Performance of Seawater-Mixed Recycled-Aggregate Concrete

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Abstract: The use of seawater and recycled coarse aggregate (RCA) in concrete mixtures leads to the production of a very sustainable concrete. The potential risk of steel reinforcement corrosion (due to chloride in the seawater) in such mixtures may be eliminated when considering plain concrete or noncorrosive reinforcement (e.g., fiber-reinforced polymer). This study investigated the fresh and hardened properties of a proposed green concrete mixed using seawater and recycled coarse aggregates. Two different concrete mixtures were studied, namely conventional concrete (Mix 1) and seawater-mixed concrete with RCA (Mix 2). Blast furnace slag was used as supplementary cementitious material at a 65% replacement level in both concrete mixtures. Fresh and hardened properties of the two concretes, including workability, strength gain, drying shrinkage, permeability, and microstructure, were characterized and compared. The results suggest that the use of seawater and RCA together has negative effects on concrete performance. Compared with the reference (Mix 1), Mix 2 concrete had approximately 5% lower density, 25% lower slump flow, 50% lower setting time, 33% lower strength gain, 10% higher drying shrinkage, 60% higher water absorption, and 100% higher charge passed (in rapid chloride permeability tests). Consequently, strategies to improve the performance of such concretes, such as a reduction in the water:cementitious materials ratio and the use of chemical admixtures, are suggested. These strategies, however, may somewhat reduce the green aspect of the proposed seawater-mixed concrete with RCA. **DOI: 10.1061/(ASCE)MT.1943-5533.0002999.** *© 2019 American Society of Civil Engineers.*

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Background

Concrete is the most commonly used construction material worldwide (Monteiro and Miller 2017) and is typically produced by mixing cement, freshwater, aggregates, and, often, supplementary cementitious materials and chemical admixtures. The environmental impacts of producing concrete from its raw ingredients using current practices are significant, primarily due to the volumes of concrete produced (Heede and De Belie 2012; Miller et al. 2018b). Consequently, there has been a growing interest in other sources of raw materials to reduce energy consumption and save natural resources to achieve green concrete (Rahal 2007; Schneider et al. 2011; Xiao et al. 2017). This study considered using two such materials, seawater and recycled coarse aggregate (RCA), together, for several reasons, to name a few:

- There is increasing global concern about freshwater scarcity. Predictions show that almost two-thirds of the world population is likely to experience water scarcity at least one month annually (Mekonnen and Hoekstra 2016). Significant savings in freshwater consumption can be achieved by reducing the use of freshwater in concrete, as the global production of concrete consumes more than 2 billion tons of freshwater annually (Miller et al. 2018a).
- Energy-intensive desalination processes are used worldwide in regions with freshwater shortages; however, there are negative environmental and cost impacts associated with these processes. The average cost of the most common desalination technique (i.e., reverse osmosis) is \$0.50–\$1.20/m^3 of water produced (Ghaffour et al. 2013), which is associated with CO_2 emissions of 1.4–1.8 kg/m^3 (Elimelech and Phillip 2011). This process also results in large amounts of brine (approximately 156 km^3 by 2050), which then is disposed of, often back into the ocean (Miller et al. 2015).
- More than 2 billion tons of construction and demolition waste is produced globally each year; this waste needs to be disposed of. In addition, the global construction industry requires over 40 billion tons of aggregates annually (Tam et al. 2018).

The idea of producing RCA from demolished concrete structures was first introduced in Europe around the time of World War II (Khalaf and DeVenny 2004), after which RCA use gained popularity and general acceptance. Currently, around 10% of the aggregate used in Europe is RCA; of this amount, 65% and 35% are used to produce new concrete for buildings and infrastructure, respectively (Tam et al. 2018). The first recorded use of seawater to produce concrete in modern times is traced back to World War II—structures were built along the coasts of California and Florida using seawater-mixed concrete (Kaushik and Islam 1995). However, some have suggested that the ancient Romans pioneered

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the use of seawater in concrete made with natural pozzolans (Witze 2017).

Recent studies generally show some negative impacts of seawater (Nishida et al. 2015) or RCA (Rahal 2007) on the fresh and hardened properties of concrete. Examples include reductions in workability, strength, and durability. Such drawbacks typically are attributed to the presence of certain ions in seawater for seawater-mixed concrete (Xiao et al. 2017) and the relatively inferior physical and mechanical performance of RCA for RCA concrete (Shi et al. 2016). These negative impacts may potentially be mitigated by adjustments in the concrete mixture design (Amario et al. 2017; Wardeh et al. 2015) or by using supplementary cementitious materials and chemical admixtures (Dimitriou et al. 2018; Kou et al. 2011; Matias et al. 2013; Younis et al. 2018b). Furthermore, life-cycle-assessment-based studies reveal considerable environmental benefits when recycling construction and demolition wastes to produce new concrete (Butera et al. 2015; Marinković et al. 2010; Shan et al. 2017). For instance, Hossain et al. (2016) reported that using RCA in concrete mixtures can result in a reduction of approximately 65% in the greenhouse gas emissions and up to 58% savings in nonrenewable energy consumption. The novelty of this study is the combined use of both seawater and RCA to achieve highly sustainable concrete. The work was carried out with dual objectives, namely to understand the negative impacts on fresh and hardened concrete properties of the combined use of seawater and RCA, and to propose strategies to minimize these impacts.

Research Scope and Significance

This paper represents a step toward redefining sustainable/green concrete (Fig. 1). It is apparent that combining seawater and RCA in concrete mixtures is significantly advantageous from a sustainability perspective, considering the increasing global concerns of freshwater scarcity, desalination impacts, construction and demolition waste, and the possible depletion of natural aggregate. However, the expected high concentration of chlorides in such mixtures potentially resulting in steel reinforcement corrosion is an undeniable challenge. This challenge may be addressed by using the proposed mixtures in plain concrete applications or with noncorrosive reinforcement such as fiber reinforced–polymer (FRP) bars. The relatively higher initial direct cost of FRP reinforcement can be recompensed in the long term by the savings associated with corrosion alleviation. Combining seawater, RCA, and FRP in structural concrete is potentially viable from technical (Baena et al. 2016; El-Hassan et al. 2017), environmental (Braga et al. 2017;

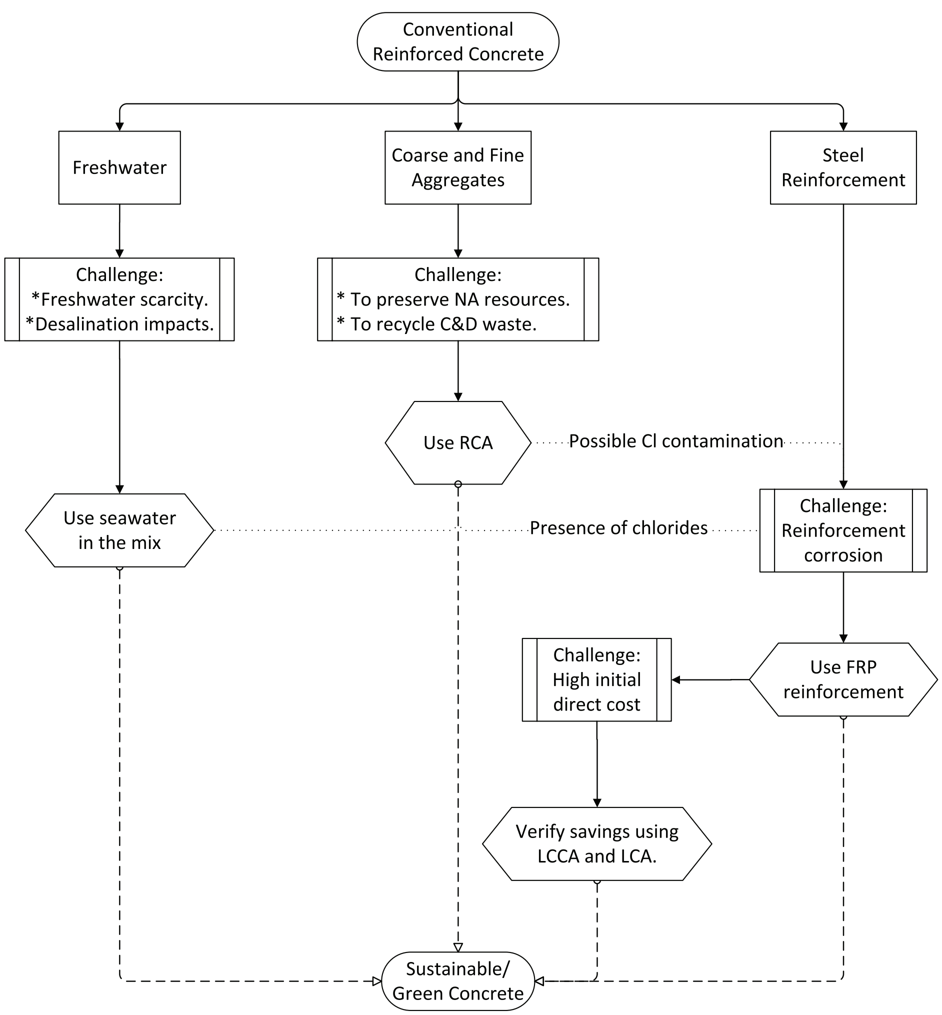


Fig. 1. Perspective toward sustainable concrete structures. NA = natural aggregates; C&D = construction and demolition; LCCA = life-cycle cost analysis; and LCA = life-cycle assessment.

Lee and Jain 2009), and economic (Braga et al. 2017; Younis et al. 2018a) standpoints.

A significant amount of research has been performed in the last 2 decades on the effects of mixing concrete with seawater (Nishida et al. 2015; Xiao et al. 2017) or RCA (Behera et al. 2014; Guo et al. 2018; Kisku et al. 2017; Neves et al. 2018; Silva et al. 2014, 2015a, b, 2018). However, studies concerning the combined effect of seawater and RCA are relatively scarce (Etxeberria et al. 2016). Therefore, further research is needed to understand the fresh and hardened properties of seawater-mixed concrete made with RCA, primarily to address the shortcomings expected in the performance of such concrete. This paper details the results of an experimental investigation on the effects of using seawater and RCA in concrete mixtures. The paper compares two concrete mixtures, namely (a) Mix 1, which was a conventional mixture produced with freshwater and natural coarse aggregate (NCA), and was regarded as a reference mixture; and (b) Mix 2, which was produced with seawater and RCA. Although various aspects of such novel and sustainable concretes need to be studied and understood before widespread implementation, this study focused on understanding and quantifying the negative impacts of the combined use of seawater and RCA on a large range of concrete properties, and on mitigating these negative impacts.

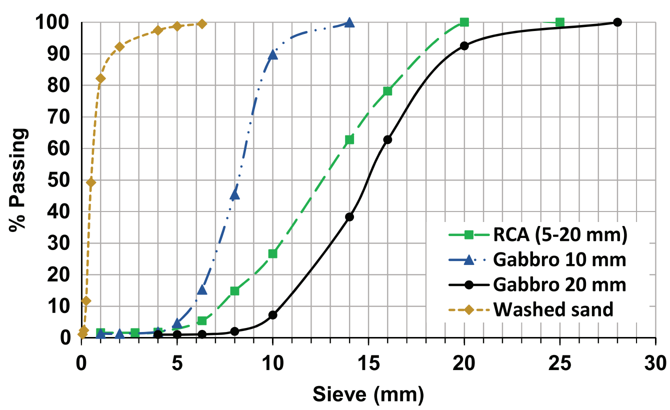


Fig. 2. Particle-size distributions of the aggregates used.

Materials

Water

Seawater was obtained from the Al-Khor coastal area in Qatar, and then fabric-filtered and stored to be used for mixing and curing concrete. The chemical characterization of both the freshwater and seawater used were provided by Younis et al. (2018b). The pH and alkalinity of the seawater (8.2 and 149 mg/L, respectively) were not significantly different from those of the freshwater (pH of 8.06 and total alkalinity of 69.5 mg/L), and both were within the allowable limits for concrete production (QCS 2014). The differences in properties between seawater-mixed and conventional concretes were expected to arise from the very high contents of certain ions, including sulfate (2.36 g/L) and chloride (18.6 g/L), in seawater. The concentration of these ions in the seawater not only higher was than in the freshwater, but also exceeded the allowable limits for concrete production.

Aggregates

Locally available washed sand was used in both concrete mixtures. The natural coarse aggregates used in Mix 1 were gabbro crushed rock (imported from Oman to meet local demand). Recycled concrete aggregates, produced and used in Qatar since 2009 from demolished concrete structures and discarded concrete from construction (Al-Ansary and Iyengar 2013), were used as coarse aggregates in Mix 2. Gradation analysis was carried out on the coarse and fine aggregates as per BS EN 933-1 (BSI 2012c), for which Fig. 2 presents the particle-size distributions. The size of the RCA used was between 5 and 20 mm: 75% of the RCAs were 10 mm or larger.

Table 1 presents the physical and chemical characteristics of the fine and coarse aggregates used in the current study, obtained according to the corresponding methods/standards as listed (ASTM 2014b, 2016c, 2017a; BSI 1990, 2006, 2008, 2009, 2010b, 2012a, b, c, 2013b). In general, the measured properties of the aggregates were within the acceptable limits (QCS 2014), except the RCA water absorption, which was significantly higher than the 2% limit (QCS 2014). This high water absorption was due to the high porosity of the RCA, the presence of adhered mortar on the RCA surface, and the relatively high percentage of clay lumps and friable

Table 1. Physical and chemical characterization of aggregates

		Results (coarse aggregates)				Results (fine aggregates)	
Test	Method/standard	20-mm gabbro	10-mm gabbro	RCA	Limit	Washed sand	Limit
Material finer than 63 μm (%)	BS EN 933-1	0.8	1	0.3	2.0 (max.)	1.1	3.0 (max.)
Particle density (kg/m^3): (a) oven dried; (b) saturated surface dried; and (c) apparent	BS EN 1097-6	(a) 2,980 (b) 2,960 (c) 2,940	(a) 2,930 (b) 2,950 (c) 2,980	(a) 2,440 (b) 2,552 (c) 2,746	2,000 (min.)	(a) 2,620 (b) 2,630 (c) 2,650	2,000 (min.)
Water absorption (%)	BS EN 1097-6	0.4	0.6	4.6	2.0 (max.)	0.6	2.3 (max.)
Clay lumps and friable particles (%)	ASTM C142	0.10	0.10	0.29	2.0 (max.)	0.10	2.0 (max.)
Flakiness index (%)	BS EN 933-3	6.9	11.7	5.2	35.0 (max.)	—	—
Particle shape index (%)	BS EN 933-4	8.2	7.7	3.4	15.0 (max.)	—	—
Lightweight particles (%)	ASTM C123	0.0	0.0	0.0	0.5 (max.)	0.0	0.5 (max.)
10% fines value (kN)	BS 812-111	360	360	189	150 (min.)	—	—
Los Angeles abrasion test (%)	BS EN 1097-2	9	10	24	30 (max.)	—	—
Aggregate soundness by magnesium sulfate %)	BS EN 1367-2	1.2	2.9	12.6	15.0 (max.)	10.3	15 (max.)
Organic impurities	ASTM C40	None	None	None	—	None	—
Acid-soluble chloride (% by weight)	BS EN 1744-5	0.02	0.02	0.02	0.03 (max.)	0.02	0.06 (max.)
Acid-soluble sulfate (% by weight)	BS EN 1744-1	0.1	0	0.19	0.3 (max.)	0.3	0.4 (max.)

particles in the RCA. The RCA had a lower particle density than the NCA. Results of Los Angeles abrasion and 10%-fines-value tests revealed an increase in material loss for RCA compared with NCA. Aggregate soundness tests showed that the RCA had potentially less resistance to disintegration by weathering compared with the NCA. Flakiness and particle-shape indexes suggested that, compared with NCA, RCA had a rougher surface texture with an irregular shape. These results taken together indicate that the RCA generally had inferior physical and mechanical performance compared with the NCA, which was somewhat expected. However, the RCA had similar results as the NCA in tests for organic impurities, acid-soluble chloride, acid-soluble sulfate, and percentage of lightweight particles.

Cementitious Materials

Ordinary portland cement (OPC) and blast furnace slag (at a replacement level of 65%) were used as cementitious materials. Blast furnace slag (referred to as slag in the rest of the paper) is known to improve the performance of fresh and hardened seawater-mixed concrete (Cheng et al. 2018) and RCA concrete (Etxeberria et al. 2016). The chemical compositions of the OPC and the slag used were provided by Younis et al. (2018b) and conformed to acceptable limits (QCS 2014). Blaine air permeability tests performed as per BS EN 196-6 (BSI 2010a) on OPC and slag revealed their fineness to be 3,350 and 4,510 cm^2/g, respectively.

Concrete Mixture Proportions

Ready-mix concrete, with a 28-day design compressive strength of 60 MPa and a water:cementitious material (w/cm) ratio of 0.34, was used. Table 2 presents the mixture design quantitates for each concrete mixture according to BS EN 206 (BSI 2013a). In Mix 2, NCA was fully replaced with RCA on a volume basis. Although both mixtures had the same w/cm, the water contents in Table 2 are different because additional mixing water was used in Mix 2 to account for the higher water absorption of the RCA. Commercial superplasticizer (Glenium 110M, BASF) at a dosage of 3.8 kg/m^3 was used in both mixtures to maintain a minimum 550-mm slump flow for 60 min in the control mixture.

Table 2. Concrete mixture proportions (kg/m^3)

Component	Mix 1	Mix 2
OPC	158	158
Slag	292	292
Gabbro 20 mm	700	—
Gabbro 10 mm	490	—
5–20-mm RCA	—	990
Washed sand	750	750
Freshwater	165	—
Seawater	—	205

Experimental Methods

Fresh Concrete

Fresh concrete properties were compared between the two mixtures. Three tests were performed on the fresh concrete: (1) a slump flow test in accordance with ASTM C143 (ASTM 2015); (2) density, yield, and air content tests in accordance with ASTM C138 (ASTM 2017b); and (3) an initial setting time test in accordance with ASTM C403 (ASTM 2016d).

Hardened Concrete

Strength Performance

Compressive and split tensile strength tests were conducted on hardened concrete in accordance with ASTM C39 (ASTM 2016b) and ASTM C496 (ASTM 2011), respectively. Three concrete cylinders (150 × 300 mm) were tested (using a mechanical testing device), and average values were presented for each test point. Three test variables were considered: (1) concrete mixture (Mixes 1 and 2); (2) test time (Days 3, 7, 28, 56, and 365 following mixing); and (3) curing condition (standard/control and seawater-immersed). In standard/control curing (E1), specimens were immersed in freshwater in laboratory conditions for 28 days, and then were left outdoors in ambient conditions. Seawater curing (E2) involved storing the specimens immersed in seawater until the testing time.

Drying Shrinkage

In accordance with ASTM C157 (ASTM 2014a), initial length measurements were taken for three concrete prisms (100 × 100 × 500 mm) at Day 1 following mixing with respect to a reference bar (ΔL_0). Specimens were then kept under air-drying conditions, and the length measurements (ΔL_t) were taken at Days 4, 7, 14, 21, 28, 56, 112, 224, and 365. The concrete shrinkage was calculated as follows:

$$S_t(\%) = \frac{\Delta L_t - \Delta L_0}{G} \times 100 \quad (1)$$

where t = test time; S_t = concrete shrinkage at age t; and G = gauge length (25.4 mm).

Permeability

Two measures of concrete permeability were investigated:

- Rapid chloride permeability (RCP) test: In this test, the electrical conductance of concrete (subject to standard curing conditions) was measured to indicate its permeability/quality. In accordance with ASTM C1202 (ASTM 2017c), a potential difference of 60 V was maintained between the two ends of a concrete specimen (100-mm-diameter and 50-mm-deep cylinder), one of which was immersed in NaCl solution and the other in NaOH solution. The total amount of electrical current passed (coulombs) during a 6-hr period was measured as an indication of chloride penetration resistance. Because Mix 2 concrete was not intended to be used with steel reinforcement, resistance to chloride penetration was not important per se; however, it was used as a general indicator of concrete quality.
- Water absorption (WA) test: In this test, the ingress of water through the surface of the concrete specimen (150-mm cube subjected to standard curing conditions) was measured in accordance with BS 1881-122 (BSI 2011). Three cylindrical cores (75-mm diameter and 47-mm deep) were extracted from the top, the middle, and the bottom of the specimen. The initial weight (W_1) was measured for the cores in an oven-dried condition. The final weight (W_2) was measured for the cores in a saturated-surface-dry condition. The water absorption (%) was determined as the ratio of the change in weight (i.e., $W_2 - W_1$) with respect to the initial weight (W_1).

Microstructure

Microstructural investigation of hardened concrete was performed using scanning electron microscopy (SEM) in accordance with ASTM C1723 (ASTM 2016a). The interaction between a projected electron beam and the atoms of the specimens generates low-energy secondary electrons, high-energy backscattered electrons, and X-rays. Based on that, three types of SEM analytical tools were considered: (1) secondary electron (SE) imaging to investigate the

J. Mater. Civ. Eng., 2020, 32(1): 04019331

morphology of the specimen's fractured surface; (2) backscattered electron (BSE) imaging to quantify the atomic distribution over the specimen's polished surface determined by surface brightness; and (3) energy-dispersive X-ray microanalysis (EDX) to identify the chemical composition of a specimen by analyzing the detected X-ray spectra. Further details on SEM are available elsewhere (Diamond 2004; Winter 2012).

Results and Discussion

Fresh Concrete

Density

The density of Mix 2 concrete (2,400 kg/m^3) was approximately 5% less than that of Mix 1 (2,555 kg/m^3). As previously reported (Younis et al. 2018b), mixing with seawater has no significant effect on the fresh concrete density, suggesting that the replacement of NCA by RCA reduced the concrete density of Mix 2. This can be attributed to the presence of adhered mortar on the surface of RCAs, which makes RCAs less dense than NCAs (Behera et al. 2014). This result is in agreement with the literature (Silva et al. 2018), which indicates 5%–8% lower concrete density when using 100% RCA. According to Bravo et al. (2015), the decrease in concrete density is strongly related to the physical properties of RCAs: those with lower density and higher water absorption generally yield further loss in the fresh density of concrete.

Air Content

The use of seawater and RCA in Mix 2 resulted in an increase in the air content (1.85%) compared with the conventional Mix 1 (1.40%). The existing literature on seawater-mixed concrete (Xiao et al. 2017) and RCA concrete (Silva et al. 2018) suggests that increases in the air content generally are attributed to the use of RCA rather than the use of seawater. In addition to their higher porosity, RCAs also possess a rougher surface with greater angularity as a result of the recycling process, which can lead to air becoming trapped on the aggregate surface (Silva et al. 2018; Souche et al. 2017). Because the RCAs were not presaturated in this study, it is possible that the air content inside mortar in the RCA also was being measured. Previous research has shown a similar impact of using RCA on the concrete air content, with the air content increasing with RCA replacement levels (Wardeh et al. 2015).

Workability and Setting

Fig. 3 depicts the slump flow as a function of time for both concrete mixtures. Younis et al. (2018b) noted that the use of seawater reduced the initial slump flow of fresh concrete by 20% compared with the reference and resulted in a somewhat lower slump retention. Here, combining seawater and RCA resulted in a more significant reduction in the workability. Mix 2 not only had an initial slump 25% less than that of Mix 1, but also remained flowable for only half the amount of time (i.e., 60 min for Mix 2 versus 120 min for Mix 1). The initial setting time (i.e., the time corresponding to a penetration resistance of 3.5 MPa) for Mixes 1 and 2 was 395 and 210 min, respectively (Fig. 4). Whereas the sole use of seawater reduced the initial setting time by almost 30% (Younis et al. 2018b), the combined effects of seawater and RCA in Mix 2 resulted in an approximately 50% lower initial setting time compared with Mix 1. These observations conform to those of previous studies indicating the accelerating effects induced by seawater (Wang et al. 2018) and RCA (Poon et al. 2007).

The reduction in workability and setting time in seawater concrete is attributed to the presence of large amounts of chloride accelerating the cement hydration (Li et al. 2018): isothermal calorimetry comparison of freshwater and seawater cement pastes revealed that the heat flow (i.e., the rate of hydration) and the heat release of the latter are higher than those of the former at early ages (Montanari et al. 2019; Wang et al. 2018). In addition, incorporation of RCA in Mix 2 resulted in a significantly higher water demand and thus a slump loss greater than those of Mix 1. In general, RCA has a harsh/granular texture because of the adhered porous mortar on its surface; hence, more water (or effort) is required for compaction due to the interparticle friction (Behera et al. 2014; Etxeberria et al. 2007). Without overlooking the simultaneous accelerating effects of seawater (Younis et al. 2018b), it is apparent that using 100% RCA in an air-dry condition hampered the concrete workability to a great extent despite the additional mixing water. Therefore, it is recommended in this particular case to consider presoaked recycled aggregates (Etxeberria et al. 2016; Ferreira et al. 2011; Poon et al. 2004) or greater amounts of superplasticizer (Matias et al. 2013) to mitigate such reductions in workability performance. Koenders et al. (2014) reported that using RCA in a saturated surface dry condition resulted in a relatively lower heat flow (i.e., rate of hydration) and a slightly longer induction period, possibly due to the unabsorbed mixing water.

Hardened Concrete

Strength

Figs. 5 and 6 show the compressive and tensile strength results of the studied mixtures, respectively. Mix 1 achieved the 60-MPa design compressive strength after 28 days, whereas Mix 2 did not.

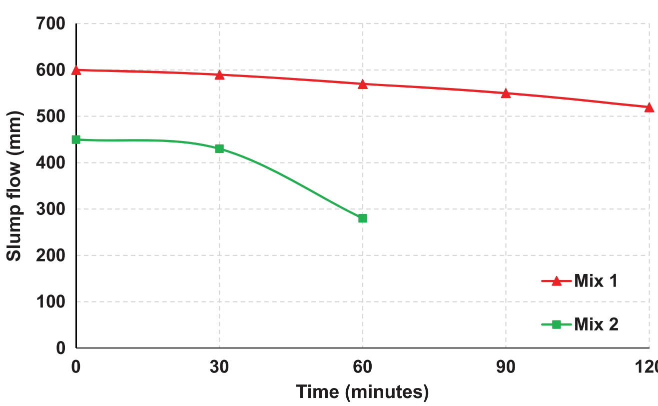


Fig. 3. Slump flow as a function of time.

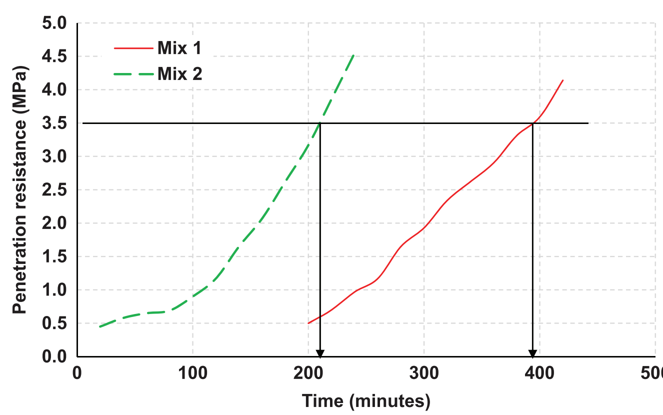


Fig. 4. Setting time test results.

J. Mater. Civ. Eng., 2020, 32(1): 04019331

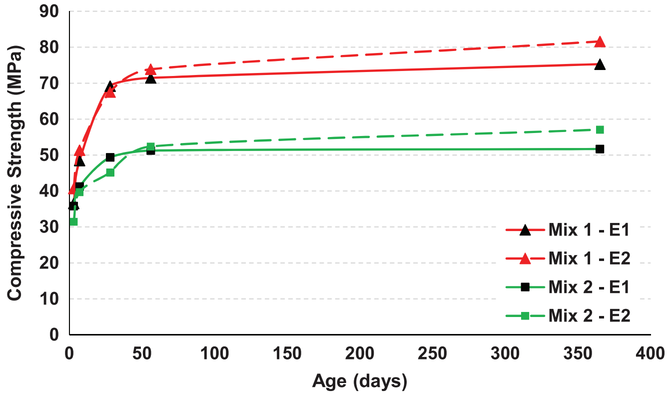


Fig. 5. Compression test results. Standard deviations at Days 3, 7, 28, 56, and 365 are 0.31, 0.11, 1.05, 2.40, and 0.67 MPa for Mix 1-E1; 1.47, 0.72, 1.88, 1.74, and 1.71 MPa for Mix 2-E1; 0.40, 0.96, 2.44, 0.80, and 0.62 MPa for Mix 1-E2; and 1.14, 1.48, 2.70, 2.24, and 0.76 MPa for Mix 2-E2.

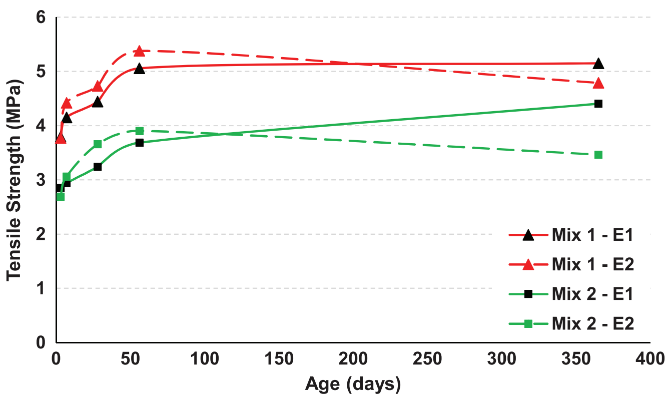


Fig. 6. Splitting tensile test results. Standard deviations at Days 3, 7, 28, 56, and 365 are 0.15, 0.24, 0.53, 0.10, and 0.88 MPa for Mix 1-E1; 0.31, 0.19, 0.23, 0.83, and 0.10 MPa for Mix 2-E1; 0.27, 0.20, 0.13, 0.25, and 0.20 MPa for Mix 1-E2; and 0.15, 0.30, 0.21, 0.14, and 0.32 MPa for Mix 2-E2.

With the sole use of seawater (Younis et al. 2018b), a slight increase (within 5%) occurred in the strength at early ages (up to 7 days), attributable to the reduced porosity due to the acceleration in cement hydration (Wang et al. 2018). At later ages (28 days or later), seawater concrete had strength values 8%–10% lower than those of the conventional concrete (Younis et al. 2018b), which may be due to leaching of hydrates (Kaushik and Islam 1995) (although this depends on specific curing conditions). Here, Mix 2 had significantly lower compressive and tensile strength values compared with those of the conventional Mix 1 at all ages. For instance, the compressive strength value of Mix 2 concrete was approximately 33% lower than that of Mix 1 after 1 year (Fig. 5). It is evident that the combined negative effects from mixing seawater and RCA worsened the mechanical behavior of Mix 2. These results are in agreement with previous research on RCA concrete (Behera et al. 2014; Silva et al. 2014), which generally indicated a reduction of up to 30% in the concrete compressive strength with the use of 100% RCA. In principle, RCA concrete has lower strength than conventional concrete due to the increased porosity, the lower strength and density of RCA, the weak interfacial bond between RCA and the matrix, and/or the presence of microcracks and fissures within the RCA because of crushing and recycling processes (Behera et al. 2014). Etxeberria et al. (2016) reported a 30% reduction in the compressive strength of concrete using both seawater and RCA in the mixture at 100% replacement level.

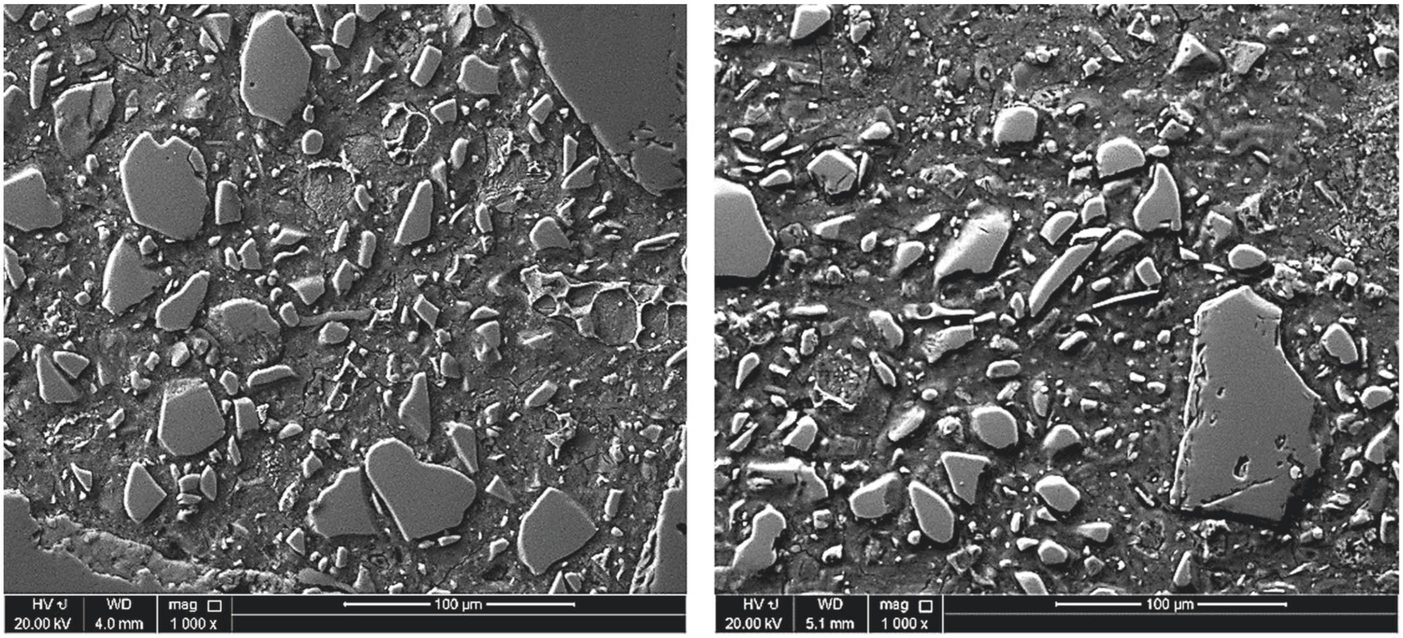
In general, continuous seawater curing resulted in greater compressive strength of concrete compared with that concrete under ambient conditions. After 1 year, the compressive strengths of the E2 specimens were on average 9% higher than those of the E1 counterparts (Fig. 5). It is possible that continuous moist curing further enhanced the cement hydration in the E2 specimens compared with the E1 specimens (under ambient conditions). This suggests that seawater-mixed concretes with the current design mixture could have good performance under marine conditions. The tensile strengths of the E2 specimens, on the other hand, decreased after 56 days, and were 12%–20% lower than those of the E1 counterparts after 1 year (Fig. 6). Similarly, Wegian (2010) reported long-term reductions in the tensile strength of concrete as a result of continuous seawater curing (comparing 3-month and 28-day results).

Microstructure

Fig. 7 shows BSE images of 56-day hardened concrete of the two mixtures. In general, the microstructure of the two mixtures appeared to be similar, although this was not quantified. In a qualitative manner, both mixtures had low porosity (black) and little anhydrous cement (white). The majority of the space was covered by hydrated cement (gray) and slag (irregular gray particles) (Diamond 2004). The SE images, however, showed a relatively less dense microstructure of Mix 2 than of Mix 1 (Fig. 8). Several microcracks and fissures were observed in the microstructure of Mix 2: those, as suggested by Xiao et al. (2012), are likely to exist within the RCA as a result of crushing of the parent concrete and recycling processes (relating fracture surfaces with concrete mechanical properties is not trivial and must be done with care because of the inherent variability of fracture surfaces). At higher magnifications, crystalline products were observed in concrete mixed with seawater (Fig. 9), suggesting that part of the calcium in the pore solution reacted with the sulfate ions (abundant in seawater) to form such phases (mostly gypsum, as per the EDX). Although it was not directly confirmed, gypsum formation could possibly yield expansive crystallization pressures that result in decreases in concrete strength, which would explain in part the reduction in the strength of Mix 2 compared with that of Mix 1. Apart from the negative effects of salt crystallization and RCA microcracks, the dual interfacial transition zone (ITZ), normally existing in RCA concrete (Bosque et al. 2017), likely played a role in the inferior properties of Mix 2. This dual ITZ (i.e., coarse aggregate/old mortar and RCA/new mortar interfaces) represents a weak link (and hence a load-transfer barrier within the concrete) and thus limited the strength of Mix 2. The microstructure of recycled-aggregate concrete was further discussed by Kim et al. (2019), Leite and Monteiro (2016), and Liu et al. (2011).

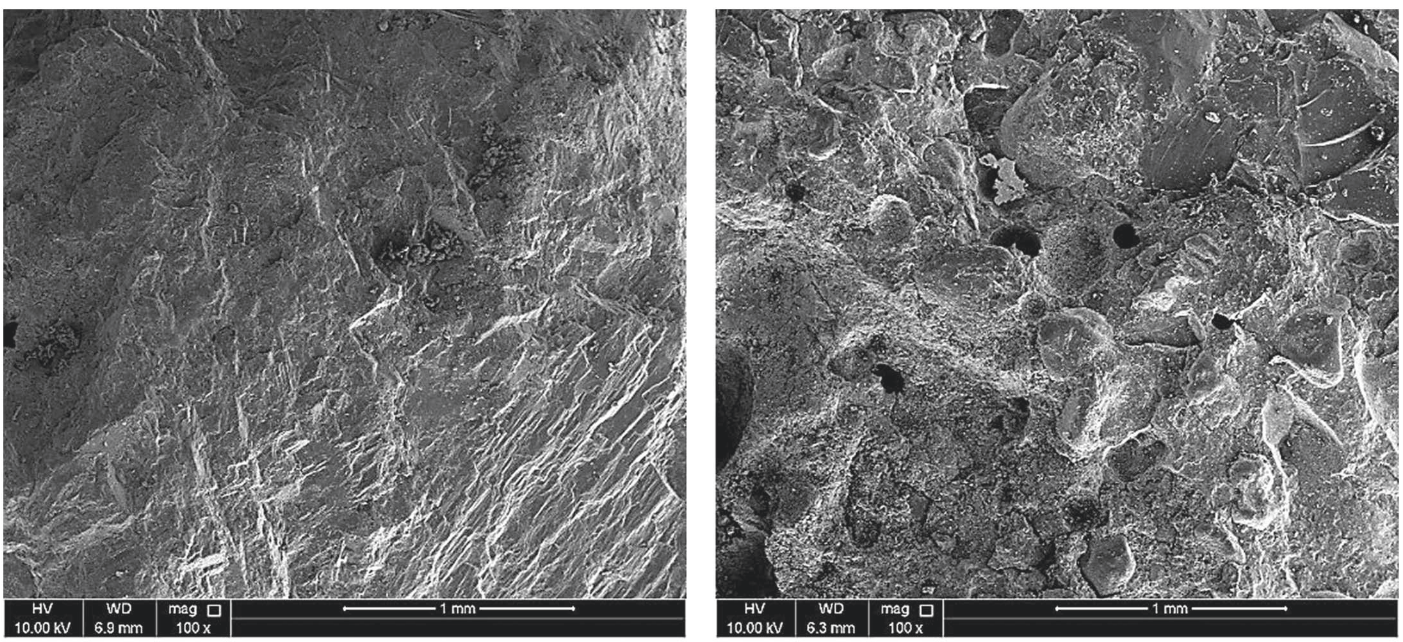
Permeability

The results of rapid chloride permeability test and water absorption are listed in Table 3. Tests were performed on hardened concrete at 28 and 56 days following mixing. The permeability performance of hardened concrete at Day 56 was better than that at Day 28 because of the reduction in porosity due to increased hydration of cement and reaction of slag. RCP test results for both concrete mixtures were within the acceptable limits (QCS 2014); however, Mix 2 passed a 100% higher charge than did Mix 1. Similarly, WA test results revealed poor performance for Mix 2 compared with Mix 1 or even the standard limits [2.5% maximum (QCS 2014)]. Whereas seawater mixing had almost no effect on the permeability performance of hardened concrete (Younis et al. 2018b), incorporating



(a) (b)

Fig. 7. BSE images taken after 56 days for concrete of (a) Mix 1; and (b) Mix 2.



(a) (b)

Fig. 8. SE images of the 56-day-aged concrete of (a) Mix 1; and (b) Mix 2.

RCA in Mix 2 reduced its permeability performance. This was attributed to the inferior quality of RCA because of the existence of microcracks, the high porosity, and the adhered old mortar which make concrete more vulnerable to permeation (Guo et al. 2018).

Shrinkage

Fig. 10 shows the concrete drying shrinkage (%) as a function of time for the two mixtures. In general, the shrinkage curve consisted of two portions. The first portion indicated a rapid increase in shrinkage until Day 28; the second portion, after 28 days, had a lower slope (a slower shrinkage rate). Similar drying shrinkage of such concrete was reported by Jianyong and Yan (2001). Mix 2 had higher drying shrinkage at all ages compared with Mix 1; a difference of approximately 10% was reported at Day 365. Seawater appeared to have little effect on the drying shrinkage (Younis et al. 2018b), especially in the long term, although this depends on exact mixture designs being tested (Khatibmasjedi et al. 2019). However, incorporating RCA in Mix 2 increased its drying shrinkage due to the higher water absorption, higher porosity, and lower modulus of elasticity, which in turn resulted in greater mass loss

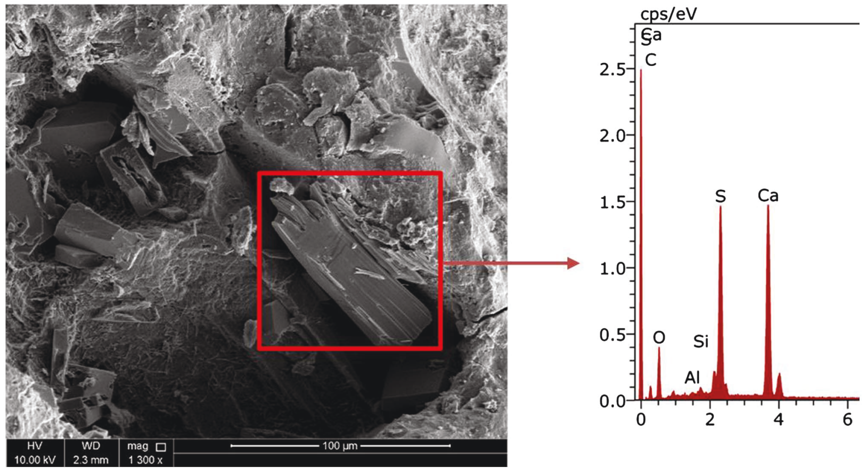


Fig. 9. Crystallization of salt impurities in seawater-mixed concrete. (Reprinted from *Construction and Building Materials*, Vol. 190, A. Younis, U. Ebead, P. Suraneni, and A. Nanni, "Fresh and hardened properties of seawater-mixed concrete," pp. 276–286, © 2018, with permission from Elsevier.)

Table 3. Summary of permeability performance test results

Specimen	RCP, charge passed (coulombs)	WA (%)
Mix 1, 28 days	407	1.79
Mix 1, 56 days	369	1.58
Mix 2, 28 days	1,100	2.87
Mix 2, 56 days	844	2.63
Mix 2, 28 days (improved)	616	1.18

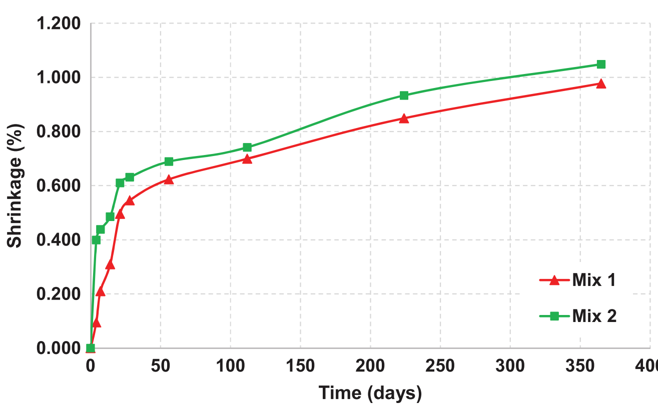


Fig. 10. Shrinkage test results. Standard deviations are 0.041% for 3-day, 0.082% for 7-day, 0.068% for 14-day, 0.078% for 21-day, 0.01% for 28-day, 0.098% for 56-day, 0.088% for 112-day, 0.12% for 224-day, and 0.097% for 1-year measures.

and shrinkage stresses. Other researchers also reported higher drying shrinkage for recycled-aggregate concrete compared with the conventional counterpart (Fathifazl et al. 2011; Silva et al. 2015a); however, the effect of RCA here was relatively less significant (within 10%), possibly due to the use of slag as a supplementary cementitious material (Kou et al. 2011).

From these results, the strong negative effect of the combined use of seawater and RCA on concrete properties is apparent. Although this was somewhat expected, the quantification of these negative impacts is important, because it allows for the design of appropriate strategies which may be used to reduce these impacts.

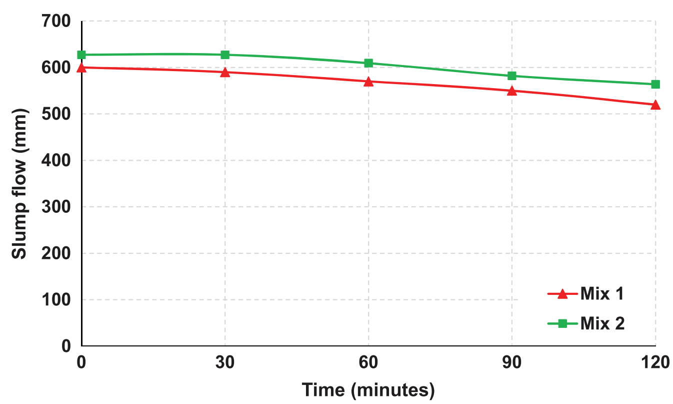


Fig. 11. Slump flow after changes in mixture design for Mix 2.

Several such strategies can be envisioned, but only some are explored here, and further studies of the feasibility and sustainability of such changes are being carried out.

Improving Performance of Concrete with Seawater and RCA

To improve the performance of concrete made with RCA and seawater, the mixture design of Mix 2 was changed to improve the slump flow, compressive strength, water absorption, and chloride permeability. The following changes were made to Mix 2: (1) a dosage of $0.75\ L/m^3$ of commercial retarder (CHRYSOPlast CQ240, CHRYSO Gulf) was used, (2) the superplasticizer dosage was increased by 40% compared with the conventional mix, and (3) the w/cm ratio was reduced from 0.34 to ~0.31 by slightly increasing the cement content (by ~9%). These changes significantly improved the workability (Fig. 11), strength (Fig. 12), and permeability (Table 3) of Mix 2 concrete. The resulting properties of Mix 2 concrete were comparable with those of the conventional Mix 1.

The improvement in fresh concrete properties of Mix 2 can be mainly attributed to the use of chemical admixtures (Matias et al. 2013), whereas the improvement in hardened properties likely resulted from reducing the w/cm ratio (Marinković et al. 2010).

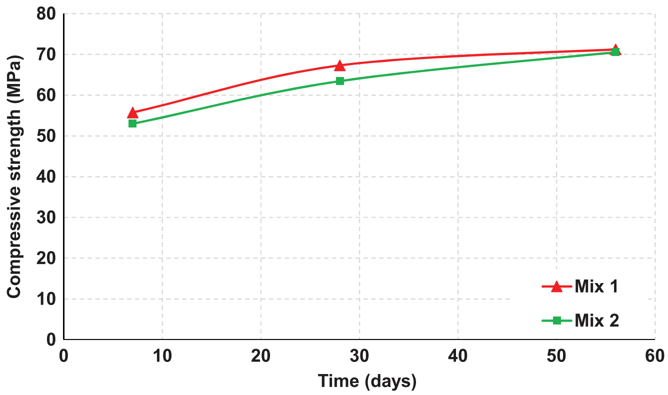


Fig. 12. Compressive strength results for Mix 2 concrete after applying mixture design improvements, considering standard curing conditions. Standard deviations at Days 7, 28, and 56 are 0.54, 1.16, and 1.74 MPa for Mix 1 and 0.67, 0.88, and 0.40 MPa for Mix 2.

These results provide evidence of the applicability of using seawater and RCA in concrete mixtures, especially with appropriate consideration of chemical admixtures and mixture proportions. However, the methods implemented here, despite being effective, are not necessarily green. Life-cycle analysis and similar analyses likely are required before optimal improvement strategies for the use of concrete containing seawater and RCA can be fully understood. Recent research efforts suggest that carbonation treatment of RCA may represent a more viable solution that not only improves the performance of RCA concrete but also represents a more environmentally friendly approach (Shi et al. 2016; Singh and Singh 2018; Zhang et al. 2015). Other strategies include the use of pulverized fuel ash, silica fume, and crystalline admixtures, which have shown potential to improve concrete performance in chloride-rich environments (Borg et al. 2018).

Summary and Conclusions

This work compared two concrete mixtures, namely conventional concrete (Mix 1) and seawater-mixed recycled-aggregate concrete (Mix 2). An experimental program was conducted to characterize the raw materials and to measure the fresh and hardened properties of the concretes. Based on the results of this study, the following conclusions were drawn concerning the effects of combining seawater and RCA in concrete (compared with conventional concrete):

- Combining seawater and RCA reduced the concrete density (by approximately 5%) and increased the air content of the fresh concrete. This is attributed to the effects of RCA rather than of seawater.
- Combining seawater and RCA resulted in a significant reduction in the slump flow (25%), initial setting time (50%), and also the workability retention (Mix 2 remained flowable for only half as much time as Mix 1).
- Combining seawater and RCA resulted in a significant reduction in the strength gain of hardened concrete (approximately 33%) at all ages. Scanning electron microscopy results showed some changes in microstructure between Mix 2 and Mix 1 which potentially could explain the poor strength performance.
- Long-term seawater curing (up to 1 year) increased the compressive strength of hardened concrete but reduced the tensile strength.
- Mix 2 had slightly increased drying shrinkage (approximately 10%) compared with Mix 1, mostly due to the effects of having RCA in the mixture.
- Combining seawater and RCA resulted in reduced permeability, evidently from the increase in charge passed and also from the increase in water absorption of Mix 2 over the allowable limits.
- Mixture design modifications were proposed to overcome the performance issues associated with the use of seawater and RCA, using chemical admixtures and adjusting w/cm ratio.

Although the fundamental observations in terms of behavior may be generalized, the preceding conclusions and specifically the numbers listed are valid for the materials and the specimens used herein. Future research is required to shed further light on the effect of combining seawater and RCA in concrete mixtures, while considering different compositions and test methods. Other greener approaches, such as RCA carbonation treatment, also can be investigated to improve the performance of the proposed concrete mixture.

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