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A potential biological approach for sustainable disposal of total dissolved solid of brine in civil infrastructure

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HIGHLIGHTS

- A sustainable method for the disposal of TDS in construction materials.
- Fly ash and microorganisms were used to stabilize TDS in the mortar.
- Microstructure analysis was performed to verify new mineral formation.

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ABSTRACT

To meet growing water demand, more water is being harvested from nontraditional sources like brackish water from underground aquifers which contain total dissolved solids (TDS). Drinkable water is produced by separating TDS from water through desalination which typically produces 50–90% potable water and the remaining water (brine) is disposed in evaporation ponds or by injecting it below the ground surface, which is not sustainable. In this study, it was proposed to use TDS partially in place of sand to prepare mortar for possible application in highway infrastructure like fill material in vertical moisture barriers or embankments, etc. Since addition of TDS weakens the integrity of the cement matrix, fly ash and mutated aerobic bacteria were added to the cement matrix. Mortar specimens were subjected to strength and durability tests. Additionally, X-ray diffraction and scanning electron microscope tests were performed on mortar specimens. The preliminary test results indicated that fly ash and microorganism application not only improves the strength and durability, but these also stabilize TDS present in the mortar.

1. Introduction

Water is the critical resource for the well-being of humans and the environment. The increase in human populations has increased the water demand (whether for direct or indirect consumption) exponentially. According to Hanjra and Qureshi [1], the water demand gap will be 3,300 cubic kilometers per year to feed the population by 2050 (global population is projected to be 9 billion by 2050). To meet this growing water demand, more water is being harvested from nontraditional sources like seawater or brackish water from deep underground aquifers. Since both of the sources contain dissolved solids (mainly salts and other minerals), drinkable water is produced by separating total dissolved solids (TDS) from water through a process commonly known as desalination. A typical desalination plant produces 35–50% potable water from sea water and 50–90% from brackish water [2]. However, the desalination process also produces a byproduct commonly known as brine [3], which consists of higher amounts of TDS (more than 7500 mg/L of minerals). To maximize the limited supply of brackish water, inland desalination plants have developed technologies to reduce brine production, which results in the production of brine with even higher concentrations of TDS (more than 10,000 mg/L of minerals). Since concentrated brine is highly corrosive, due to the presence of concentrated sodium, chloride, phosphate, nitrates ions etc., an improper discharge can be detrimental to the environment in which it is disposed. To mitigate

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environmental damage, common disposal practices include, but are not limited to: evaporation ponds (with proper lining) and injection below the ground surface.

The disposal of such a large quantity of TDS (roughly 145 tons/day) in an economical and sustainable environmentally friendly manner can be possibly achieved by using the solids as a construction material, and that is the main focus of this research. The most logical place to dispose of TDS can be mortar (consisting of TDS, sand, water, and cement) which can be used in highway infrastructure such as fill material in vertical moisture barriers or embankments, etc. that require lower strength and no reinforcement.

A comprehensive literature review indicated that the presence of TDS reduces the strength and durability of mortar [4–9]. According to Berke et al. [4], the presence of highly concentrated sodium chloride may weaken the integrity of the cement matrix. Also, Barberon et al. [5] have reported that the presence of free chloride ions inside pores of cement paste hinders hydration by disintegrating a part of AFm/AFt hydrate, thus reducing the rate of strength gain. To compensate for the loss of durability and strength due to the addition of TDS, researchers [6] added fly ash to the cement matrix. Furthermore, researchers [7,8] found that the presence of NaCl induces formation of Friedel's salt by adsorption or anion-exchange. Interaction of Cl^- ions with the AFm phase of the cement system releases more OH^-/SO_4^{2-} ions in the cement-sand matrix systems. Researchers [9–14] observed that use of a chemical activators can improve the pozzolanic reaction of fly ash in that case, since both OH^- and SO_4^{2-} act as an activator for fly ash. The research performed by Ma et al. [15] further substantiated fly ash efficacy for adsorption and binding of ions like Na^+, Ca^{2+}, Cr^{3+} and Cl^- in order to improve the durability of concrete.

To further enhance the strength and durability, bacterial induced carbonate mineralization (a.k.a. Biocementation) has been demonstrated as a new additive to improve the strength and performance of mortar or concrete [16]. Ramachandran et al. [17] also observed that the presence of microorganisms can induce precipitation of calcite (a.k.a MICP) over the surface and in the pore system of mortar, which can improve its strength as well as durability by reducing the porosity. Achal et al. [18] also found that microbial calcite can further enhance the compressive strength and durability in the presence of fly ash. Park et al. [19] established that bacteria strains like *Arthrobacter crystallopoietes* (ATCC 15481), *Sporosarcina pasteurii* (ATCC 11859), *Bacillus sphaericus* (ATCC 14577), and *Lysinibacillus fusiformis* (ATCC 7055) etc. have the potential to precipitate calcium carbonate under optimum conditions. The microbial calcite precipitation process is described in Eqs. (1)–(6). Initially, the bacteria gathers nutrition from culture medium and secretes urease enzyme (Urea–amino–hydrolase), which is converted to ammonia (NH_3) and carbonic acid (H_2CO_3), as shown in Eq. (1). Then, the ammonia and carbonic acid equilibrate in water to form bicarbonate (HCO_3^-), ammonium (NH_4^+), and a hydroxide ion (OH^-) (Eqs. (2) and (3)), which also results in the pH increase due to formation of NH_4^+ (an essential element for creation of calcite). This rise in pH shifts the bicarbonate equilibrium to form carbonate ions (CO_3^{2-}), which in the presence of soluble calcium (Ca^{2+}) precipitates out of solution as calcium carbonate ($CaCO_3$) crystals near and surrounding the microorganism cell [20,21].

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_3 + H_2CO_3 \quad (1)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (2)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad (3)$$

$$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O \quad (4)$$

$$CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3 \quad (5)$$

$$CO(NH_2)_2 + 2H_2O + Ca^{2+} \leftrightarrow 2NH^{4+} + CaCO_3 \quad (6)$$

Halder et al. [22] observed that mutation of bacteria improved the compressive strength and durability of mortar more than mortar treated with wild bacteria as it is capable of precipitating more rhombohedral crystal calcite than wild bacteria in the same environment.

2. Research objective and scope

The main objective of this research was to explore the feasibility of using TDS as a construction material in a sustainable environmentally friendly manner. Since TDS mainly consists of concentrated salts (which can leach out and may weaken the integrity of the mortar), fly ash and mutated aerobic bacteria *Bacillus pasteurii* were added to the mortar.

The evaluations in this study were limited to TDS obtained from one desalination plant and Class-F fly ash from one source. Although strength gain continues beyond 28 days, the mortar strength was not evaluated beyond 28 days due to constraints of the project and hence, limited to short term testing.

3. Experiment design

To develop the test matrix, an initial investigation [23] was performed to identify a suitable amount of sand that can be replaced with TDS. The investigation showed that more than 5% (by wt.) of sand replacement with TDS reduced the strength significantly (crumbling of the specimen under loading). Although the addition of fly ash and bacteria improves the strength, the durability of mortar can be an issue. Therefore, it was decided to replace only 5% by wt. of sand with TDS. The strength evaluation at various fly ash contents indicated that an increase in fly ash of more than 5% by wt. negatively impacted strength [9]. Therefore, only 5% by wt. of fly ash content was evaluated. Since mortar consisting of bacteria requires the use of sodium phosphate buffer (discussed later), an initial investigation was conducted to identify the influence of sodium phosphate buffer instead of water on strength gain. The results of the investigation indicated that the influence of sodium phosphate buffer (SPB) is minimal for aging of 28 days or less. Therefore, the mortar specimens were prepared using SPB for strength and durability evaluation.

The compressive strength, absorption, and freeze–thaw tests were performed according to ASTM C109-08, ASTM C1645M-09 and ASTM C1585-11, respectively, on 50 mm cube specimens while permeability tests were performed conforming to CRD-C 163–92 on 100 by 100 mm cylindrical specimens. The size of the cylindrical specimens was selected due to constraints of the equipment used for performing the tests (and it is allowed per the CRD-C 163–92 procedure). Although some of the test procedures are not commonly used, the results from these tests can be used to compare relative changes rather than absolute changes. To minimize the number of tests, the strength tests were initially performed and mixture designs meeting or exceeding control specimen strengths were evaluated for durability; therefore, the number of specimens for durability tests is significantly lower than for compressive strength tests. The strength of mortar was evaluated by performing tests after 3, 7, and 28 days of curing. To evaluate the influence of each component on strength and durability (freeze–thaw and absorption test), three specimens were prepared and tested while only two specimens were prepared for permeability testing. Since strength and durability tests are standard test methods, the procedures followed are not discussed in this paper for the sake of brevity.

The specimens were prepared by maintaining a cement–sand–water ratio of 1–2.75–0.485 and the amount of each component is shown in Table 1. The amount of each component is for six 50 mm cube specimens while for cylindrical specimens the amount is for one specimen.

3.1. Material and specimen preparation procedure

Commercially available Type I/II OPC was used throughout the study, which satisfies the requirement of ASTM C 150. Quickrete-All Purpose sand was used as fine aggregate in the experimental program. The sand was sieved to fulfill the gradation requirements of ASTM C 33. A commercially available Class-F fly ash was collected from Boral Material Technology as a partial replacement of cement. This Class-F fly ash meets the requirement of ASTM C 168. Highly concentrated brine from the KBH Desalting Plant (El Paso, TX) was gathered and dried to obtain TDS for specimen preparation and testing. The brine was oven dried at 100 °C and the remaining sol-