Sustainable Cement Production: Utilizing Seawater and Alternative Components to Reduce Freshwater Consumption

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Abstract - *Cement production is a highly water-intensive process that negatively contributes to freshwater depletion amid the growing global freshwater scarcity. This study explores the feasibility of using seawater as a sustainable alternative to freshwater in concrete construction and aims to reduce concrete's heavy dependence on rapidly depleting water resources. Accordingly, we conducted unique experiments to analyze the effects of seawater concentrations, salts, surfactants, and polymers on curing, strength, and durability to determine the optimal formulation: 40% seawater, 60% freshwater, and 1% magnesium chloride. The ideal formulation discovered appears to be associated with a faster curing rate. The findings of this research suggest that concrete quality can be maintained while conserving freshwater by replacing a portion of freshwater with seawater. Our approach not only addresses water scarcity but also aims to mitigate the environmental concerns from desalination and cement manufacturing.*

Key Words: Cement, Concrete, Seawater, Water, Curing, Hardness.

1 Introduction

Water is essential for both Earth and humans because it supports life. About 70% of Earth's surface is covered with water, and about 97.5% of the total water is seawater. Out of the remaining 2.5% that is freshwater, a significant portion is locked in glaciers and ice caps or buried underground, leaving less than 1% of Earth's total water available for human use. The human population was 2 billion in 1930 and is currently about 8.2 billion. The human body has an average of 60% water. Therefore, if the average body weight is 55 kg, we have 33 kg of water trapped in our body. Thus, more water gets locked in human bodies as the global population increases, reducing the total available water for consumption.

To meet the water demands of 8.21 billion people and a greater number of mammals, birds etc., seawater must be converted into freshwater. Plenty of seawater is available. However, the desalination process is highly energy-intensive and expensive. According to a Bloomberg report, about 15,000 kilowatt-hours of power are used for every million gallons of freshwater produced[1]. This high energy consumption contributes to carbon emissions and global warming. Secondly, according to a study published in Science of the Total Environment in 2018, producing approximately 95 million cubic meters of freshwater generates 141.5 million cubic meters of brine (water containing high concentrations of salt), a harmful waste product[2]. High amounts of brine can cause severe environmental damage when discharged into oceans or other bodies of water, as its high salinity can disrupt marine ecosystems and harm aquatic life.

2 Environmental Effects of Cement Consumption

The issues related to the shortage of freshwater in the world are particularly relevant to the construction industry, as cement production relies on freshwater. Over the years, cement production has experienced a dramatic increase due to global industrialization and urbanization. In the early 1900s, global cement production was relatively modest: in 1950, global production was approximately 80 million metric tons[3]. By 1980, global cement production surged to about 800 million metric tons[4]. This increase was further accelerated by the construction booms in developing countries and the rise of modern infrastructure. By 2010, global cement production had surpassed 3 billion metric tons annually. Today, cement production levels have continued to rise, exceeding 4 billion metric tons annually[5,6]. Demolition of thousands of buildings in recent wars has increased the demand for cement. Also, we have a limited supply of lime and silica, the two major components of cement.

While this growth reflects cement's critical role in construction and modern life, it also underscores the associated environmental challenges, specifically high carbon emissions and water usage. On average, it takes about 1,200 to 1,500 liters of water to produce one metric ton of cement. This water is used for processes such as cooling, mixing, and curing. Therefore, producing the required amount of cement annually (4 billion metric tons) would require between 4.8 and 6 trillion liters of water. This means that every year, cement production uses between 0.045% and 0.057% of Earth's total water supply, highlighting the criticality of this issue.

Cement production not only exhausts a substantial amount of water, but also relies on freshwater, which is often produced by desalination. If 50% of the freshwater used for cement undergoes the desalination process (a conservative estimation), then around 4.5 billion cubic meters of brine and 6 million metric tons of carbon dioxide would be generated annually.

3 Composition of Cement and the Hydration Process to form Concrete

The hydration of cement is a complex chemical reaction that further depletes the amount of freshwater in concrete production to construct commercial buildings, bridges, and more[7].

Before detailing the process of hydration, it's important to understand the composition of cement[7,8]. Cement is composed of basic compounds including calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), water (H_2O), and the polyatomic ion, sulfate (SO_3). These compounds are derived from burning limestone and clay together. The materials are blended, after which gypsum (containing calcium sulfate dihydrate, or $CaSO_4 \cdot 2H_2O$) is added to the mixture. After being cooled, the mixture is finely granulated to produce cement[7,8].

Cement is converted to concrete through hydration. During this process, the compounds in cement, such as tricalcium aluminate, form chemical bonds with water molecules to become hydration products. Reaction of water with tricalcium silicate (Ca_3SiO_5) contributes to the cement's initial durability, and the reaction of water with dicalcium silicate (Ca_2SiO_4) provides long-term strength[8]. Moreover, the reaction of water with tricalcium aluminate and Tetracalcium aluminoferrite helps in the initial setting of the cement. The hydration process is crucial, and an optimal water-to-cement ratio must be used to ensure the production of firm concrete. Excessive water reduces the concrete's strength, while minimal water leads to dry, brittle concrete that cannot be shaped[8]. After determining this ratio, cement, water, and the aggregate (a solid, chemically inert structure like sand or coarse rock) are mixed to develop a concrete paste, which is left to cure.

The hydration reaction between tricalcium silicate and water is provided below:

$$2\,Ca_3SiO_5 + 7\,H_2O \rightarrow 3\,CaO \cdot 2\,SiO_2 \cdot 4\,H_2O + 3\,Ca(OH)_2 + 173.6\text{ kJ}$$

The tricalcium silicate reacts with water to produce calcium ions, hydroxide (OH^-) ions, and heat (measured in kilojoules, or kJ). The calcium hydroxide crystallizes (i.e., develops a crystal lattice structure) while calcium silicate hydrate (CSH) begins to form, contributing to the cement's initial strength. This process continues as long as water is present and compounds in the cement have not undergone hydration. Dicalcium silicate produces less heat when reacting with water, reflecting the compound's decreased reactivity compared to tricalcium silicate[8].

4 Assessing Current Utilization of Seawater in Concrete Production

The limited supply of freshwater on Earth and the increasing global population requires a sustainable solution for cement production. The large amount of seawater can be used to produce concrete, a method used by ancient civilizations.

Particularly, the Ancient Romans prepared concrete with natural mineral admixtures and seawater[9]. They developed a recipe of volcanic ash, lime, and a mineral called aluminum tobermorite, which formed a strong concrete when mixed with seawater[9].

In a review, Su et al. summarized an in-depth knowledge of using many additives in concrete formation[10]. Like the Romans, modern society can develop innovative and sustainable concrete formulations. Although most studies indicate that seawater has not been adopted in the United States due to concerns over the corrosion of reinforcing steel and long–term durability, seawater in concrete is a promising alternative to the traditional use of freshwater, and its significance is being re-evaluated in the context of contemporary water challenges. Although stainless steel undergoes corrosion reaction, the alkaline environment of concrete generates a thin oxide layer (passivating layer) on the steel and reduces the corrosion rate. We have to study the effect of electrolytes on generating or disturbing such a passivating layer on steel. Corrosion is an electrochemical reaction and needs energy. One can also include corrosion inhibitors. One can also coat stainless steel with corrosion resistant coatings.

Despite its historical use, the influence of seawater in cement and concrete production has been relatively marginal over the centuries. This is because the composition of seawater can have varying effects on concrete and the environment. Water makes up 96.5% of seawater, while the remaining 3.5% consists of dissolved salts, primarily sodium chloride, along with other ions such as magnesium, calcium, potassium, sulfate, bicarbonate, and bromide. Seawater also contains trace elements, dissolved gases, organic compounds, nutrients, and microbes. These additional components can alter the chemical environment within concrete, affecting its microstructure, potential durability, and resistance to environmental stressors. Understanding these interactions is crucial for optimizing the performance of seawater concrete in various applications.

Yet many components of seawater benefit concrete production. For instance, high chloride concentrations in seawater accelerate the hydration process in cement, enhancing the concrete's initial strength (as seen by the earlier production of CSH gel). The ions weaken the cement's passivating layer (composed of hydration products such as CSH) and expedite the breakdown of these products to heighten the speed of hydration[11]. This may make seawater cement a superior option for concrete production, creating stronger concrete in less time. Based on the article by Su et al.[10], it is not just inorganic components, but other biological products in the seawater that can make concrete stronger and long-lasting.

Overall, seawater's use in cement can revolutionize cement production by avoiding or reducing the use of valuable freshwater. Freshwater is a limited resource, and traditional concrete production demands substantial amounts — approximately 180 liters of freshwater per cubic meter of concrete. On the other hand, seawater is abundant, covering about 70% of the Earth's surface. Utilizing seawater for cement hydration can substantially reduce pressures on freshwater resources and benefit regions grappling with water scarcity. Future research can confirm or refute these findings to institute seawater as a sustainable alternative for cement production.

5 Experimental and Results

We purchased Top'N Bond Concrete produced by Sakrete of North America, LLC. Our research focused on determining the rate of weight loss due to the evaporation of water during the curing process and evaluating the hardness of the concrete produced.

In each batch of concrete, we mixed 50 grams of cement with 25 grams of water; additional materials such as salts, surfactants, and polymers were measured based on batch requirements. The concrete was left to cure at room temperature, and the weight of the cement was recorded regularly. In the first experiment, concrete prepared using tap water was compared to that made with seawater. The seawater-based concrete demonstrated greater hardness. The graph (**Figure 1**) displays the weight of the cement /water sample during curing. The cement samples containing tap water and seawater lost about 30.5% and 25.0% weight, respectively. This suggests that the electrolytes present in seawater may have contributed to greater water retention during the curing process. The weight loss stopped after about 200 hours, or 8 days.

In another study, various mixtures of seawater and distilled water were prepared. More than 30% of seawater mixtures produced harder cement. Large amounts of electrolytes in concrete may have a deleterious effect, and therefore, it was decided to use a mixture of 40% seawater with 60% distilled water in further experiments.

Another experiment combined distilled water with 0%, 1%, 2.5%, and 4% sodium chloride to prepare concrete. A correlation was observed between the hardness of concrete and percent sodium chloride in water—more sodium chloride produced harder concrete. During the first 100 hours, the percent weight loss per hour was observed to be about 0.125. The percent weight loss per hour was 0.16 when we used tap water.

In yet another experiment, 1% Rheomax, Alcomer, and cocomidopropyl hydroxy sultaine were added to tap water. These polymers and surfactants did not help reduce the curing time or increase the hardness of the concrete block. More work is needed to determine the effects of other polymers/starches/surfactants on concrete properties.

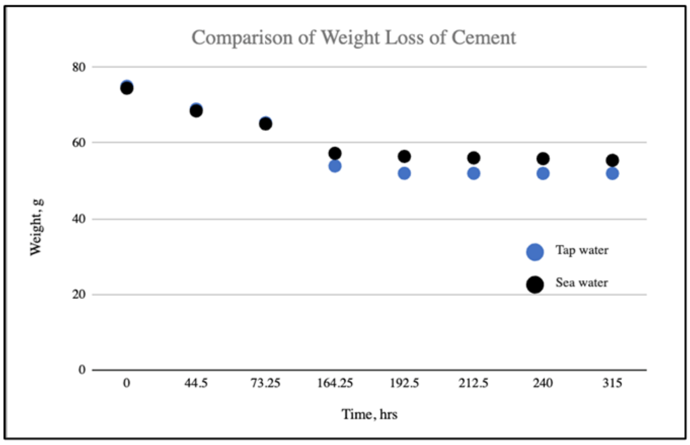

Figure 1: Effect of freshwater on the rate of weight loss during curing of concrete.

As seawater contains various salts, the effect of individual salts on the properties of concrete was evaluated (**Table 1**). We tried to make a dent in the concrete with the back of a paintbrush to assess the concrete's strength at regular intervals. At the end of the experiment, the hardness was examined by tapping with a metal bar or sound of the concrete when the container was tapped on the hard surface or breaking the concrete block with a hammer.

Our data showed that copper sulfate and zinc chloride have little effect on the concrete. In contrast, calcium, magnesium, iron, and barium salts made the concrete harder. In another experiment, calcium silicate and synthetic silica made the concrete soft, highlighting these electrolytes' varying effects on concrete's durability.

In the following experiment, a mixture of 40% seawater and 60% distilled water was prepared. This mixture was developed to determine if mixing seawater with distilled water improved concrete strength compared to using seawater or distilled water alone. We tested the effects of additional sodium chloride, ferric chloride, calcium chloride, and magnesium chloride on this combination. We had two control samples without the salts (these samples only contained 40% Seawater + 60% Distilled Water). The control samples seemed softer than all other samples (**Table 2**), while the electrolytes made the concrete harder. In the case of magnesium chloride, the water loss of the formulation was higher compared to other samples. Thus, there seems to be a positive effect of seawater and distilled water on the quality of concrete, and additional salts such as magnesium chloride may help further.

We calculated the percent weight loss per hour for all the samples during the first 100 hours. Overall, the value was about 0.18% to 0.2% per hour for all the samples containing seawater or electrolytes. Additionally, the formulations of cement containing 40% seawater had similar durability to the freshwater formulation.

Table 1: Effect of various electrolytes on the concrete properties.

#	Sample Description	% L, 15 days	Comments
25	40% SW + 60% DW + 0.5% NaCl	29.1	Hard, dent possible
26	40% SW + 60% DW + 1% $FeCl_3$	29.2	Hard, no cracks, dent possible
28	40% SW + 60%DW+ 1% $CaCl_2$	28.0	Hard, no crack
29	40% SW + 60% DW	29.6	Slightly softer, slight dent possible
30	40% SW + 60% DW, 0.1% $MgCl_2$	35.1	Hard, slight dent possible
31	40% SW + 60% DW + 0.2% $MgCl_2$	39.2	Hard, slight dent possible
32	40% SW + 60% DW + 0.5% $MgCl_2$	36.4	Very hard, dent not possible
27	40% SW + 60% DW + 1% $MgCl_2$	40.7	Very hard
33	40% SW + 60% DW	28.5	Slightly softer, dent possible

DW= Distilled water, L= Loss, SW = Seawater

After testing different cement compositions and inputs, we found that using 40% seawater with distilled water yielded equally good or improved concrete compared to that prepared using freshwater. Notably, the composition containing 40% saltwater, 60% distilled water, and 1% magnesium chloride achieved improved hardness while offering a faster curing time. The total percent weight loss was greater in samples containing magnesium chloride in a solvent mixture with 40% seawater and 60% distilled water.

The quality of concrete produced in various batches was examined by the cracks formed on the top, the amount of free cement from the concrete slab, the sound of concrete when tapped on a hard surface (this test is very promising), and the amount of force needed to break the concrete block using a hammer.

The positive effect of seawater on the properties of concrete may not solely be due to its electrolyte contents, but also due to organic matters present in the seawater. More work is needed in this area.

Table 2: Effect of various salts on the quality of concrete produced using a mixture of 40% Seawater and 60% distilled water.

#	Sample	% loss 7 days	Comments
11	DW + 1% $FeCl_3$	21.7	Very hard, dent not possible
12	DW + 1% $BaSO_4$	26.7	Very hard, dent not possible
13	DW + 1% $FeSO_4$	25.6	Hard, slight dent possible
14	DW+ 1% $CuSO_4$	25.8	Too soft, many cracks, terminated
15	DW + 1% $MgCl_2$	23.6	Very hard, little dent possible
16	DW +1 % $CaCl_2$	22.8	Very hard, dent not possible
17	DW+ 1% $ZnCl_2$	27.5	Not very hard, dent possible

DW= Distilled water

Despite of advantages, usage of seawater in concrete as drawbacks too. Seawater's composition, mainly electrolytes, can have adverse effects on concrete. The accelerated hydration process reduces the workability of cement and weakens the concrete's steel reinforcements. Being a natural product, the composition of seawater (organic and inorganic contents) in different regions is variable. If we start using the seawater in construction, the composition of seawater must be monitored carefully.

A partial replacement of freshwater with seawater to make concrete will make cement production more sustainable. This not only conserves freshwater resources but also reduces the carbon footprint associated with the energy-intensive processes required to source and produce freshwater via desalination.

6 Conclusion and Future Directions

The energy–intensive desalination process that converts seawater to freshwater continues to degrade the environment, resulting in greater carbon emissions and global warming. Partially replacing freshwater with seawater for industrial use may help combat this issue. Our research implements seawater as an innovative partial alternative to traditional freshwater to produce concrete. Not only does seawater provide a sustainable partial alternative to freshwater, but it also results in more efficient production of concrete. The particular formulation we developed with 40% saltwater, 60% distilled water, and 1% magnesium chloride resulted in better curing times and efficiency, making seawater a promising partial replacement for freshwater. Our research studied the effects of different concentrations of polymers and surfactants, water types, salts, and seawater dilutions to determine an optimal mixture. Future studies can further our understanding of seawater usage in concrete, developing new formulations that improve curing times and concrete quality (including corrosion prevention of reinforced steel) to protect our environment. Attention must be paid to prevent the corrosion of reinforcing steel used in the concrete blocks, which are prepared using a mixture of seawater and tap water.

References

1. Herndon, A. (n.d.). Energy Makes Up Half of Desalination Plant Costs: Study. Business. https://www.bloomberg.com/news/articles/2013-05-01/energy-makes-up-half-of-desalination-plant-costs-study .

2. Jones, E., Qadir, M., van Vliet, M. T., Smakhtin, V., & Kang, S.-M. (2019). The state of desalination and brine production: A global outlook. Science of the Total Environment, 657, 1343-1356. https://doi.org/10.1016/j.scitotenv.2018.12.076 .

3. Mineral commodity summaries 2019. (2019). Mineral Commodity Summaries. https://doi.org/10.3133/70202434.

4. World Cement Production Statistics. (2020). World Cement Association. World Cement Association. https://www.worldcementassociation.org/.

5. Cement Technology Roadmap 2009. (n.d.). International Energy Agency, 1-36. International Energy Agency. https://iea.blob.core.windows.net/assets/897b7ad9-200a-4314-b870-394dc8e6861a/CementTechnologyRoadmap-CarbonEmissionsReductionsupto2050.pdf.

6. Global Cement Production. (n.d.). International Energy Agency. Retrieved February 10, 2025, from https://www.iea.org/energy-system/industry/cement?

7. Composition of cement. (n.d.). Penn State Engineering. Retrieved March 8, 2025, from https://www.engr.psu.edu/ce/courses/ce584/concrete/library/construction/curing/composition%20of%20cement.htm .

8. Concrete: Scientific Principles. (n.d.). Illinois Materials Science and Engineering. Retrieved March 8, 2025, from https://matse1.matse.illinois.edu/concrete/prin.html .

9. Witze, A. (2017). Seawater is the secret to long-lasting Roman concrete. Nature, 1-3. Nature. https://www.nature.com/articles/nature.2017.22231.pdf .

10. Z. Su, Z. Yan, K. Nakashima, C. Takano, and S. Kawasaki; Naturally derived cements learned from the wisdom of ancestors: A literature review based on the experience of ancient China, India and Rome; *Materials* **2023**, *16*(2), 603; https://doi.org/10.3390/ma16020603

11. Saxena, S., & Baghban, M. H. (2023). Seawater concrete: A critical review and future prospects. Developments in the Built Environment, 16, 100257. https://doi.org/10.1016/j.dibe.2023.100257

BIOGRAPHIES

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