

Article

Mechanical Properties of Seawater Sea-Sand Concrete Exposed to Daily Temperature Variations

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Abstract: The durability of a concrete structure is affected by temperature cycles that occur during the structure's service life. This paper presents an experimental and theoretical study of the mechanical properties of seawater sea-sand concrete when exposed to temperature variations. By using compressive tests on cylindrical concrete specimens, the effects of thermal cycling (e.g., the amplitude of temperature variations and cycling times) on the mechanical properties of seawater sea-sand concrete, such as failure modes, compressive strength, stress–strain relationship, Young's modulus, ultimate strain, Poisson's ratio and toughness are investigated. Microstructures of both unconditioned and conditioned concrete samples are examined by using scanning electron microscopy (SEM) to understand the mechanisms behind the strength changes. Finally, the stress–strain model is proposed for seawater sea-sand concrete subjected to daily temperature variations, and the proposed model is verified by the experimental data.

Keywords: daily temperature variations; seawater sea-sand concrete; compressive strength; microstructure; stress–strain model



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1. Introduction

In recent decades, a shortage of raw materials for concrete has led to the use of recycled materials [1–4] and seawater sea-sand concrete (SSC) in construction [5–7]. As they are abundant marine resources, the usage of seawater and sea-sand also provides social, economic and environmental benefits. Past studies [8] indicated that sea-sand has a desirable particle size, high hardness and low mud content. These features make it a suitable constructional sand, given the fact that sand with higher mud content can reduce the strength and durability of concrete. Although river sand generally has desirable particle shape and particle size distribution and low mud content, the extensive exploitation of river sand can negatively impact ecosystems and the environment. However, a major concern regarding the application of SSC into structures is that the chloride ions in seawater and sea-sand can rapidly erode the conventional steel reinforcements in concrete [9–11]. Commonly, sea-sand requires desalination treatment to remove the corrosive ions, but this process certainly increases the construction cost. Recently, scholars proposed using fiber-reinforced polymer (FRP) materials to reinforce SSC [12–14]. As FRP is immune to chloride corrosion, no special treatment is needed for FRP-SSC structures [15]. Therefore, with the utilization of corrosion-resistant reinforcing materials, SSC structures can potentially be applied to marine structures [16], coastal infrastructures, bridges [17] and pavements [18]. Seawater and/or sea-sand concrete has been used in some engineering projects, especially plain concrete in Japan [16]. A demonstration project in an EU–US project named SEACON has successfully used FRP bars to reinforce concrete bridge decks that came into contact with de-icing salt [8] (Figure 1).

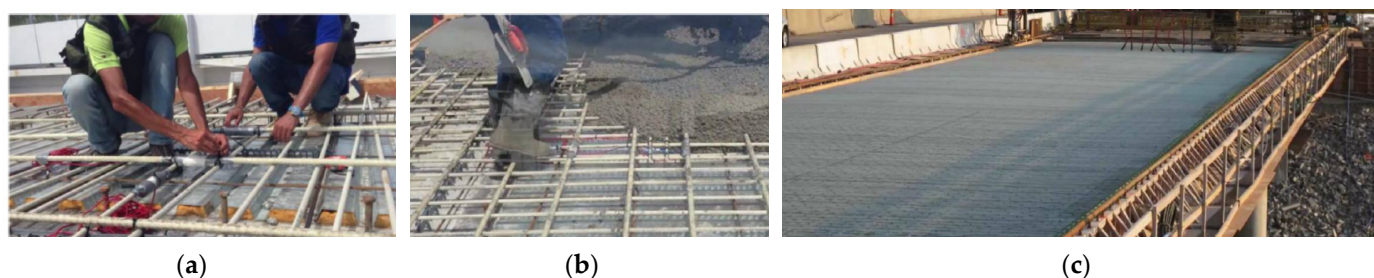


Figure 1. Demonstration project for FRP-SSC bridge decks: (a) FRP mesh; (b) concrete casting; (c) bridge deck (Adapted from Ref. [8]).

Concrete structures are likely to be subjected to various factors that affect their durability [19], such as corrosive agents [20], freezes and thaws, alkali–aggregate reactions, cyclic loads [21], elevated temperatures [22], temperature cycles [23] or a combination of these factors [24]. Among them, the daily temperature is one of the most common types of environmental loads. In some coastal areas, the surface temperature of concrete could reach 60–70 °C upon being directly exposed to sunlight, and the temperature could quickly decrease during the night or due to rainfall, resulting in a periodic change in temperature. Although the natural temperature may not obviously affect concrete durability, large numbers of temperature cycles could deteriorate its mechanical properties. Temperature variations cause curling and the expansion/contraction of concrete slabs, which is a critical factor affecting the behavior of pavements [25]. Nam et al. [26] investigated the effects of daily temperature variations on the continuous deflection profiles of airfield-jointed concrete pavements. The internal stress of concrete caused by daily temperature variations can lead to cracks, reducing the durability of concrete structures. Liu et al. [27] found that the changes in modal frequencies induced by temperature variations can be more obvious than those caused by structural damage and proposed a new method to quantify the effects of temperature on modal frequencies. An et al. [28] analyzed the influence of temperature cycling on the mechanical behavior of high-performance concrete and indicated that the compressive strength, splitting strength and elastic modulus decreased when the number of temperature cycling times increased. Liu et al. [29] found that the static and dynamic behavior of recycled aggregate concrete decreased obviously due to the daily temperature variations. Thus far, only a few studies have been conducted to understand the behavior of concrete subjected to temperature variations, and no study, to the best of the authors' knowledge, has been conducted on seawater sea-sand concrete subjected to daily temperature variations. As daily temperature variations are an important factor affecting the durability of concrete, it is necessary to fill the aforementioned knowledge gap to promote the further application of SSC structures.

In this paper, axial compressive tests were conducted on SSC cylindrical specimens to measure mechanical properties such as compressive strength, Young's modulus, ultimate strain, Poisson's ratio, toughness and the stress–strain relationship. The effects of daily temperature variations (e.g., thermal cycling times and temperature amplitude) on the mechanical properties of SSC were discussed. With the help of scanning electron microscopy (SEM), the microstructures of SSC exposed to temperature variations were examined. Finally, theoretical models were proposed to predict the stress–strain relationship after thermal cycles.

2. Experimental Program

2.1. Materials

In this study, three grades of seawater sea-sand concrete (SSC) were investigated, and the mixtures are listed in Table 1. SSC was made up of ordinary Portland cement, sea-sand, coarse aggregate, seawater and superplasticizer (SP). Class of the cement was 42.5 MPa, and its specific density was 3112 kg/m³ (data from supplier). Fineness modulus of sea-sand was 2.6 and its apparent density was 2893 kg/m³. The coarse aggregate was made from

the crushed granite, which was in continuous gradation with a minimum size of 5 mm and maximum size of 20 mm, and its apparent density was 2827.5 kg/m^3 . Artificial seawater was used for SSC, and it was prepared in accordance with ASTM D1141-98 [30] by mixing NaCl (24.53 g/L), MgCl_2 (5.2 g/L), Na_2SO_4 (4.09 g/L), CaCl_2 (1.16 g/L), KCl (0.695 g/L), NaHCO_3 (0.201 g/L), KBr (0.101 g/L), H_3BO_3 (0.027 g/L), SrCl_2 (0.025 g/L) and NaF (0.003 g/L) with distilled water. Density of the simulated seawater was 1016 kg/m^3 . The solid mass content and density of superplasticizer were 20% and 1030 kg/m^3 , respectively. Mixing and casting of SSC were conducted in accordance with [31].

Table 1. Mix proportions of SSC.

Concrete	Cement: Seawater: Sea Sand: Gravels: SP (by Weight)
C40	1:0.55:2.101:3.151:0.008
C70	1:0.38:1.613:3.276:0.01
C90	1:0.295:1.054:2.24:0.01

2.2. Simulation of Daily Temperature

Daily temperature variations were simulated by temperature cycles created by an environmental chamber (Figure 2). Parameters of temperature variations were same as the authors' previous study [32], which included four kinds of temperature variations (e.g., 25~40, 25~60, 25~80 and 25~100 °C) and five cycling times (e.g., 30, 60, 90, 120 and 150 times). Based on past studies [33], the average annual temperature and humidity of the coastal city Guangzhou are 24 °C and 70%, respectively (Figure 3). The maximum temperature of bridge surface is about 50 °C. Therefore, this study selected 25 °C as the baseline temperature and temperature variations of 25~40 °C and 25~60 °C. The selection of 25~80 and 25~100 °C in this study is to accelerate the degradation rate of concrete. The relative humidity is selected as 70%. Heating regime for a temperature cycle included heating to the target temperature at $1.25 \text{ }^\circ\text{C/min}$, a maintained temperature stage for 4 h, a natural cooling stage to the ambient temperature and another maintained temperature stage for 3 h. Relative humidity for specimens was set as 70% to simulate the humidity of a specimen encountered in a real environment.

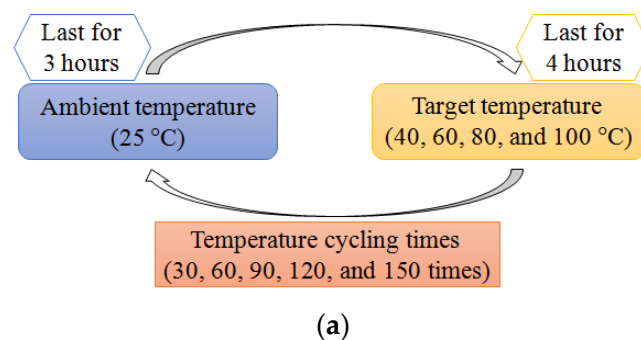


Figure 2. Simulation of daily temperature variations: (a) cyclic temperature regime; (b) programmable environmental chamber (Adapted from Ref. [32]).

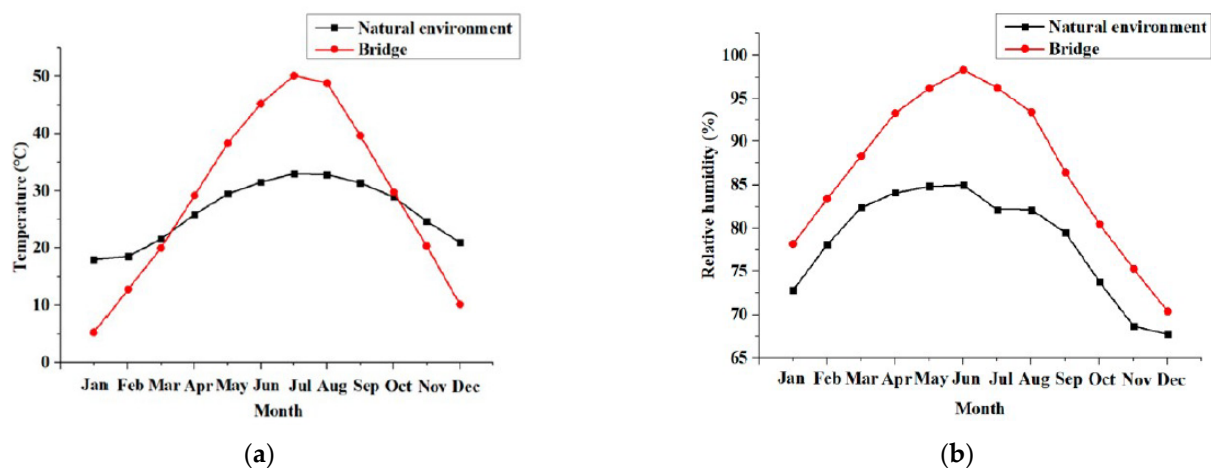


Figure 3. Recorded data for Guangzhou, China: (a) temperature; (b) relative humidity (Adapted from Ref. [33]).

2.3. Specimens

To investigate the influence of daily temperature variations on SSC, concrete cylinders with a diameter of 150 mm and a height of 300 mm were prepared. There were thirteen groups of compressive specimens, as listed in Table 2. For each group, three identical specimens were prepared. In total, thirty-nine compressive specimens were tested. The labels of SSC specimens consist of a strength grade (C40, C70 or C90), “T” followed by target temperature, and “t” followed by cycling times. Letter “N” after strength grade means unconditioned specimens. For example, “C70T60t120” refers to a group of SSC cylinders with a concrete grade of C70 being exposed to cyclic temperatures of 25~60 °C 120 times. Based on the method in [34] that converts concrete cubic strength to cylindrical strength (f_c'), the minimum cylindrical compressive strengths for concrete grades C40, C70 and C90 are 31.6 MPa, 55.3 MPa and 71.1 MPa, respectively.

Table 2. SSC specimens and key experimental results.

Specimen	f_c' (MPa)	E_c (GPa)	ν	ϵ_c ($\mu\epsilon$)	Toughness (MPa)
C40-N	34.1	26.9	0.19	1940	513
C70-N	58.4	37.0	0.23	2250	905
C90-N	77.2	41.5	0.20	2340	977
C40T60t90	42.1	29.8	0.17	1990	1025
C70T60t90	65.7	39.5	0.20	2200	1394
C90T60t90	80.1	42.4	0.20	2380	1447
C70T60t30	61.9	39.7	0.21	2120	1256
C70T60t60	63.3	40.0	0.24	2200	1297
C70T60t120	66.0	38.4	0.19	2140	1647
C70T60t150	67.3	37.9	0.18	2200	1700
C70T40t90	59.9	37.3	0.22	1860	923
C70T80t90	58.3	34.3	0.18	2040	1248
C70T100t90	50.0	32.3	0.18	1760	744

2.4. Experimental Setup and Instrumentation

Compressive tests were conducted on SSC cylinders by using a 4000 kN testing machine in accordance with ASTM C39/C39M [35], and the loading rate was 0.18 mm/min (Figure 4). Two pairs of 50 mm-long strain gauges (one vertical and one horizontal strain gauge for each pair) were oppositely fixed in the middle of cylinders. Due to the appearance of cracks underneath strain gauges, the readings were not accurate during the late loading stage. As shown in Figure 5, if cracks formed underneath the strain gauge, the reading from strain gauge included the influence of the crack openings and no longer represented

the real strain in concrete [36]. The strain gauge readings were only adopted for the measurement of Young's modulus and Poisson's ratio before the cracks started to propagate. Nevertheless, the full-range stress–strain curves were obtained by using linear variable differential transducers (LVDTs), where the strain is equal to the axial shortening (measured by LVDTs) divided by the specimen height. Two LVDTs were installed at the middle height to measure the axial deformation of the middle portion of cylinders (Figure 4). The axial strain is taken as the average value of LVDTs' reading divided by their gauge length, which is 100 mm. Prior to testing, all cylinders were capped with high-strength gypsum, which is a commonly used capping material for concrete compressive tests, to ensure the two ends were smooth and parallel.

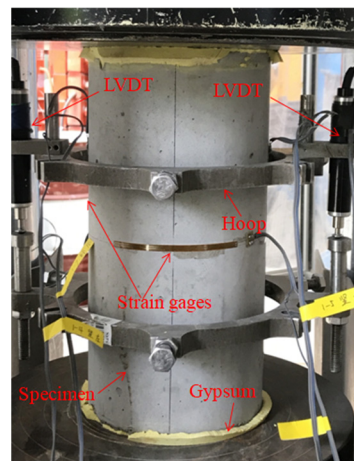


Figure 4. Experimental setup for SSC compressive test.

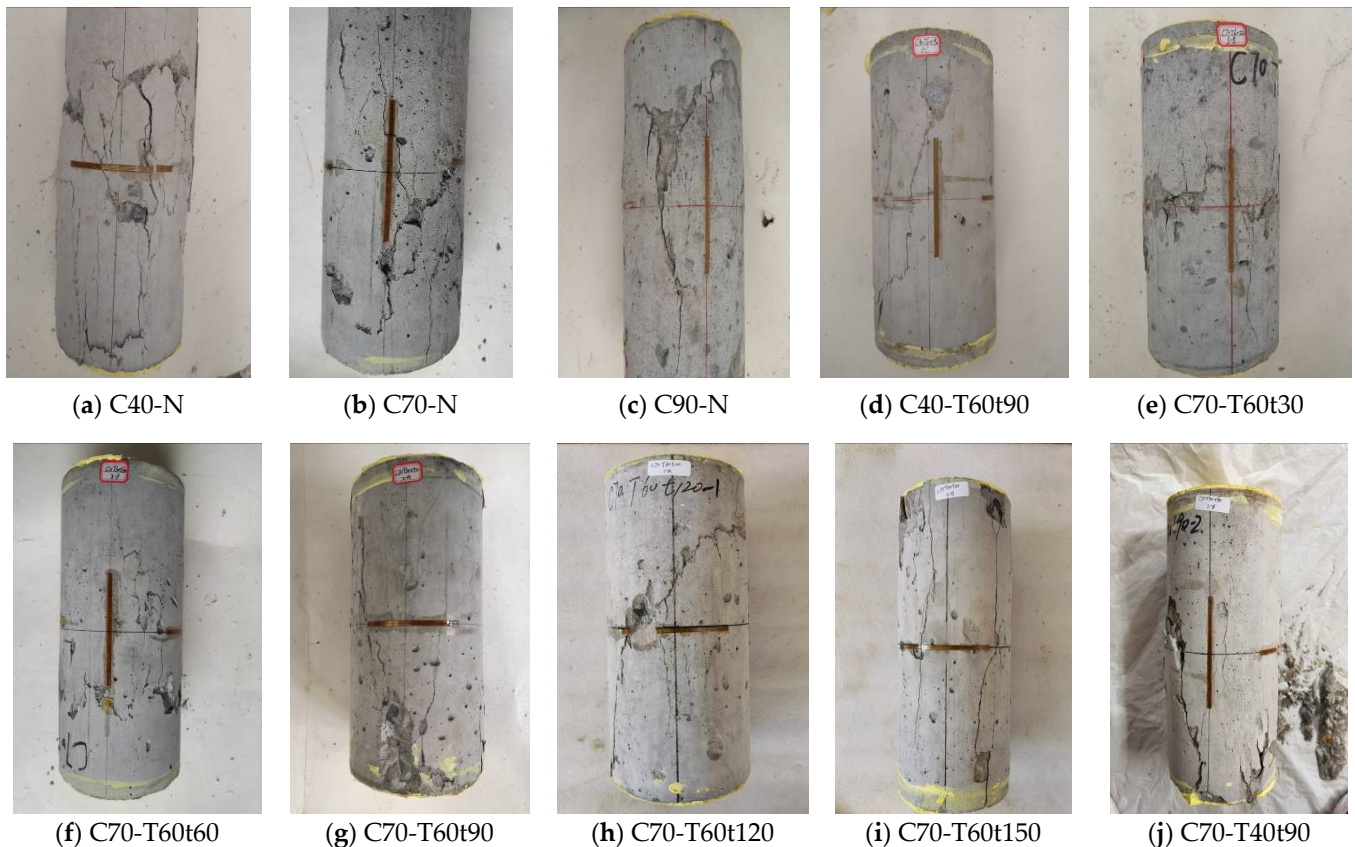


Figure 5. Cont.

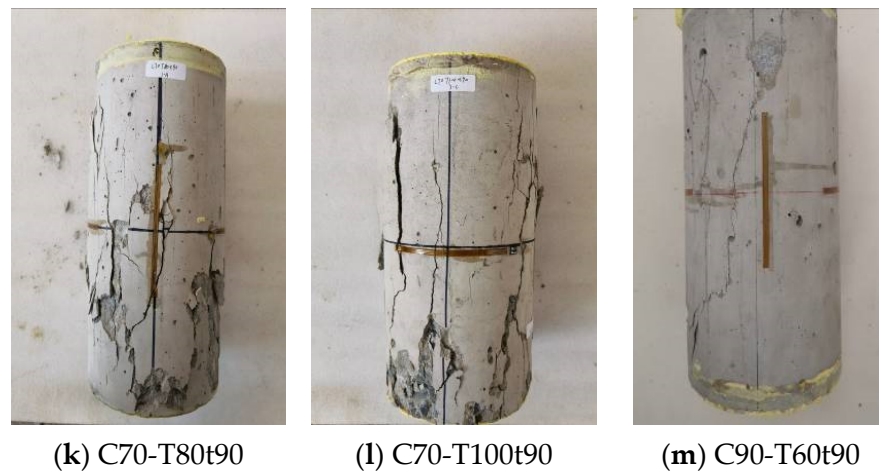


Figure 5. Failure modes of SSC cylinders.

3. Experimental Results and Discussions

3.1. Failure Modes

The failure modes of SSC cylinders under axial compression are shown in Figure 5. Before reaching the peak load, the cracks on the cylinders' surfaces were not obvious, which is in agreement with previous studies [37]. Thereafter, vertical cracks appeared at the middle height. When a further increase in deformation occurred, diagonal cracks appeared and widened, and concrete peeled off. In general, the failure modes of SSC are similar to those of ordinary concrete.

As shown in Figure 5a–c for unconditioned cylinders, when concrete strength increases, the number of cracks is reduced, and the failures become more brittle. Specimens subjected to temperature variations exhibited slightly more severe damage compared to unconditioned specimens. This damage was caused by the deterioration of the internal structure of SSC after temperature variations. Nevertheless, the influences of temperature and cycling times on the failure modes are not obvious based on the current study.

3.2. Stress–Strain Relationship

The stress–strain curves of the SSC cylinders are plotted in Figure 6, where the stress is equal to the applied load divided by the cross-sectional area, and the strain is derived from the LVDT readings. The stress increases linearly, up to about two-thirds of the ultimate stress. At higher stresses, SSC exhibits obvious plasticity. After the peak stress, the applied load drops dramatically until the concrete is crushed.

As shown in Figure 6a, the post-peak curve of unconditioned concrete with a lower strength is less steep, indicating less brittleness, which agrees with the observations of the failure modes. After 60 thermal cycles with a target temperature of 60 °C, SSC strength is enhanced, probably due to further hydration of cement. Nevertheless, the drop in the stress of the conditioned SSC is less rapid than that of the unconditioned specimens. Figure 6b shows the effects of the target temperature, and Figure 6c shows the effects of thermal cycling times on the stress–strain relationship of SSC. In general, thermal cycles substantially affect the post-peak behavior of SSC and lead to less brittle failures. With the increase in target temperature and cycling times, the post-peak portion of the stress–strain curve becomes flatter. However, as shown in Figure 6, the effects of thermal cycling on the ascending part of the stress–strain response are negligible.

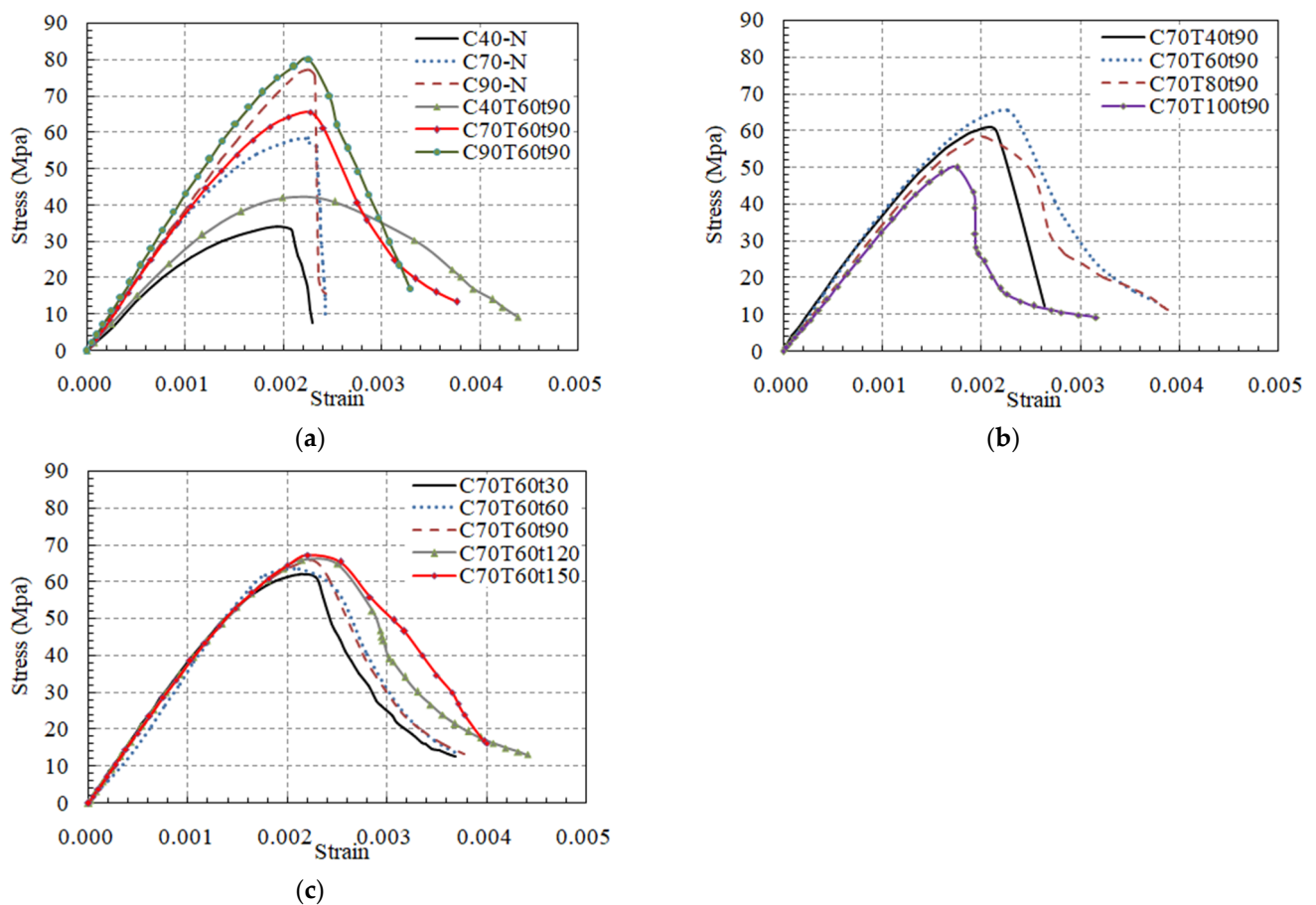


Figure 6. Stress–strain curves of SSC: (a) unconditioned and conditioned specimens; (b) specimens with various target temperatures; (c) specimens with various cycling times.

3.3. Compressive Strength

The cylindrical compressive strength (f_c) of unconditioned SSC and SSC subjected to thermal cycles is listed in Table 2, and the comparison of compressive strength is plotted in Figure 7. After thermal cycles (target temperature = 60 °C and cycling times = 90), the compressive strength increases by 23%, 12% and 4% for SSC with grades of C40, C70 and C90, respectively (Figure 7a). This is mainly caused by the further hydration of cement at 60 °C. SSC with a grade of C90 has the lowest strength increase due to its low free water content during the hydration process. Figure 7b shows the effects of the target temperature on the compressive strength of SSC (cycling times = 90). A strength increase is observed at 40 °C and 60 °C for SSC. However, when the temperature further increases to 100 °C, compressive strength decreases due to the thermal effect, and this observation agrees with past studies on concrete at elevated temperatures [38]. As shown in Figure 7c, when cycling times increase at 60 °C, the compressive strength increases gradually. This is caused by the further hydration of cement at 60 °C, and an increase in cycling times means longer exposure time for SSC. It is expected that this beneficial effect will be mitigated when the hydration process is completed. It is noted that the temperature of SSC subjected to real environments is generally less than 60 °C, and the detrimental effects of these daily temperature variations on SSC strength are not found in the current study.

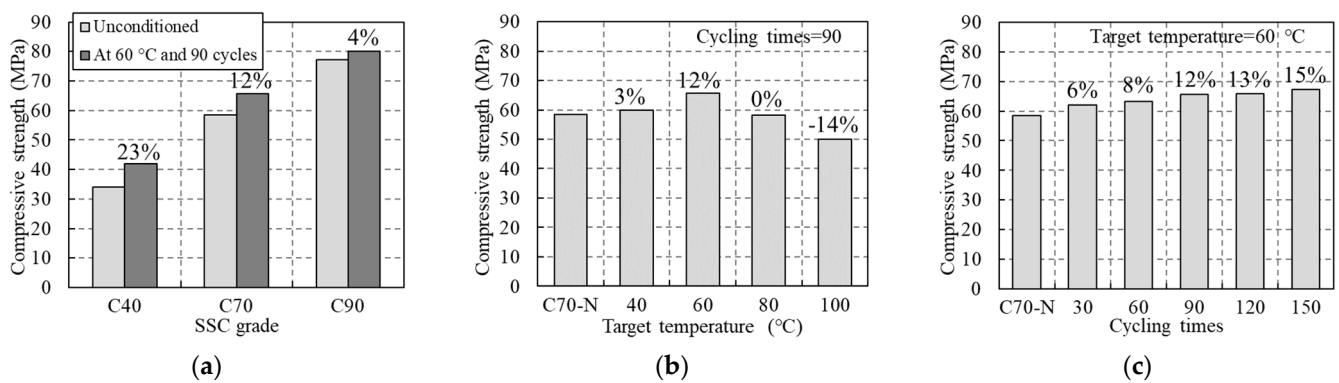


Figure 7. Compressive strength of SSC: (a) effects of SSC grade; (b) effects of target temperature; (c) effects of cycling times.

3.4. Young's Modulus, Ultimate Strain and Poisson's Ratio

It is known that Young's modulus (E_c) of concrete is related to compressive strength (f_c), and a simplified formula is given in ACI318-11 [39].

$$E_c = 4730 \sqrt{f_c} \quad (1)$$

where E_c and f_c are in MPa. Figure 8 shows the experimental data of unconditioned SSC and SSC subjected to thermal cycles, as well as the curve of Equation (1). In Figure 8, specimen C70T60t90 is the benchmark specimen, and the legends "SSC grade", "Cycling time" and "Target temperature" mean conditioned specimens with various grades (C40, C70 and C90), cycling times (30, 60, 90, 120 and 150) and target temperatures (40, 60, 80 and 100 °C), respectively. As shown in Figure 8, the effects of thermal cycles on Young's modulus of concrete are negligible and solely depend on the compressive strength. The relationship proposed in ACI318-11 can be used to estimate Young's modulus of SSC subjected to daily temperature variations.

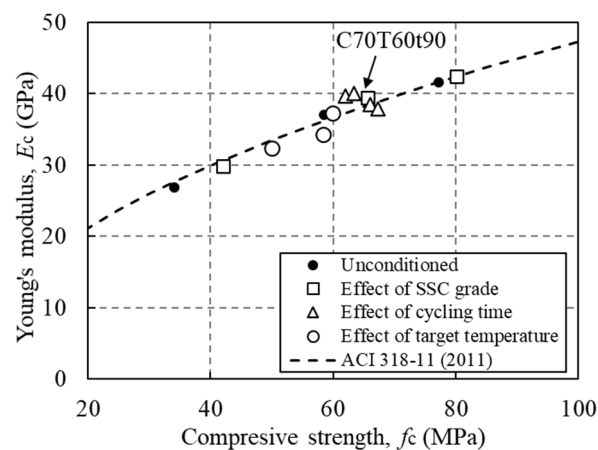


Figure 8. Young's modulus of SSC.

Ultimate strain (ϵ_c) is the strain of concrete at compressive strength (f_c). Past research found that ultimate strain is related to f_c , and Popovics [40] proposed Equation (4) to estimate the ultimate strain of concrete:

$$\epsilon_c = 0.000937 \sqrt[4]{f_c} \quad (2)$$

where f_c is in MPa. The relationships between the ϵ_c and f_c of tested specimens are presented in Figure 9, along with Equation (2). In general, the ultimate strain of SSC is mainly controlled by its compressive strength, and the effects of thermal cycling (e.g., target

temperature and cycling times) are insignificant. The form of Equation (2) is still suitable for SSC, but the coefficient needs to be refined.

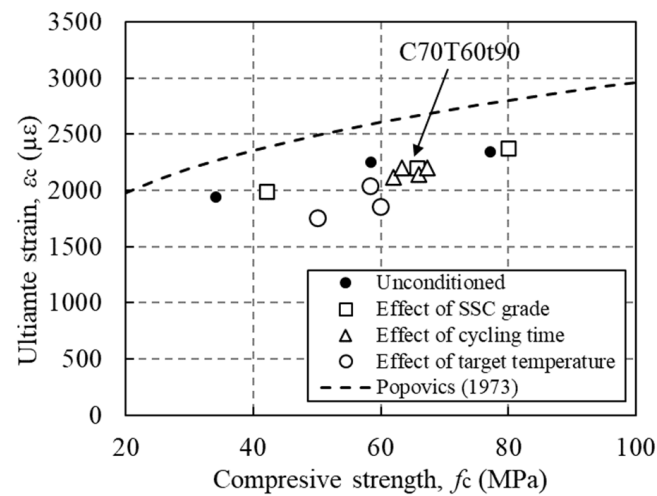


Figure 9. Ultimate strain of SSC.

Poisson's ratio is the ratio of the transverse strain to that of the axial strain of SSC under axial compression. It is a parameter representing the dilation property of concrete. As shown in Figure 10, Poisson's ratio of SSC ranges from 0.17 to 0.24 regardless of compressive strength. The relationship between Poisson's ratio and compressive strength is not clear. Figure 11 indicates that thermal cycling could affect Poisson's ratio of SSC to some extent. With the increase in target temperature and cycling times, Poisson's ratio is generally in a decreasing trend. This is probably due to the changes in the microstructure of SSC after thermal treatment. Nevertheless, if accounting for the discrepancies between Poisson's ratio and the measurements, the effects of thermal cycling on Poisson's ratio of SSC is not significant.

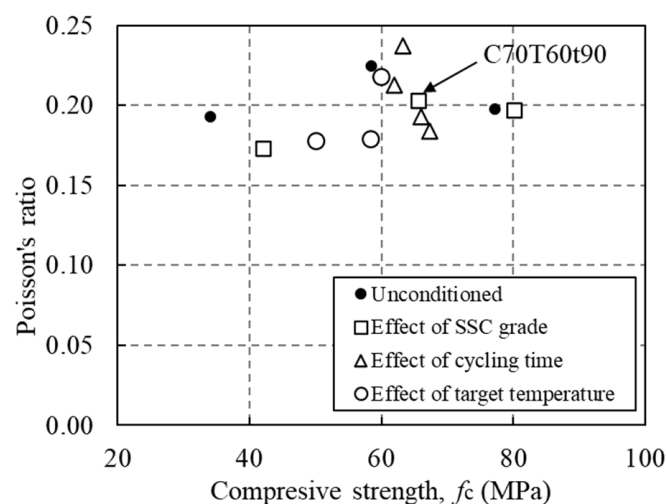


Figure 10. Relationship between Poisson's ratio and compressive strength.

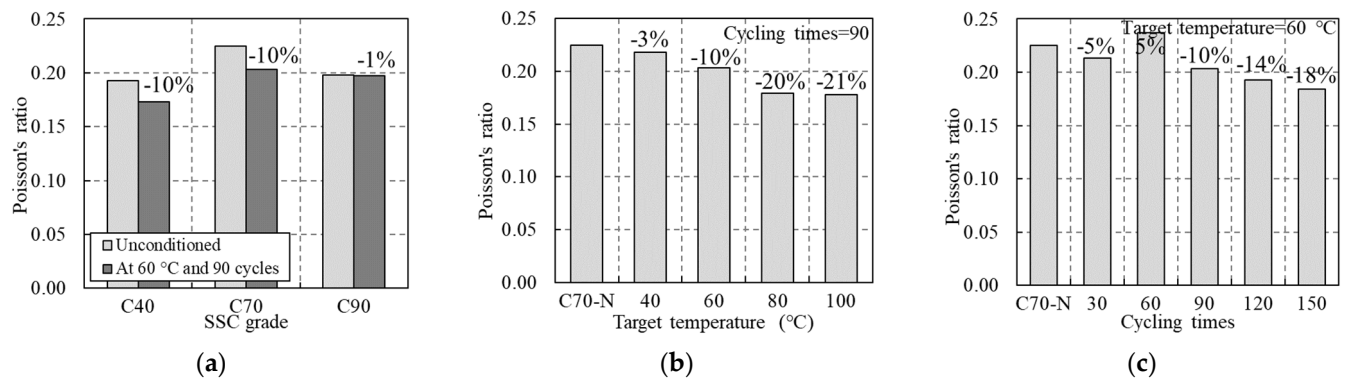


Figure 11. Poisson's ratio of SSC: (a) effects of SSC grade; (b) effects of target temperature; (c) effects of cycling times.

3.5. Toughness

Toughness is an index that represents the capability of concrete to absorb energy, which is generally defined as the area covered by the stress–strain curve of SSC. Due to the difficulty of obtaining a full-range curve of concrete, a “cut-off” method is adopted in which the stress–strain curve is terminated when the stress drops to 20% of the compressive strength [41]. The toughness of the specimens is listed in Table 2. Figure 12 shows the relationship between the toughness and the compressive strength of SSC, and Figure 13 shows the effects of concrete grade, target temperature and cycling times on the toughness. In general, concrete with high compressive strength and a flat post-peak branch of the stress–strain curve has a higher toughness. As shown in Figure 12, toughness increases when concrete strength increases. The toughness of SSC subjected to thermal cycling is higher than that of unconditioned SSC (Figure 13a). When the target temperature increases, toughness first increases and then decreases (Figure 13b). Furthermore, toughness increases when the number of cycling times increases (Figure 13c). These changing trends are similar to those of the compressive strength shown in Figure 7.

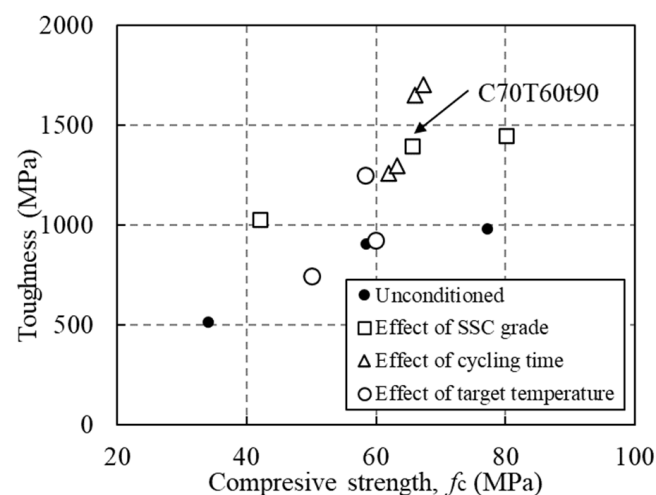


Figure 12. Relationship between toughness and compressive strength.

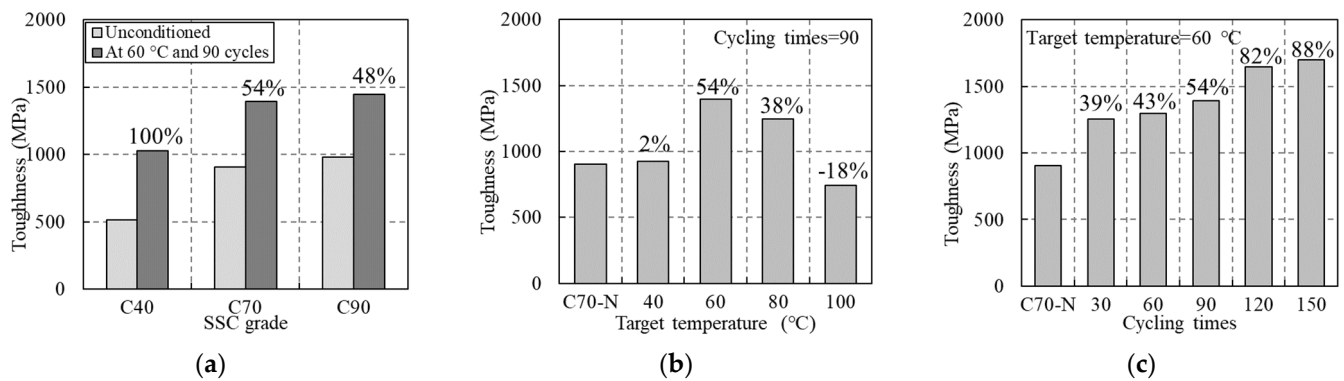


Figure 13. Toughness of SSC: (a) effects of SSC grade; (b) effects of target temperature; (c) effects of cycling times.

3.6. Microstructures of SSC

In order to understand the strength change mechanism of SSC, scanning electron microscopy (SEM) was conducted on SSC before and after thermal cycling using a scanning electron microscope TM3030. The samples were preheated at 40 °C for 2 days to remove any moisture. SEM images of SSC are presented in Figure 14. In unconditioned specimen C70-N, small pores, which are the capillary voids not filled by hydration products, can be found (Figure 14a). After thermal cycling (at 40 °C and 90 times of thermal cycling, Figure 14b), the surface becomes relatively smooth, as some voids are filled during further hydration. Nevertheless, if the temperature is high (e.g., 100 °C), microcracks are observed in the aggregate-to-paste interface. These microcracks are caused by the unmatched expansion of paste and aggregates. Due to the repeated expansion and contraction that occurred during thermal cycles, the microcracks are noticeable, and they deteriorate the strength of SSC. Furthermore, some minor cracks are found in the paste, probably due to drying shrinkage (i.e., water loss at high temperature). For specimens with a target temperature of 60 °C and various cycling times (Figure 14d,e), microcracks in the interfacial transition zone are not obvious. Based on the SEM images, thermal cycling of 60 °C does not deteriorate the microstructure of SSC. These observations agree with the experimental results of SSC strength, as discussed in Section 3.3.

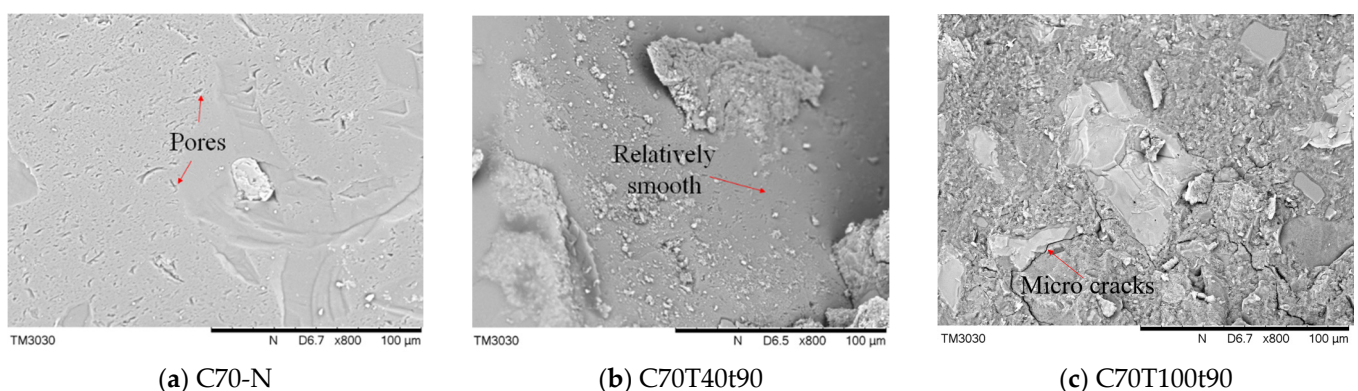


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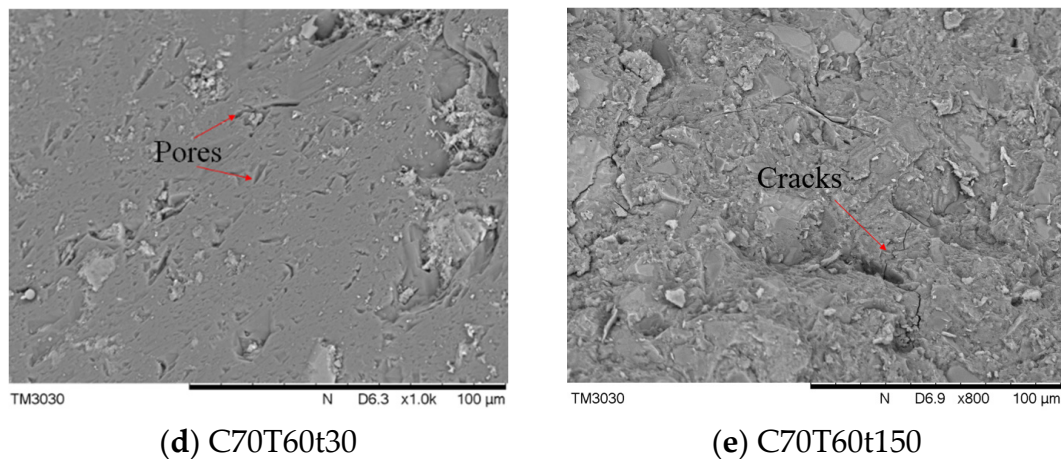


Figure 14. SEM images of SSC.

4. Stress–Strain Model for Seawater Sea-Sand Concrete

4.1. Concrete Strength and Corresponding Strain

Based on the experimental observations, the compressive strength of SSC after thermal cycling is mainly governed by its original strength (i.e., the strength of unconditioned SSC), the target temperature and the thermal cycling times. By using regression analysis, Equation (3) is proposed to estimate the strength of SSC:

$$f_c^T = f_c(139 - 0.46f_c)(-0.13T^2 + 15.8T + 503)(0.68P + 926) \times 10^{-8} \quad (3)$$

where f_c^T is the compressive strength of SSC after thermal cycling, f_c is the compressive strength of unconditioned SSC, T is the target temperature and P is the number of cycling times. As discussed in Section 3.4, Equation (2) for predicting the ultimate strain of SSC is still applicable, but the coefficient needs to be refined. Therefore, Equation (4) is proposed to estimate the ultimate strain of SSC after thermal cycling (ϵ_c^T).

$$\epsilon_c^T = 0.000747 \sqrt[4]{f_c^T} \quad (4)$$

where f_c^T is in MPa and can be determined by Equation (3). It is necessary to mention that Equation (4) is also applicable to unconditioned SSC. A comparison between the experimental and predicted results of the compressive strength and ultimate strain is shown in Figure 15. The average predicted-to-experimental ratio of f_c^T for specimens tested in this study is 0.99 with a coefficient of variation (COV) of 0.02, whereas the average ratio of ϵ_c^T is 1.00 with COV = 0.07. The prediction shows good accuracy. It is necessary to mention that Equation (3) is valid for $T = 40\text{--}100\text{ }^\circ\text{C}$ and $P = 30\text{--}150$, and further experimental verification is needed if the parameters are out of the range.

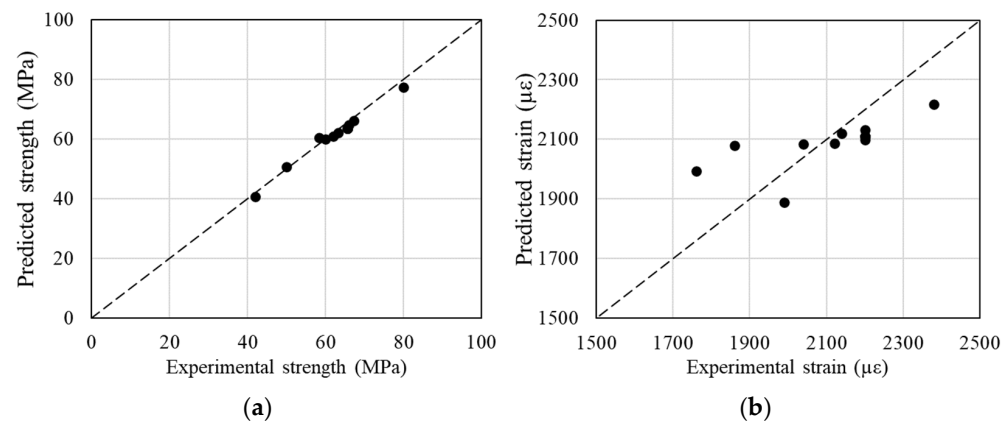


Figure 15. Comparison between the experimental and predicted results: (a) compressive strength; (b) ultimate strain.

4.2. Stress–Strain Relationship

The stress–strain relationship is a graphical representation of concrete behavior that relates applied stress to concrete deformation. Knowledge of the deformability of concrete is necessary to compute the deflections of structures. Furthermore, the stress–strain relationship is a compulsory input for finite element analysis when accounting for material nonlinearity. Due to the degradation of concrete properties, the stress–strain relationship of SSC exposed to temperature variations may differ from that of conventional concrete. Based on an existing stress–strain model, new formulas were proposed to estimate the stress–strain curve of SSC.

In Li et al.'s study [42], a two-range stress–strain (σ – ϵ) model was proposed:

$$\sigma = \begin{cases} f_c \left[a \frac{\epsilon}{\epsilon_c} + (3 - 2a) \left(\frac{\epsilon}{\epsilon_c} \right)^2 + (a - 2) \left(\frac{\epsilon}{\epsilon_c} \right)^3 \right] & (\epsilon < \epsilon_c) \\ f_c \frac{\epsilon/\epsilon_c}{b(\epsilon/\epsilon_c - 1)^2 + \epsilon/\epsilon_c} & (\epsilon \geq \epsilon_c) \end{cases} \quad (5)$$

where ϵ_c is the ultimate strain, f_c is the compressive strength and a and b are factors controlling the shape of the stress–strain curve. As shown in Figure 6, thermal cycling does not affect the ascending branch of the σ – ϵ curve of SSC. In Li et al.'s study [42], factor a represents the ratio of Young's modulus to the secant slope at the peak stress of the SSC σ – ϵ curve (i.e., E_c -to- f_c/ϵ_c ratio). As Young's modulus is a function of concrete strength (Equation (1)), factor a could be determined by:

$$a = \frac{3.53}{\sqrt[4]{f_c^T}} \geq 1 \quad (6)$$

A high value of factor a for SSC means the nonlinearity of the ascending branch of the σ – ϵ curve is insignificant. Factor b mainly controls the steepness of the descending branch of the σ – ϵ curve, which can represent the ductility and toughness of concrete. Based on the experimental results of this study, an empirical formula is proposed to estimate factor b :

$$b = (0.29f_c^T - 9.16)(-0.067P + 16)(0.234T^2 - 30.56T + 1092) \times 10^{-3} \quad (7)$$

where f_c^T is the compressive strength of SSC after thermal cycling, T is the target temperature and P is the number of thermal cycling times. After determining factors a and b , the stress–strain relationship of SSC subjected to thermal cycling could be obtained by utilizing Equation (5). A comparison between the predicted and experimental stress–strain curves of SSC specimens is shown in Figure 16. The prediction closely matches the experimental results, which verifies the reasonability of the proposed model.

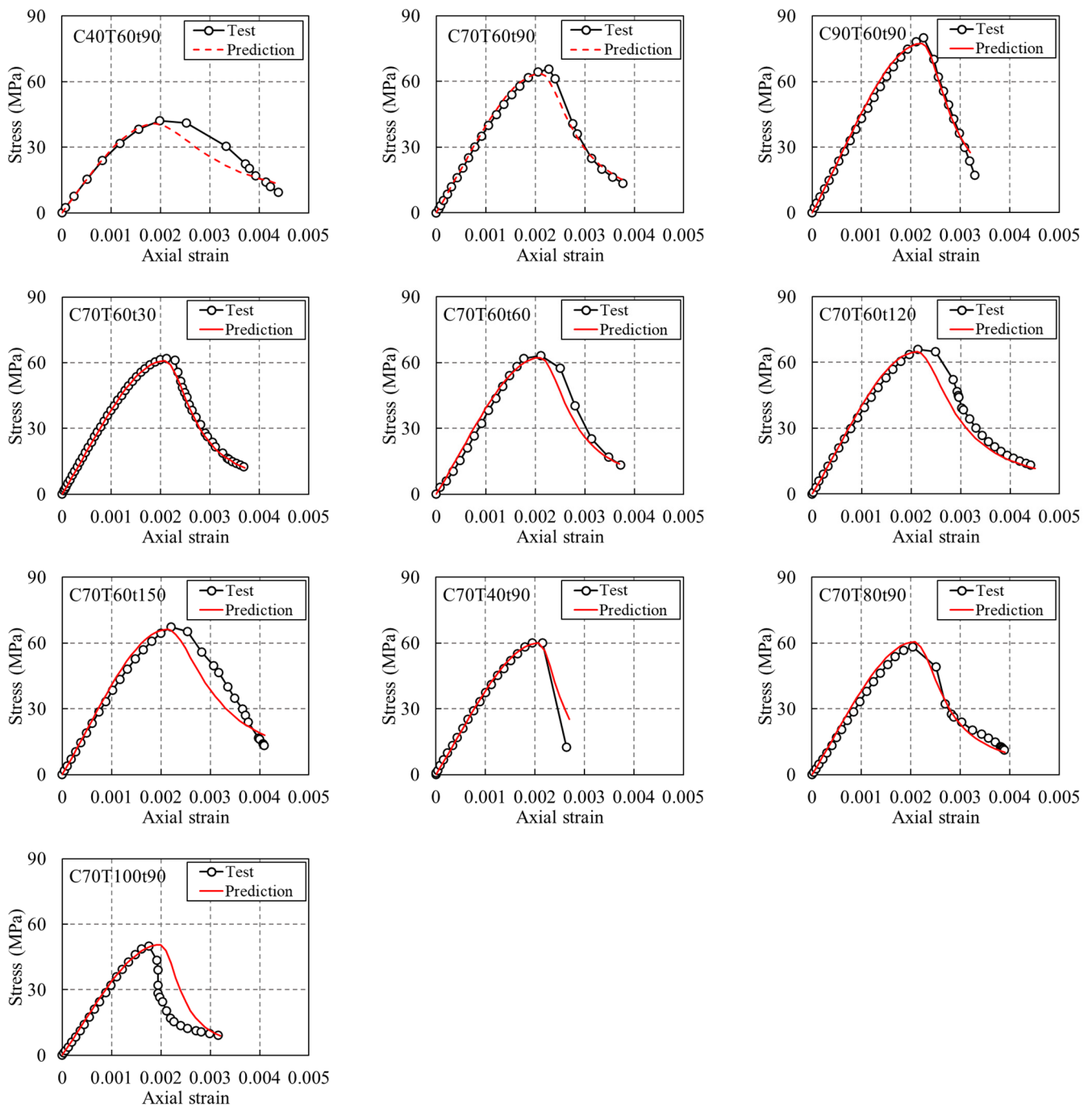


Figure 16. Prediction of stress–strain relationship of SSC subjected to thermal cycles.

5. Conclusions

This paper mainly investigates the effects of temperature variations (e.g., target temperature and thermal cycling times) on the mechanical properties of seawater sea-sand concrete (SSC). The conclusions drawn are as follows:

- (1) At 60 °C, the compressive strength of SSC increases when the number of thermal cycling times increases due to the further hydration of cement. However, if the target temperature is 100 °C, the compressive strength of SSC is reduced, as microcracks are formed in the SSC interfacial transition zone by the unmatched expansion and contraction of aggregates and paste.

- (2) Young's modulus and the ultimate strain of SSC are functions of compressive strength, and the influence of thermal cycling is indirect. Poisson's ratio of SSC decreases slightly with the increase in cycling times.
- (3) Compared to that of unconditioned SSC, the toughness of SSC subjected to thermal cycling is higher, as the strength is increased, and the post-peak branch of the stress–strain curve is flat.
- (4) A theoretical model is proposed to predict the stress–strain relationship of SSC under temperature variations, and the prediction closely matches the experimental results. It is necessary to mention that the proposed formulas are based on the specimens with temperatures ranging from 25 to 100 °C and cycling times ranging from 30 to 150 times.

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