past 100 years, due to overpopulation, urbanization, climate change, pollution, poor water resource management and environmental factors, the freshwater demand does not meet the water supply that resulted in global water scarcity [2].

Besides water, concrete is the second most widely used material on this planet. Water is responsible for the strength gain, workability, and overall durability of concrete as it is responsible for its hydration [3]. Generally, it is accepted that any potable water is suitable for drinking and making concrete. However, the construction industry is water-consuming and contributing to the country's Gross Domestic Product (GDP). The largest cement-producing countries are China and India with 2.2 billion and 320 million metric tons in 2019 [4] under global water stress conditions by 30% and 40%, respectively. To reduce the water stress in the construction industry, various alternative water types are being used as mixing water to the concrete. Fortunately, different countries have shown interest in reusing non-potable water when possible. Seawater (SW), Wash water from Ready Mix Concrete plants (WWRMC), Greywater (GW), Treated Sewage Wastewater (TSWW), and Magnetized water (MW) were experimented in concrete for mixing and curing. Seawater (SW) can pose many negative effects on concrete due to the high concentration of salts. Roman Concrete structures such as Pantheon and Colosseum arena are more durable and long-standing for more than 2000 years by using SW with a mixture of volcanic ash and lime. In United Arab Emirates (UAE), water used for concrete production is desalinated seawater [5]. Many researchers suggested incorporating mineral admixtures such as Blast Furnace Slag (BFS) for seawater concrete which enhanced the corrosion resistance steel reinforcement [6]. In Germany, Recycled water (RW) or WWRMC were used for mixing water for concrete production [7]. Using treated wastewater not only helps to use non-potable water in producing concrete but also has the merits of minimizing the high cost of wastewater treatment [8]. By using MW in concrete resulted in the enhancement of mechanical properties. The quality of water used for mixing plays an important role in concrete's fresh and hardened properties. The permissible limits of constituents of mixing water in concrete as per Indian Standard IS 456 (2000) [9], American Society for Testing and Materials, ASTM C1602 (2018) [10], British Standard BS EN1008 (2002) [11], and Australian Standard AS 1379 (2007) [12] are listed in **Table 1.**

Table 1

Performance Requirements for mixing water by international standards

Standards	Compressive strength	Setting time	Chemical limits
American Standard ASTM C1602(2018)	7-day strength of non-potable water mixed concrete/mortar ≥ 90% of control specimen with 100% distilled or potable water	From 1 hr early to 1hr:30 min later than control specimen	SO_4^{2-}: ≤ 3000 ppm $Cl^{-\,(a)}$: ≤ 500 ppm $Cl^{-\,(b)}$: ≤ 1000 ppm TS: ≤ 50000 ppm TSS: ≤ 2000 ppm Alkalis: ≤ 600 ppm
British Standard BS EN 1008-(2002)	7-day strength of non-potable water mixed concrete/mortar ≥ 90% of control specimen with 100% distilled or potable water	Initial set ≥ 1 hr and final set ≤ 12 hr with both do not differ by more than 25% from control specimen time	SO_4^{2-} : ≤ 2000 ppm $Cl^{-\,(a)}$: ≤ 500 ppm $Cl^{-\,(b)}$: ≤ 1000 ppm $Cl^{-\,(c)}$: ≤ 4500 ppm pH: ≥ 4
Indian Standard IS 456(2000)	28-day strength of non-potable water mixed concrete/mortar ≥ 90% of control specimen with 100% distilled or potable water	Initial set ≥ 30 min and not differ by ±30 min from the control specimen time	SO_4^{2-} : ≤ 400 ppm $Cl^{-\,(b)}$: ≤ 500 ppm $Cl^{-\,(c)}$: ≤ 2000 ppm TSS: ≤ 2000 ppm pH: ≥ 6

Australian Standard AS 1379(2007)	7- and 28-day strength of non-potable water mixed concrete/mortar ≥ 90% of control specimen with 100% distilled or potable water	From 60 min earlier to 90 min later than control specimen time	pH:>5, Sugar:100 ppm, Oil & grease: 50 ppm Chloride and sulfate content are described for concrete rather than mixing water. Acid soluble SO_3 ion content of hardened concrete ≤ 50g/kg of cement. Acid soluble Cl^- ion content of hardened concrete ≤ 0.8 kg/m^3

Note: SO_4^{2-} - Sulfate ions, Cl^- - Chloride ions, (a) = in prestressed cement concrete, (b) = in reinforced cement concrete, (c) = in plain cement concrete, TS – Total solids, TSS – Total suspended solids.

The motivation for this comprehensive review was to assess the possibility of using 5 non-potable water such as Seawater (SW), Wash water from Ready Mix Concrete plants (WWRMC), Greywater (GW), Treated Sewage Wastewater (TSWW) and Magnetized water (MW) for mixing and curing of normal concrete by studying their effects on fresh and hardened properties in a broad picture. Furthermore, detailed discussions on the microstructural properties were also made for the concrete mixed and cured with the above five non-potable water using SEM images from the published works of literature.

2. Methodology and Scope

This review was conducted using a conventional content analysis method where information is derived directly from the publications to scope the potential use of 5 non-potable water for concrete production. The collected publications are segregated based on the following parameters: Binder is ordinary Portland cement, and Supplementary Cementitious Materials (SCMs) are not incorporated. The water-cement ratio is in the range of 0.35 – 0.50. Aggregates such as river sand or Manufactured sand (M sand) are selected. The influence of 5 non-potable water on the fresh properties, mechanical property (compressive strength at 7 and 28 days of curing) and durability properties are presented in this review article. The compressive strength results of concrete specimens were represented as percentage change compared with control specimens. The detailed methodology of this review article is given in the form of a flowchart in **Fig. 1.**

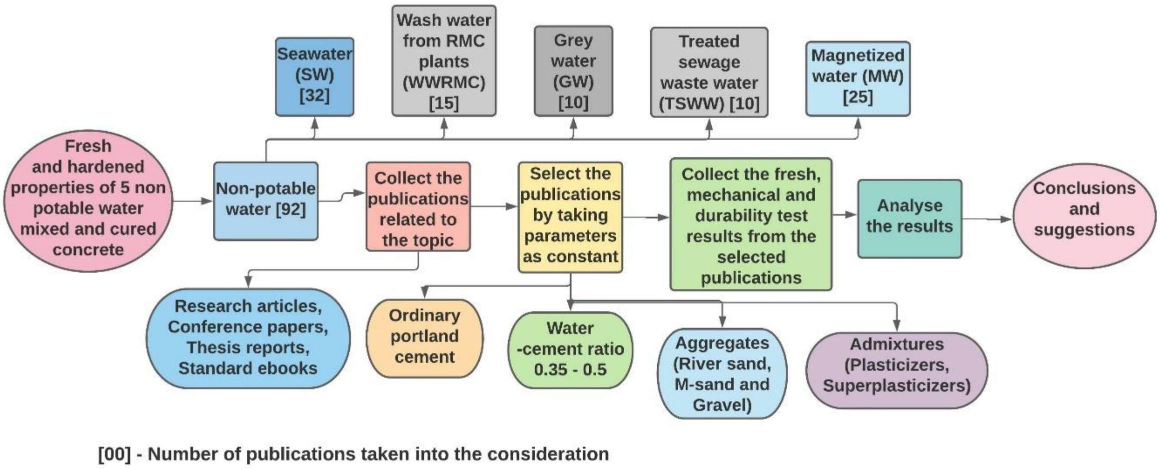


Fig. 1. Methodology flowchart

3. Non-potable water for mixing and curing of conventional concrete

Based on the numerous literature and case studies worldwide on using different types of non-potable water in concrete, a comprehensive and systematic literature review covering the articles on substituting non-potable water for mixing and curing on the fresh, mechanical, and durability properties of concrete are discussed. Therefore, up-to-date literature for the past 20 years has been identified (110 literature), out of which 95 articles that extensively focused on the replacement of water in concrete are discussed in this review article. This review article encompasses the existing reports on the use of SW, WWRMC, GW, TSWW and MW to better understand its effects on concrete. Moreover, this is the first study to review the effects of using different sources of water apart from potable water for developing concrete.

3.1. Seawater (SW)

Seawater is salty and has an average total salinity of 35 parts per thousand (ppt), of which typically has around 78% of sodium chloride (NaCl) [13]. The most important components of SW that influence the concrete are salinity, dissolved gases (mostly oxygen and carbon dioxide), and pH. It was reported that there was a strength gain and no significant corrosion of mild steel when the salinity of 25 g of salt per kg of solution [14]. The major ions such as chloride (Cl^-) contribute around 50 to 55% of total ions in SW [15–17]. Sodium ions (Na^+) contribution was 30% of total ions in SW [15–17]. The ratio of chloride/hydroxyl ion (Cl^-/OH^-) plays an important role in protecting the passivation layer around the reinforcement [18]. Chlorides present in SW can penetrate through concrete and accelerate the corrosion rate of reinforcement in concrete by destabilizing the passivation layer around the reinforcement [18,19]. It is known that chloride ion presents inside the concrete in two forms, free and immobilized. The water-soluble Cl (free) ions directly destroy the passivation film around the reinforcement bars resulting in corrosion [6]. Sulfate ions (SO_4^{2-}) cause sulfate attack on cement paste and lead to cracking [19–21] and reduced the chloride binding capacity of cement paste [19]. Sodium (Na^+) and Potassium (K^+) ions intensify the alkali-aggregate reaction if reactive aggregates are used [19,22,23]. High contents of chloride and sulfate ions affect the pH of water, which has a notable impact on the strength gain of concrete [21]. The pH value of SW varies between 7.4 and 8.4. If pH is below 11, there is a high chance of corrosion in reinforcement [19].

3.2. Wash water from Ready-Mix Concrete plant (WWRMC)

Ready-mixed concrete plant operations are the largest consumers of water. Producing one cubic meter of concrete in these plants requires around 200 liters of potable water. Therefore, around 500-700 liters of wash water is required for a single truck to transport concrete [24–26]. The water and concrete mix created through the cleaning process of the exterior and interior of the concrete trucks, the chutes, concrete pumps, and tools are known as concrete wash water [27]. The wash water obtained from the plants has a very high pH level (ranging from 12 to 13) due to large quantities of limestone solids [28]. Also, there are traces of heavy metals present in the WWRMC, which can decrease the homogeneity of concrete, thereby affecting the structural integrity. Therefore, WWRMC obtained from washing the trucks is recycled in specially designed tanks to remove solid particles and reduce other unwanted elements in the water. Since a huge amount of water is used in concrete plants, the disposal and recycling of this wastewater have become an environmental concern [29]. **Table 2** shows the physical and chemical properties of WWRMC.

Table 2

Physical and Chemical properties of Wash Water from Ready Mix Concrete plants (WWRMC)

Properties	Unit	References		
		Bahraman et al. (2021) [30]	Ghrair et al. (2020) [31]	Mohammed et al. (2016) [28]
pH	-	13	12.6	13.05
SO_4^{-2}	mg/L	439	5	685
Mg^{2+}	mg/L	6	2	-
Cl^{-1}	mg/L	191	49.7	88
TDS	mg/L	2380	7097	5890
COD	mg/L	196	3216	-

Total Dissolved Solids (TDS), COD – Chemical Oxygen Demand

It is observed from **Table 2**, WWRMC was caustic with a pH value of 13 (Hazardous), and this is due to the presence of dissolved alkali hydroxides such as $Ca(OH)_2$, $Mg(OH)_2$, NaOH and KOH. This alkali hydroxide can cause an Alkali-Silica reaction (ASR). Therefore, according to the United States Environmental Protection Agency (USEPA), Total Dissolved Solids (TDS) are classified as secondary contaminants.

3.2.1. RMC wastewater management practices

The common ways to handle wash water from RMC's includes:

- Baton wash technology was adopted by Ultra tech RMC company in India from 2011 to achieve the status of zero discharge plant. A zero discharge plant is termed to separate the solid materials from WWRMC that can be reused in concrete production [32].
- Using chemical compounds like calcium carbonate ($CaCO_3$), barium chloride ($BaCl_2$), disodium hydrogen phosphate (Na_2HPO_4), sodium hydroxide (NaOH), sulfuric acid (H_2SO_4), and ferrous sulfate ($FeSO_4$) to remove heavy metals from wash water samples in Dubai [28].
- Matec’s Concrete Water Recycling (CWR) Plants are designed to recover and re-use washing water by automatically filtering out the solids without chemical additives. It

will also provide a manageable solid without the need to clean out weir pits. In addition, CWR allows recovering aggregates (sand and stone using a screw separator) which can be further separated if desired (using a dewatering screen) to provide sand and stone products. Finally, the remaining cement slurry water is sent to the filter press for filtration and dewatering, returning approximately 90% – 95% of water back for reuse. The stages of RMC wash water treatment process are depicted in a pictorial form as shown in **Fig. 2.**

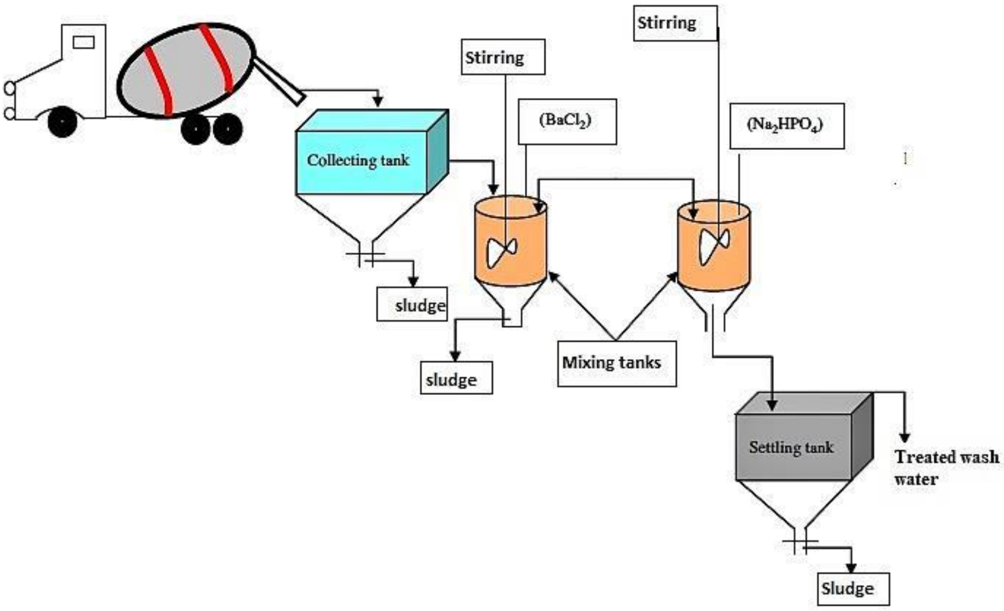


Fig. 2. Stages of RMC wash water treatment [28]**.**

3.3. Greywater (GW)

Household wastewater is mainly divided into greywater and black water. Blackwater, the wastewater obtained from toilets, cannot be directly recycled and used due to sanitary issues. Greywater (GW) is wastewater that consists of all domestic wastewater except for toilet wastewater [33–36]. Based on the concentration of contaminants in the sources, GW is divided into two types: Light Greywater (LGW) and Dark Greywater (DGW). Wastewater collected from bathroom sinks, bathtubs, hand basins, and showers are classified as LGW, whereas wastewater from washing machines, kitchen, and dishwashers contribute as DGW [33]. The pH of GW depends on the pH and alkalinity of the water supply [37]. The workability of concrete depends on the Total Dissolved Solids (TDS) of water. Higher TDS concentration in the water reduces the workability of fresh concrete by increasing the specific surface area of the fine materials in the concrete [38]. Chloride permeability resistance of concrete will be adversely affected due to an increase in TDS of water [38]. **Table 3** provides the physical and chemical properties of GW**.**

Table 3

Physical and chemical characteristics of Greywater (GW)

Characteristics of GW	Parameters	RGW	RGW	TGW	RGW	RGW	Maximum concentration^{a}
		Kaboosi et al. (2019) [39]	Ghrair et al. (2018) [34]		Peche et al. (2015) [40]	Alqam et al. (2012) [41]	
Physical	TSS (mg/l)	80	436	2	170	140	2000
	TDS (mg/l)	1184	980	803	-	403	2000
Chemical	pH	7.9	7.5	7.9	7.9	7.3	6-8
	BOD_5 (mg/l)	196	536	2.98	18	100	-
	COD (mg/l)	310	900	6.97	29	640	500
	Chloride (mg/l)	269.5	243	208	26	265	500
	Sulfate (mg/l)	153.7	222	137	1.4	95	2000

TDS – Total Dissolved Solids, TSS – Total Suspended Solids, BOD – Biochemical Oxygen Demand measured at 5 days, COD – Chemical Oxygen Demand, RGW – Raw Grey Water, TGW – Treated Grey Water, ^{a} Permissible limits of mixing water according to ASTM C94 (2018) [42].

The biodegradability of GW is determined by BOD_5/COD ratios [37]. BOD is the standardized unit for measuring organic water pollution. BOD_5/COD ratio determines the ease with which bacteria can decompose the organic matter in the GW. It is observed from **Table 3**, that the BOD_5 /COD ratio falls in the range between 0.15 – 0.62. The value of BOD_5 should be low for clean water, and hence the TGW sample had low BOD_5 values. Low BOD_5 GW concrete specimens can perform well than high BOD_5 GW concrete. An increase of COD results in more reduction of mechanical and durability properties of concrete. More COD means more pollution leads to high permeability, especially in a high water-cement ratio.

According to ASTM C94 (2018) [42] and the IS 456 (2000) [9], both types of GW are suitable for concrete productions. The characteristics of GW cannot be unique as it depends on several factors like age and number of occupants, various sources, living standards, types of detergents used [43].

3.4. Treated Sewage Wastewater (TSWW)

Wastewater is defined as "a combination of one or more of domestic effluent consisting of blackwater (excreta, urine, and fecal sludge) and greywater (hand basin, kitchen, laundry, and bathing wastewater); water from commercial establishments and institutions, including hospitals, industrial effluent, stormwater, and other urban runoff, agricultural, horticultural and aquaculture effluent, either dissolved or as a suspended matter [44]. **Table 4** outlines the characteristics of TSWW.

Table 4

Characteristics of Treated Sewage Wastewater (TSWW)

Characteristics	Parameters	Sheikh et al. (2020) [8]	Kaboosi (2017) [45]	Asadollahfardi et al. (2016) [46]
Physical	pH	8.1	7.73	7.7
	Turbidity (NTU)	13.5	30	12
	TSS (mg/l)	-	29	30
Chemical	COD (mg/l)	160	80	93
Biological	BOD_5 (mg/l)	50	44	30

All the above parameters shown in **Table 4** are in the acceptable range [42], and hence the TSWW can be used for concrete production.

3.5. Magnetized water (MW)

Magnetic field (MF) treated water is also called Magnetized water (MW). Two main ways of making MW have been reported. The first is passing water through a MF, and the other is using a static magnet near a certain volume of water. The MF strength and the time of magnetization greatly impact the properties of MW [47]. The water passing through a magnetic field is broken down into smaller molecules, making it easier to pass through cement particles readily, thereby improving the hydration process [48,49]. The magnetization process changes the properties of water. The strength of the magnetic field and duration of exposure are the main factors that influence the properties of MW. [50–52]. The properties of MW are different from that of normal potable water. MW is also widely used in industry, medicine, and the agricultural field due to its specific properties [53]. The influence of magnetism on the properties of water is as follows: surface tension of pure water decreases while applying MF [47,53–55], and viscosity increases [47].

4. Effects of non-potable water on fresh properties of concrete

Seawater (SW) effects on the fresh properties such as workability and heat of hydration are explained in this section: The density and yield of the fresh concrete are similar to both the mix of Fresh water (FW) and SW concrete. However, there is a notable reduction in workability and initial setting time (about 30%) when using SW in concrete. This was due to the Cl ions, which are known to speed up the hydration process [56]. In addition, chlorides are known to accelerate cement hydration [56–59]. Thus, there are two reasons for accelerating the effect of chloride ions in hydration, as illustrated in Equations 1 and 2.

$$CaCl_2 + 3Ca\,(OH)_2 + 12H_2O \rightarrow \underset{\text{(Calcium Oxychloride)}}{3\,Ca\,(OH)_2.\,CaCl_2.\,12H_2O} \qquad (1)$$

$$C_3A + 2\,NaCl + Ca\,(OH)_2 + 10H_2O \rightarrow \underset{\text{(Friedel's salt)}}{C_3A.CaCl_2.10H_2O} + 2Na^+ + 2(OH) \qquad (2)$$

First, the $CaCl_2$ from SW would react with cement hydration product as $Ca\,(OH)_2$ to form insoluble solid phase calcium oxychloride. During this reaction, chloride reduces the alkalinity and promotes the dissolution of cement particles, thus accelerating cement's hydration. Secondly, Sodium chloride (NaCl) reacts with C_3A and form Friedel's salt [60] as shown in Equation 2. Friedel's salt can chemically immobilize chloride ions and reduce the presence of free chloride ions in the pore solution. This is an effective measure to manage seawater concrete with steel reinforcement. Faster hydration of SW cement paste is due to NaCl, $MgCl_2$, and $CaCl_2$ [16]. There is no difference in the hydration reaction rate of SW cement paste at later ages [17,56]. SW cement pastes showed the peak of heat flow 35 % increase and 102 minutes earlier in peak time over FW cement paste. No difference was observed in the heat flow rate at 40 hours due to SW [17]. The exothermic peak appeared 90 min earlier in SW cement paste compared to FW cement paste, and the peak value was 41% higher than FW cement paste [16].

The exothermic peak appeared 100 min earlier in SW cement paste than DW cement paste, and the peak value was 19% higher than Demineralized water (DW) cement paste [61]. The cumulative heat developed in SW cement paste was 1.12 times higher than Deionized water (DI) cement paste for 72 hours [62]. The maximum heat flow of SW cement paste was 104 min earlier than FW cement paste, and the corresponding peak value was 35% higher than FW cement paste [56].

WWRMC or Recycled water (RW) effects on the fresh properties of cement/concrete like workability, setting time, and heat of hydration are discussed as follows: RW concrete exhibited a slump lower than the control specimens [63–66], and higher in RW content resulted in an increase in water demand [67]. The slump value for WWRMC concrete varied between 12 to 15 cm [68]. WWRMC contains porous sediments that require more water for hydration, resulting in increased slump loss than the control concrete [63]. The cement made with WWRMC had the highest setting time (150 minutes) than tap water-cement specimens (140 minutes) [68]. Incorporating 100% RW increased the heat flow peak by 9% compared to the control concrete specimen. In addition, the alkaline pH of RW enhanced the cement hydration [67].

Greywater (GW) effects on the fresh properties like setting time and workability of cement/concrete are explained as follows: Using RGW and TGW led to a decrease in the slump of 26% and 31% than control specimens [34]. This might be due to the presence of TDS in GW, and it is consistent with the previous study [69]. The initial setting time of cement made with RGW and TGW was 20 and 25 minutes later than control specimens. The presence of TDS, TSS and organic materials in RGW and TGW led to an increase in the water-cement ratio resulted in a longer setting time [34]**.** There was little or no effect of TGW on the setting time of cement paste [41]**.**

Treated Sewage Wastewater (TSWW) mainly depends on water content, presence of solids [70]. The slump value and workability of tertiary treated wastewater (TTWW) and secondary treated wastewater (STWW) were reduced due to the presence of solids and sludge content. The porous surface of sludge particles has a high absorption ability and therefore decreased the slump value by 25% and 50% for TTWW and STWW, respectively, compared to control concrete [70]. Incorporating the TSWW in concrete samples increased initial and final setting times compared to control concrete [71] but were satisfactory based on international standards [42].

Magnetized water (MW) enhances fresh properties like workability and heat of hydration. The effect of magnetization leads to a 32% increase in the slump value of concrete, and it is due to the decrease in viscosity and an increase in the surface area of the mixture [72,73]. The use of MW can also reduce the amount of cement used in concrete. The cement content was reduced up to 75% without affecting the compressive strength [73]. Less slump and slump retention were achieved when stored MW (3 days) was used. However, the slump values for the stored MW concrete are higher than those for the concrete specimen containing potable water. This shows that storing MW had a negative impact on the slump and slump retention [74]. Low heat of hydration (99.4 Cal/gm) was observed for the cement mixed with MW than normal water, resulting in reducing thermal stress and avoiding the cracks at early ages in concrete [75].

5. Effect of non-potable water on compressive strength of concrete

SW mixing leads to an increase in compressive strength (10%) of concrete at early ages (upto 7 days) [19, 56, 76–78]. The compressive strength of mixtures with Sea-sand (SS) in SW concrete was approximately 10% higher than control specimens cured at 7 days [80]. This behavior is due to the acceleration effect of chloride ions present in seawater and sea-sand on cement hydration and this is compatible with previous studies [19,20,56,61,78,79,81]. Probable reasons for an early age strength gain are faster cement hydration, ettringite formation, and Friedel's salt in the air voids in concrete [77]. There was an increase in compressive strength of 24% at 56 days [79] due to the presence of rich chloride ions in the SW, but the long-term compressive strength of concrete (90 days) with SW exhibited poor behavior compared to ordinary concrete [19]. The crystallization of the salts present in SW was the reason for the lesser long-term strength of SW concrete. The presence of magnesium sulphates ($MgSO_4$) in SW leads to the formation of magnesium hydroxide and gypsum after reacting with cement. These compounds will exert expansive crystallization pressure that decreased the concrete strength [19], and the high early strength was due to the blocking of pores by the expansive crystallization, and the later reduction in strength was due to the leaching of the crystals due to environmental factors. The early age compressive strength of concrete is shown in **Fig. 3.**

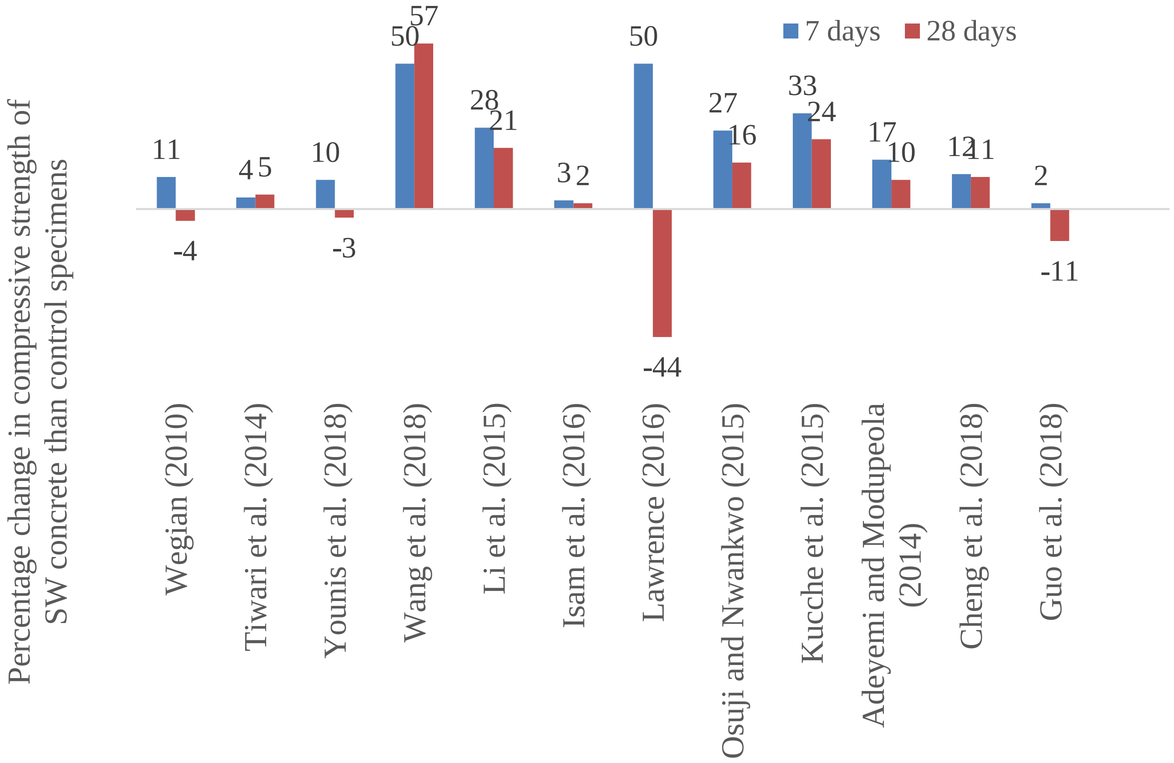


Fig. 3. Percentage change in compressive strength of SW concrete at 7 and 28 days curing regime [19,20,56,62,79,82–88].

The percentage change in compressive strength of SW concrete at 7 days exhibited 10% more than control specimens from many literature, as shown in **Fig. 3**. The term control specimens indicate that the concrete specimens are casted using potable water (Tap water, Freshwater, Distilled water and Deionized water) and natural aggregates. Few literature results showed a negative impact on the compressive strength at 28 days [83].

WWRMC concrete specimens attained up to 18% higher compressive strength than the control specimens [67]. A similar increase in the compressive strength was also observed in the concrete specimens with WWRMC at an early age [66]. This strength gain can be interesting in precast concrete applications, which require high strength in a few hours. However, increasing the WWRMC content reduced the compressive strength of the concrete [63,67]. This is due to the requirement of higher amounts of water to reach the required slump. Therefore, the compressive strength of concrete tends to decrease with an increase of WWRMC [64]. The compressive strength of WWRMC concrete without superplasticizer was between 92 and 96% of the control specimens measured at 1, 3, 7, 28, 56, and 91 days of curing, respectively [63]. The percentage change in compressive strength of WWRMC concrete than control specimens is shown in **Fig. 4.**

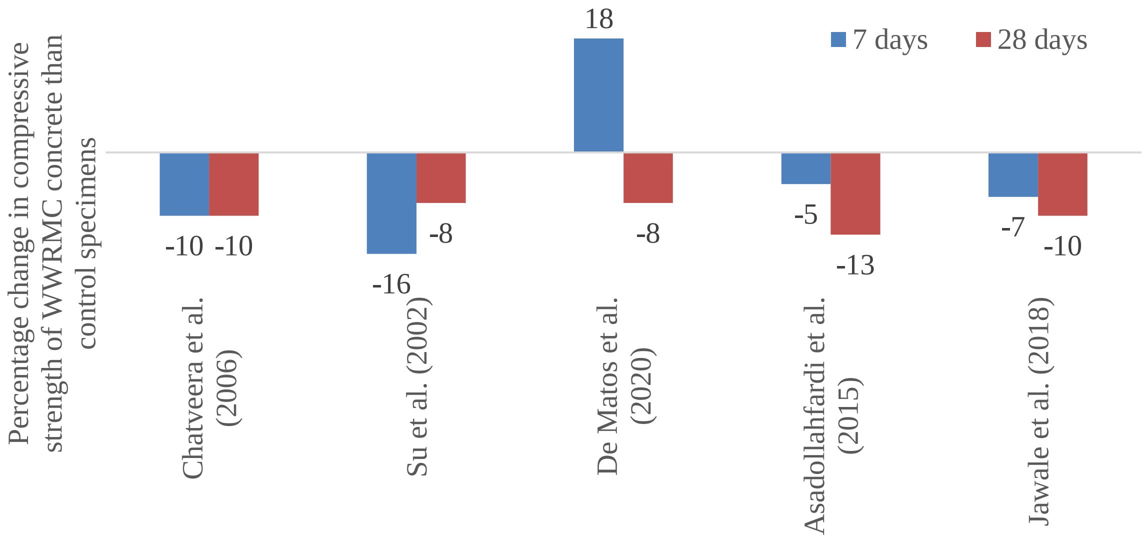


Fig. 4. Percentage change in compressive strength of WWRMC concrete at 7 and 28 days curing regime [64,66–68,89,90]**.**

From **Fig. 4**, it is inferred that the reduction in compressive strength at 28 days crossed the 10% line. However, few test results showed a positive impact on 28 days compressive strength.

RGW concrete shows a reduction in the compressive strength of up to 7.7% and 13.9% at 28 and 120 days [34], which was well within limits specified in IS 456 (2000) [9]. Few literature regarding the effect of GW on the compressive strength of concrete is shown in **Fig 5**. From **Fig 5**, there is a slight positive trend in the compressive strength of GW mixed concrete than control specimen**.**

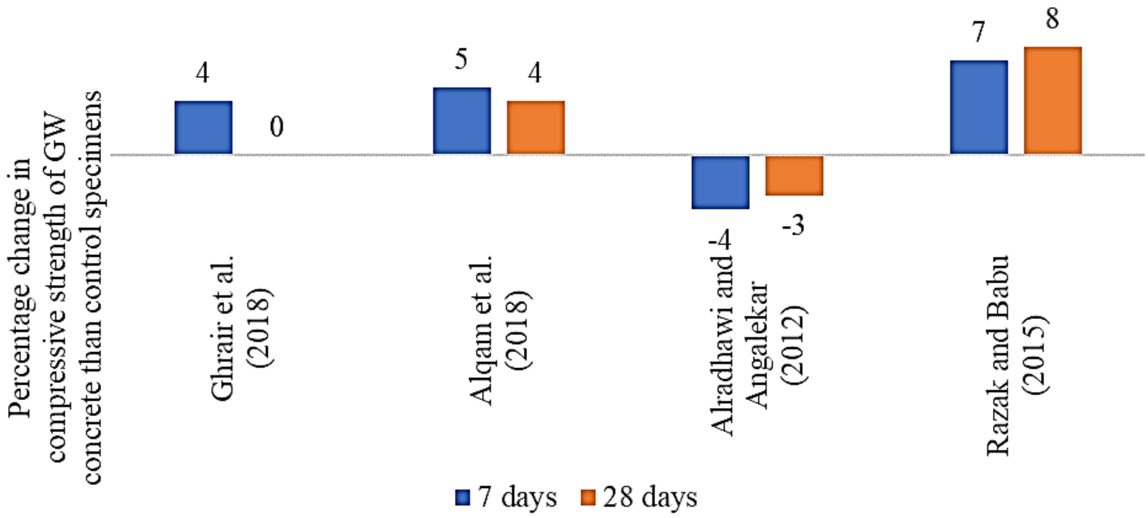


Fig 5. Percentage change in compressive strength of GW concrete at 7 and 28 days curing regime [34,41,91,92].

The researcher found that converting ettringite into mono sulfate aluminates and the resultant dissolution during the hydration process due to the increase in the **TSWW** content reduced the compressive strength by 14.70% at 7 days, 14.32% at 28 days. This was also due to the formation of the thickness of the duplex film layer within the interfacial transition zone between cement paste and aggregate, which decreases the compressive strength of concrete [70]. As a result, the compressive strength of TSWW concrete at 28 days decreased to between 93 to 96% of the compressive strength of control specimens [46]. The percentage change in compressive strength of TSWW concrete over the age of concrete from a recent literature study is shown in **Fig. 6.**

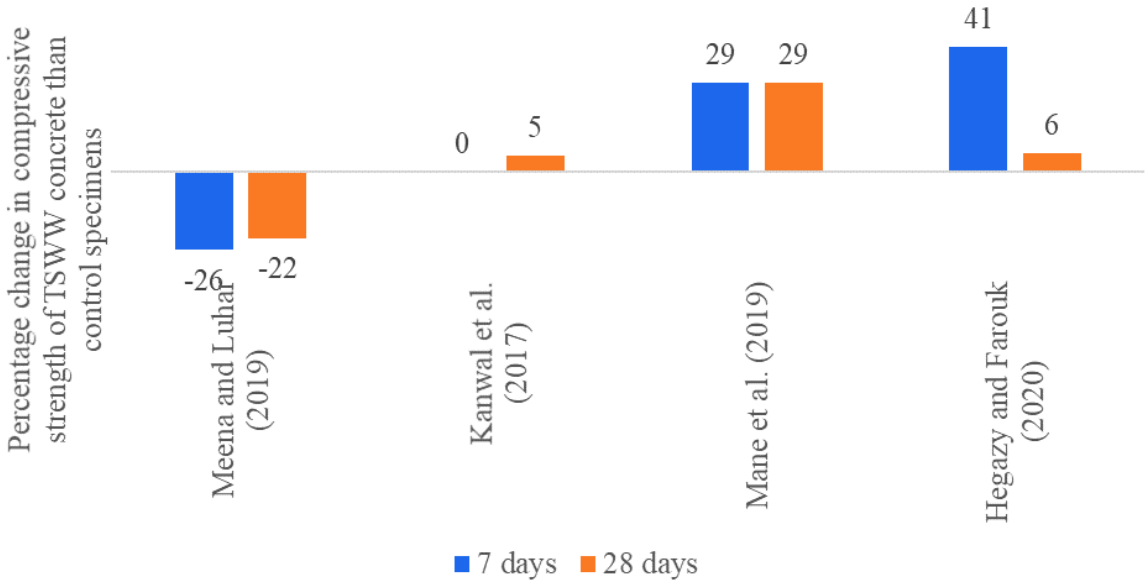


Fig. 6. Percentage change in compressive strength of TSWW concrete at 7 and 28 days curing regime [70,93–95].

MW acts like water mixed with superplasticizers by reducing the thickness of the water layer around the cement due to the smaller size of the water molecules in MW [49,50,96]. The compressive strength of MW concrete increased to 30% when the magnetic strength is 260 milli Tesla and the length of the magnetic field is 280 mm than control specimens [97]. The increase in strength was due to the high hydration rate of cement [72]. It was found that storing MW had a negative impact on compressive strength [74]. MW is more active than tap water during the hydration process, leading to increased compressive strength [97]. The percentage change in compressive strength concerning freshwater against the age of concrete is shown in the **Fig. 7.**

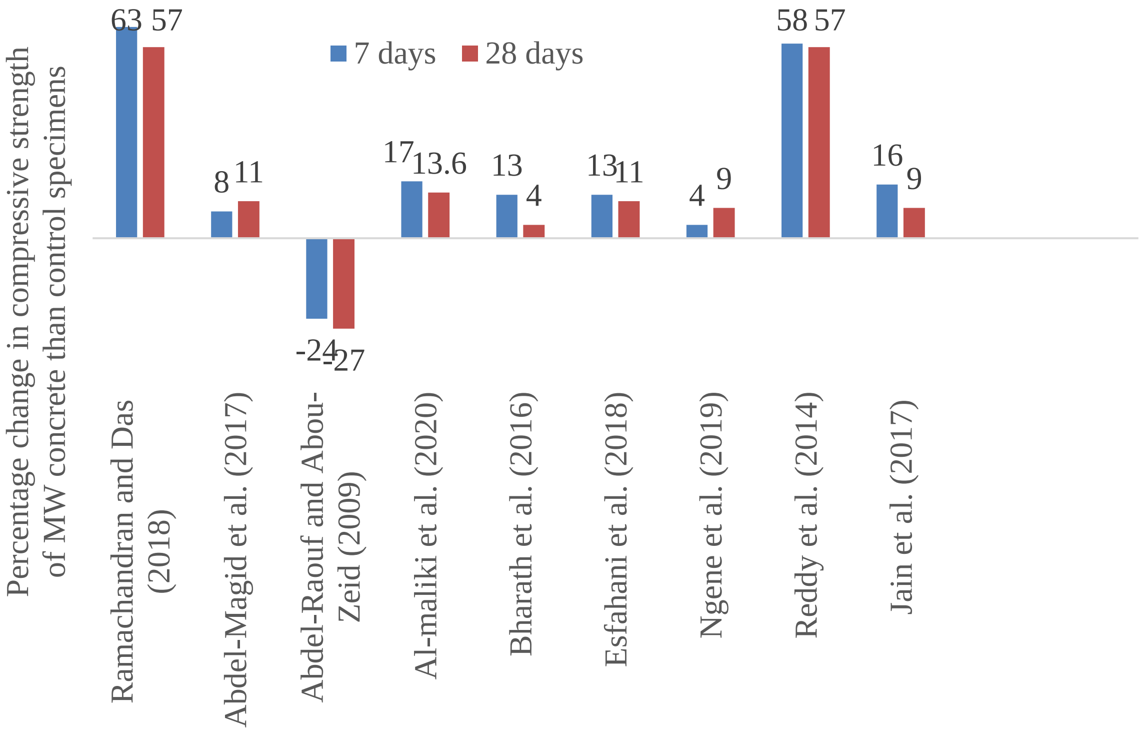


Fig. 7. Percentage change in compressive strength of MW concrete at 7 and 28 days curing regime [72–74,98–103].

From **Fig 7,** the effect of MW shows the positive effect on the compressive strength of concrete. The increase in strength at 28 days MW mixed concrete is above 10% than the control specimen. The 7-day compressive strength shows slightly higher than 28 days strength from all literature.

6. Effect of non-potable water on durability properties of concrete

The durability of concrete is a vital property that plays a major role in the service life of concrete structures. The durability of concrete is a research hotspot for several decades. However, only a few pieces of literature are available on the investigation of durability properties of concrete with an alternate water source for mixing and curing.

The major issue regarding the usage of SW in concrete is durability properties. Based on previous research articles, it is inferred that the high concentration of chloride ions and few salts in SW resulted in the deterioration of concrete structures. Based on the experimental investigation, specific properties such as water absorption, porosity, chloride resistance, drying shrinkage, carbonation and corrosion tests of SW concrete were discussed as follows:

Incorporation of Sea-sand (SS) in SW concrete leads to the reduction in initial (30 min) and final (3 days) water absorption of 14% and 27% than control specimens [80] and this observation is in line with previous studies about SW and/or SS mixed concrete [56,104]. The smaller particle size of sea-sand (SS) resulted in more densified microstructure [105]. By adding SW, the porosity of the concrete specimens cured at 7 days was reduced by 25% compared to 3 days. This is due to the acceleration in hydration of SW cement paste that resulted in the decrease in the pore diameter, which improved the compressive strength of concrete at early ages [79]. Mixing the SW and increasing curing age enhanced the chloride resistance of the concrete specimens by performing the Rapid Chloride Permeability Test (RCPT). The total charge passed through SW concrete specimens cured at 56 days decreased from 2000 to 1750 Coulombs, which showed an 18% increase in chloride resistance of the concrete. The reason for the improvement was the refinement of the pore structure due to the acceleration of cement hydration of SW [59]. An insignificant effect was observed by using SW on the permeability of hardened concrete by performing the rapid chloride permeability, chloride migration, and water absorption tests [56]. There was a slight increase in drying shrinkage of SW concrete (within 5%) at 56 days compared to control specimens and this is due to the formation of fine pore structure in the SW concrete [56]. The results showed an 83% increase in drying shrinkage of SW concrete than control concrete [86]**.** By incorporating SW for mixing and curing, the carbonation depth (0.4 mm) was low when compared to the control specimens (1.2mm) [106]. It was found that the 40% replacement of Blast Furnace Slag (BFS) was the most efficient against steel corrosion in concrete mixed with SW because BFS have a low oxygen environment around steel bar, chloride ion diffusion coefficient and thus makes the water-soluble Cl ion immobilized [6]. The carbonation depth of SW concrete was 30% more than control specimens measured at 7 days [107]. Researchers studied the corrosion of steel in SW concrete by half-cell potentiometer cured from 28 to 91 days and up to 13 weeks. The measured potential value was less than -350 milli Volt [108,109], and it is inferred that the probability of steel corrosion was 90% as per ASTM C 876 – 15 [110].

WWRMC effects on the durability properties of concrete like drying shrinkage, acid resistance, water absorption, and permeability were experimented. The percentage increase in drying shrinkage of WWRMC concrete specimens mixed and cured (at 7 days) was 25% compared to control specimens if the w/c ratio is 0.50. The concrete with the same w/c ratio of 0.50, the percentage increase in drying shrinkage was 26% at 120 days. This implies that the drying shrinkage rates are higher in the early days, and this is due to the presence of unstable ettringite in the WWRMC that yields more capillary pores than control concrete resulting in a more porous matrix and shrinkage. The higher w/c ratio yields higher drying shrinkage at an earlier period due to the availability of water that leads to evaporation [64]. A negative effect was observed on acid resistance leading to a porous concrete matrix due to the formation of unstable ettringite. The percentage of weight loss due to the acid attack increased when increasing the WWRMC content. Similar to drying shrinkage, the water to cement ratio plays a major role in the resistance to acid attack [64]. The weight loss of WWRMC concrete specimens was approximately 4 % greater than the control specimens [63]. It was observed that 26% decrease in water absorption of the WWRMC concrete specimens compared to the control specimens [65]. This illustrates that the fine suspended particles in the WWRMC can act as fine fillers in the hardened concrete. The water permeability of WWRMC concrete specimens showed 70% increase than control specimens [63].

GW effects on the properties of water absorption and chloride resistance of concrete are specifically studied. The average water absorption of concrete made with RGW, TGW, and distilled water is 1.69, 1.75, and 1.74%, respectively [34]. TGW concrete had better chloride resistance than RGW performed by using RCPT test [91]. The use of GW has the potential to reduce drying shrinkage in concrete mixes since the average length change for the GW mixes was approximately 34 % of that measured for the control specimens at 7, 14, 21, and 28 days [41].

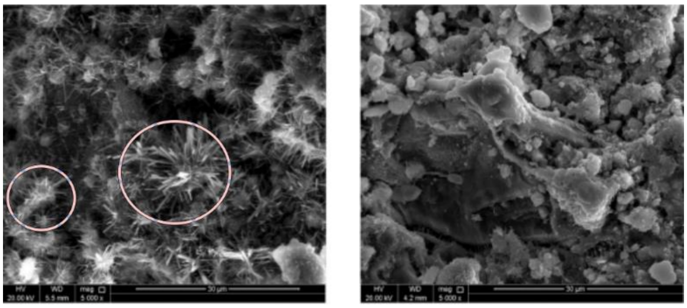
TSWW effects on the properties like carbonation, chloride migration, and abrasion resistance are considered. The carbonation resistance was decreased due to a decrease in the quality of mixing water by using TTWW for both mixing and curing. The depth of 9.33 mm was achieved at 28 days [70]. Chloride resistance was decreased by using TTWW, and this was due to the increase in chloride ion concentration with the decrease in the quality of mixing water. At 4 hours duration, the Chloride ion concentration of TTWW mixed concrete was higher (206 mg/l) than control specimens (97 mg/l) [70]. The rate of ingress of chloride ions into concrete depends on the pore structure of the concrete. TSWW concrete specimens had high porosity [46,71]. TSWW concrete at w/c ratio of 0.40 possess a high chloride ion diffusion coefficient of 1.64×10^{-11} m^2/s than FW concrete of 1.04×10^{-11} m^2/s. The chloride ion diffusion coefficient is directly proportional to the w/c ratio. Chloride ion diffusion directly links the corrosion of reinforcement bars, which plays an important role in the quality and durability of reinforced concrete structures [8]. Abrasion resistance was measured as the depth of wear was increased to 8% when TTWW was used for mixing and curing because the TTWW in concrete reduces the capillary water absorption and improves the durability of the concrete [70].

MW concrete had notable effects on the durability properties such as water absorption, cracking resistance, abrasive resistance, permeability, acid attack, and shrinkage. It was observed that there was a slight decrease in water absorption values (in %) of MW concrete than control specimens [111]. This result was in good agreement with previous findings [102,112]. The decline in water absorption values of MW concrete is attributed to the reduction of pores in their microstructures [97]. It was found that 43% reduction in the water absorption value of concrete specimens by using MW [113]. The cracking resistance of concrete mixed with MW has improved than those mixed with TW, and the corresponding magnetic strength is 260 mT (millitesla), with the length of the magnetic field is 280 mm. The number of cracks and the maximum width of cracks were decreased for concrete specimens by MW compared to the TW concrete specimens [97]. The abrasive resistance of MW concrete specimens (1.2% mass loss) was higher than conventional concrete (2.7% mass loss) [74]. An insignificant effect was observed by using MW in Rapid Chloride Penetration Test (RCPT) and the water permeability test because the w/c ratio has a stronger impact than the type of water used [74]. MW improved the chloride ion penetration resistance of the concrete specimen by 41% during RCPT and 43% reduction in the water absorption test [113]. Water absorption and porosity of the concrete specimens using MW of 1 Tesla were reduced compared to the control specimens [103]. MW enhanced the rate of growth of compressive strength of the concrete specimen by 45% during the acid attack test, 128% during the chloride attack test, and 49% during the sulfate attack test [113]. MW concrete showed the lower shrinkage strain rate of ($-112\ \mu\varepsilon / \mathrm{day}^{0.5}$) than TW concrete ($-140\ \mu\varepsilon / \mathrm{day}^{0.5}$) when the magnetic strength of 260 mT with a magnetic field length was 280 mm [97].

7. Microstructural properties of cement/concrete with non-potable water

The microstructure of hardened concrete with non-potable water was investigated using Scanning Electron Microscope (SEM), Energy Dispersive Spectroscopy (EDX) and X-Ray Diffraction (XRD) to observe the changes in the concrete prepared with different water sources at a micro-level.

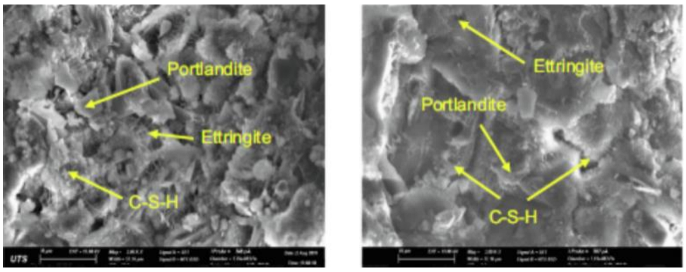
Based on **Fig. 8-a**, the C-S-H needles (few needles are encircled on two spots) were less densified and highly distributed in the case of freshwater (FW) cement paste and SW cement paste had a more densified structure at an early age [56,79] as shown in **Fig. 8-b**. In addition, ettringite and gypsum crystals fill in the voids in the SW paste and thus further densify the microstructure [81].



(a) 3- day FW cement paste (b) 3- day SW cement paste

Fig. 8. SEM images [56]

Similar results were also observed [16], as shown in **Fig 9**. Initially, the C-S-H gels precipitated on the surface of C_3S particles due to the accelerating effect of salts in the SW. However, after 2 days of hydration, products like ettringite, C-S-H, and portlandite form a denser microstructure (**Fig 9-b**) compared to FW cement paste (**Fig 9-a).**



(a) 2-day FW cement paste (b) 2-day SW cement paste

Fig. 9. SEM images [16]

The major elements observed in SW cement paste using Energy Dispersive X-Ray Spectroscopy (EDX) were Magnesium (Mg), Silica (Si), Sodium (Na), Aluminium (Al), Chloride (Cl), Calcium (Ca), and Iron (Fe) as shown in **Fig. 10.**

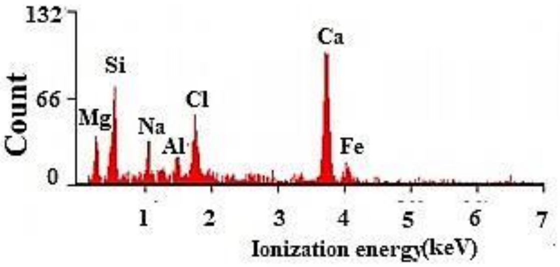
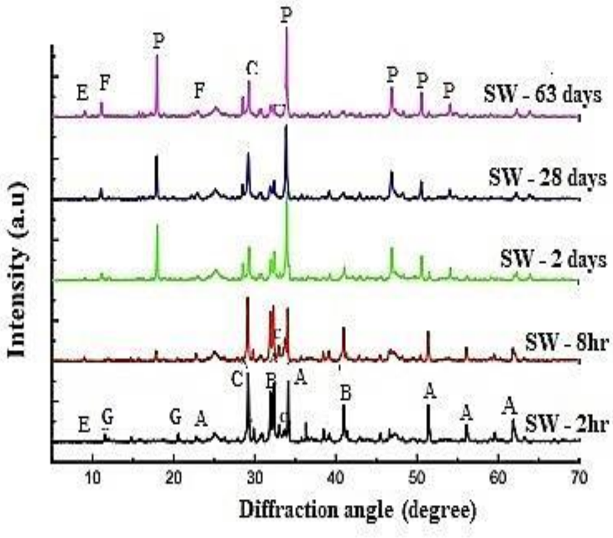


Fig. 10. EDX image of SW cement paste [114].

Fig. 11 shows the XRD of SW cement paste with different hydration time at w/c of 0.5.



Abbreviations

A - C_3S

B - C_2S

C - Calcite

E - Ettringite

F - Friedel’s salt

G - Gypsum

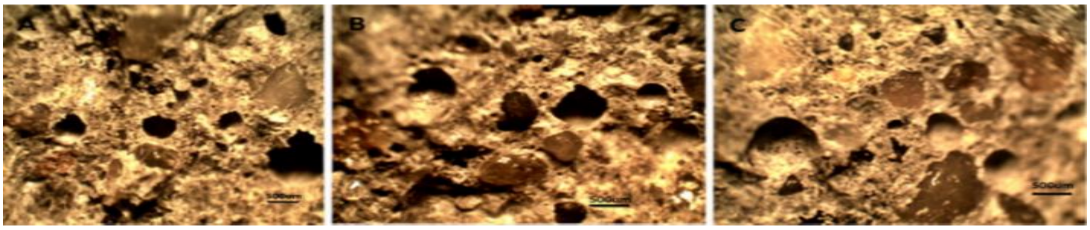
P - Portlandite

SW – Seawater

Fig. 11. XRD pattern of SW cement paste at w/c ratio of 0.5 with various hydration time [16]

It is inferred from **Fig. 11** that the crystalline phases produce sharp diffraction peaks. Gypsum (G) reacts with Portlandite (P) liberated during hydration of cement and form Ettringite (E) in SW cement paste at the hydration of 2 hours. In addition, the Cl ions present in SW react with portlandite and C_3A to form Friedel’s salt (F) at the hydration of 63 days. Friedel's salt densifies the cement matrix [115]. Based on **Fig. 11**, it could be concluded that there were especially huge peaks for portlandite. The presence of a calcite section within the tested pastes implies the carbonation on the surface area of the specimens [114].

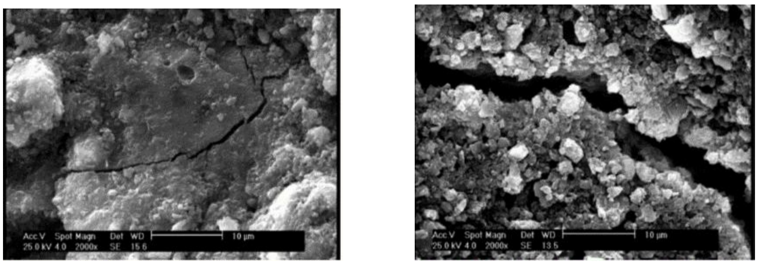
The three-dimensional photos revealed no significant differences in the air void size and distribution between mortar specimens made with TGW, RGW, and distilled water, as shown in **Fig. 12**, and no microcracks were found [41].



(a) TGW (b) RGW (c) Distilled water

Fig. 12. Stereo microscope images of mortar specimens [41].

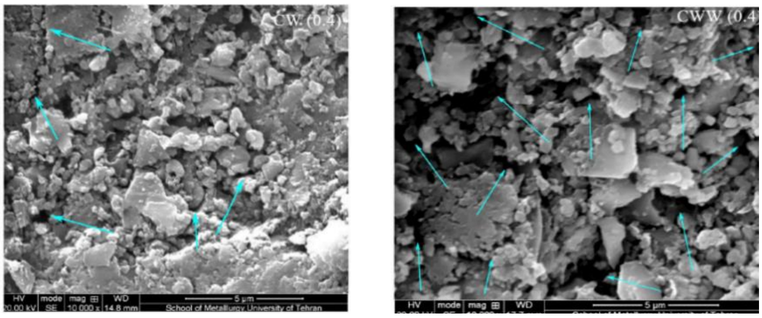
It was observed that FW concrete had less porosity, the formation of more cement gel [71] from the SEM images as shown in **Fig. 13-a** (magnification 2000x). On the other hand, the TSWW concrete exhibited higher porosity and less cement gel formation, as shown in **Fig.13-b**, similar to [46].



a. FW concrete specimens [71] b. TSWW concrete specimens [46]

Fig. 13. SEM images

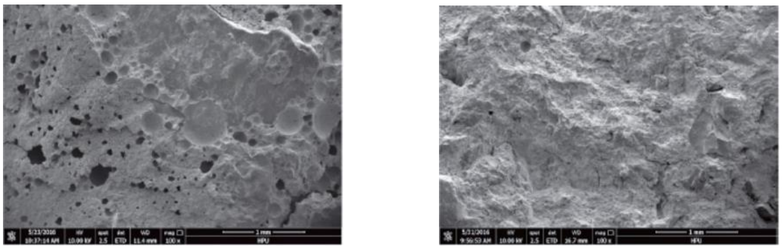
TSWW concrete had more pores and cracks than FW concrete by High Resolution Scanning Electron Microscope (HRSEM) images, as shown in **Fig. 14** (magnification 10000x) [8].



a. FW concrete specimens b. TSWW concrete specimens

Fig. 14. HRSEM images [8], Blue arrows show the pores and cracks on the concrete surface.

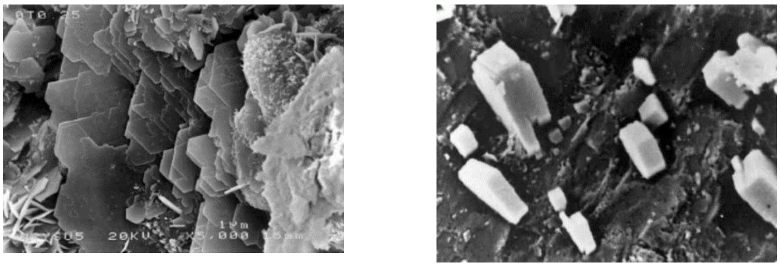
The SEM images of the specimens (magnification of 100x), from which fractional voids can be observed in **Fig. 15**. The highest number of fractional voids was observed in the control concrete specimen are shown in **Fig. 15-a.** However, the MW concrete specimens **(Fig. 15-b)** caused a decrease of voids and resulted from the denser structure. This results in the enhancement of compressive, splitting tensile strengths and cracking resistance during the early-age shrinkage of concrete [97].



a. Control specimens b. MW concrete specimens

Fig. 15. SEM images of the concrete specimen (100x) [97].

SEM image exhibits the use of MW instead of Tap water (TW) in concrete that leads to smaller calcium hydroxide $Ca(OH)_2$ crystals as shown in **Fig. 16** [49], and therefore it enhanced the compressive strength.



a. TW cement paste specimens b. MW cement paste specimens

Fig. 16. SEM images of $Ca(OH)_2$ crystals [49].

8. Problems encountered by using non-potable water in the concrete industry

SW imparts negative effects on the properties of concrete: strength reduction at later ages, accelerates the corrosion rate of steel, dampness, efflorescence, Alkali aggregate reaction, increase in concrete permeability, and high carbonation depth. The above effects depend on the ion concentration in the seawater. It shows fewer positive effects in the strength of concrete at an early age. Suppose the ion or salt concentration in the seawater is below the threshold value as per international standards by various treatment methods. In that case, the SW can be used as an alternate water source for potable water. However, many treatment methods like desalination and Reverse Osmosis are cost-effective to use seawater in the concrete industry in the future.

WWRMC poses major environmental issues due to high alkalinity (pH of around 13) and heavy metal content to be removed before reuse. Few RMC plants worldwide have installed a separate treatment plant and adopt technologies to convert the wash water into reusable water. Setting new technologies and treatment plants will be cost-effective. For example, the Ultratech Cement company reused the slurry wash water from the Baton wash (concrete recycling system) partially for concrete production in their RMC plants [116].

GW characteristics can vary from one household to another household. The challenges that occurred in using TGW in construction industries are as follows. First, lack of transportation facility on time, storage of TGW for more than 24 hours is not recommended at all. Secondly, in most countries, there is no provision of a separate greywater treatment system. The greywater and sewage water are mixed in the sewers to avoid additional costs. Hence GW quantity does not meet the demand of water required for concrete production. Finally, irrespective of the above challenges, the treated greywater contains soapy, oil, grease, and pathogens detrimental to mass concrete production.

TSWW had the same effect as similar to GW on the properties of concrete. Therefore, during the transportation of TSWW to the construction site, agitation and aeration should be provided to prevent anaerobic digestion resulting in a bad odour that causes discomfort for the workers.

One of the main problems in **MW** is that the magnetization process takes a long time to ensure the required level of magnetization. An effective system should be built from non-magnetic components because of the following: the water is magnetized and show diamagnetism (substances that are magnetized in a way opposite to the direction of the magnetic field). For mass concreting, a huge magnetization setup is required. No full-scale research is performed using MW in concrete, so it cannot be employed in the mass construction industry.

9. Deficit of experimental work in using five different types of water to make concrete

Leaching action was observed while using seawater for curing concrete specimens. Efflorescence was also observed on the surface of the concrete specimen. Ingress of ions present in the SW into the concrete specimens may result in deterioration. Working with wet WWRMC concrete requires several precautions, primarily to protect our skin from the high alkalinity. Rubber gloves and safety shoes are typically required to provide protection. A major hurdle to the use of treated wastewater is the psychological barrier of the consumer because of a perceived "unhygienic" factor associated with health concerns. This one is probably the most difficult to overcome. Moreover, treated wastewater contains chemicals, pathogens, etc., that can be harmful during experimental work, and hence safety precautions (waterproof gloves, wear rubber shoes) must be followed. In addition, treated wastewater should not be stored (during curing of concrete) due to aerobic and anaerobic digestion resulting in a bad odor that is uncomfortable. The limitation of MW is the water memory that can maintain magnetic properties for up to 12 hours [117]. After that range, this advantage may be lost, a proper schedule for mixing and curing concrete is necessary while experimenting with lasting the MW memory. Storing of MW leads to a reduction in compressive strength.

10. Conclusions

Based on the extensive review and the results of globally published research articles on the use of alternate water other than potable or drinking water such as seawater (SW), wash water from RMC plants (WWRMC), Greywater (GW), Treated Sewage Wastewater (TSWW), and Magnetized water (MW). Therefore, the following can be concluded based on the fresh and hardened properties.

- SW concrete had a fluctuation in compressive strength values (high early strength and low later strength), a high rate of heat evolution, and dense microstructure at an early age, and a negative effect on durability properties (carbonation depth, corrosion, and chloride migration). Therefore, the properties of SW concrete mainly depend on salt content concentration.
- WWRMC had some negative effects on concrete's fresh and mechanical properties like low slump value, high rate of heat evolution, less compressive, tensile, and flexural strength. Furthermore, a negative correlation exists between the quantity of WWRMC and the strength of concrete. In addition, it showed a negative impact on durability properties. Like TGW, the effect of WWRMC mainly depends on the presence of solids.
- TGW showed the higher setting time of cement, strength gain in longer days of concrete, and does not affect the durability properties. The properties of concrete mainly depend on the presence of solids in the GW.

- TSWW showed lower slump value, delayed final setting time of cement, low initial compressive strength, high compressive strength at ages, and reduction in chloride resistance of concrete. Therefore, Tertiary Treated Waste Water (TTWW) is suitable to make concrete wherever durability is not concerned.
- Performance of MW on fresh, mechanical and durability properties of concrete showed improvement due to the less cement content, less water requirement, faster hydration, high slump value, improved early age shrinking cracking resistance, enhancement in compressive, split tensile, and flexural strength. Moreover, it also exhibited good abrasive resistance. The above performance depends on the magnetization process, such as velocity, magnetic strength, and the length of the magnetic field.

Finally, it should be emphasized that the above summary is solely based on the available literature study.

11. Future recommendations

If the major ions in SW like chlorides and sulfates are reduced to some extent, then the properties of SW concrete will be enhanced and can be used as an alternate water source. All treated wastewater and SW can be used in the magnetization process and convert into MW, but until now, full-scale research is not performed on MW to make it the best alternative source of potable water in the concrete.

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