Investigation on compression properties of seawater-sea sand concrete

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Abstract. This paper introduces the experimental results of the influence of sea sand replacement rate and mixing water on the basic mechanical properties of sea sand concrete. A total of thirty test blocks were designed for uniaxial compression test. In this test two parameters were considered: (a) sea sand replacement ratio (i.e., 0%,25%, 50%,75%, 100%); (b) water for mixing (i.e., freshwater, seawater). The entire stress-strain curve of sea sand concrete under uniaxial compression was obtained. Based on the test results, the influence of sea sand replacement rate and mixing water on the peak stress, peak strain, and deformation performance of sea sand concrete were analyzed. Test results showed that the stress-strain curves of seawater sea sand concrete were steeper than that of ordinary concrete, which indicated that seawater sea sand concrete was slightly more brittle. On the whole, the sea sand replacement rate had no significant effect on the axial compressive properties of sea sand concrete. Under the same sea sand replacement rate, the deformation performance of freshwater sea sand concrete (FSC) was slightly greater than that of seawater sea sand concrete (SSC). Seawater had an enhanced effect on the early strength development of sea sand concrete.

Keywords: entire stress-strain curve; mixing water; sea sand concrete; sea sand replacement ratio; uniaxial compression

1. Introduction

Concrete is currently the most widely used building material. The rapid development of concrete projects also consumes a large amount of fresh water and river sand, which exacerbates the shortage of resources. On the other hand, if the common aggregate and freshwater are used in the construction of island reef project, they will be transported by ships from mainland. This mode of transportation will face problems of high freight, and vulnerability to wind, waves and is difficult to guaranteeing time limits (Yang et al. 2020, Ma et al. 2018). In order to solve these challenges, various new types of concrete are emerging in endlessly. Combining with the geographical characteristics of the island and reef project construction, there are abundant sea sand and seawater resources on the island. So seawater concrete and sea sand concrete have become the research hotspots. Sea sand concrete refers to the concrete made with sea sand in which sea sand as fine aggregate partially or completely replaces the natural fine aggregate (Belkacem et al. 2014). Seawater concrete refers to the concrete mixed with seawater instead of freshwater. Based on the construction background of coastal and marine island reef projects, this paper uses undisturbed sea sand and seawater to prepare seawater sea sand concrete. Focus on the analysis of characteristic point parameters such as peak stress, peak strain, and deformation performance of seawater sea sand concrete. Discuss the possibility of using seawater-sea sand concrete in actual engineering. It is hoped that the shortage of natural aggregates and fresh water can be solved, and the construction of the island and reef projects can be promoted.

The exploitation and utilization of marine resources have attracted the attention of all countries in the world and scholars from all over the world have carried out research on the aspects of sea sand and seawater preparation concrete and achieved some results. In the 1960s, the application of sea sand as a building material was carried out in the United Kingdom earlier and in 1973 Japan desalinated sea sand into the main fine aggregate of concrete preparation (Xiao et al. 2017). Sea sand has some different characteristics compared with natural river sand fine aggregates, such as containing a large number of shells, less mud content and higher water content. And particle size distribution of sea sand in different sea areas will be different. Regarding the effects of sea sand on the workability of concrete, Limeira et al. (2012) indicated that the mortar's slump decreases as the amount of sea sand added increases, but Liu et al. (2014) believed that the impact of sea sand on the slump of fresh concrete can be ignored. However, most studies have concluded that the workability of concrete decreases with the increase of shell content of sea sand (Chapman and Roeder 2017, Yang et al. 2010, Safi et al. 2015). Compared with freshwater, using seawater to mix concrete can significantly shorten the initial and final setting time of concrete (Ghorab et al. 1990).

The concrete structure in the marine environment is susceptible to chloride ion corrosion. The main manifestation is that the compounds in the concrete are...
corroded by salt solution and acid, which affects the response of concrete structure to different forms of loads. (Ayinde et al. 2019, Deepankar et al. 2016). Sea sand and seawater contain chloride salt, affecting the cement hydration process and accelerating corrosion of the steel bar (Li et al. 2019, Wu et al. 2016, Sajal et al. 2014). Chlorine salt and shells may lead to differences between sea sand concrete and ordinary concrete in mechanical properties and durability (Teng et al. 2019). Compared with ordinary concrete, the early strength of seawater sea sand concrete developed rapidly, and the long-term strength decreased due to the chloride salt (Xiao et al. 2018). In 1998-1999, Cagatay (2004) found that the grain size of sea sand aggregates was small, the content of chloride ions was 20 times that of chlorine ions in ordinary river sands, and the 28-day strength and long-term compressive strength of sea sand concrete were lower than that of ordinary river sand concrete. The durability of seawater sea sand concrete is lower than that of ordinary concrete. Exteberria et al. (2016) studied the mechanical properties of dyke blocks using coarse mixed recycled aggregates, steel slag aggregates and seawater. And the study showed that seawater could improve the compressive strength of concrete for 7 days, the compressive strength of concrete for 28 days is equivalent to that of ordinary concrete, but the compressive strength of one year is lower than that of ordinary concrete. But Liu et al. (2014) demonstrated that chlorine ions and a small number of shells in sea sand have no significant effect on workability, pressure strength, flexural tensile strength and elastic modulus. Dias et al. (2007) and Zhou et al. (2019) conducted the accelerated corrosion tests by changing the content of Cl⁻ in sea sand, and found that when the concentration of free Cl⁻ in sea sand reached 0.3%, the corrosion of reinforcement became obvious. In addition, Mohammed et al. (2004) revealed that using seawater as mixing water makes the reinforcement more vulnerable to corrosion. Karthikeyan and Nagarajan (2017) found the lowest acceptable chloride ion content in sea sands was 0.075%. Liu et al. (2016) studied sandwater ratio, chloride ion content of seawater, moisture content of sea sand and particle size on chloride ion content of sea sand, and the results showed that chloride ion content of seawater and water content of sea sand were significantly linearly correlated with chloride ion content of sea sand.

At present, some scholars have carried out the research of seawater sea sand concrete, but there is less research on the stress-strain constitutive relationship of sea sand concrete, and the influence mechanism of the relevant mechanical properties is not clear. Therefore, based on the construction background of coastal and marine island reef projects, test blocks were prepared from sea sand, seawater, river sand and freshwater. The replacement rate of fine aggregate and mixed water were considered as the variation parameters. Based on the experimental data, the whole process curve of stress and strain of sea sand concrete was studied, the characteristic point parameters such as peak stress, peak strain and ductility were analyzed, and the constitutive relationship of sea sand concrete was discussed. The research results obtained by this paper could provide rich theoretical reference for the construction of coastal and marine reef projects.

### 2. Materials and methods

#### 2.1 Raw materials

In this study, conch P•O 42.5 Portland cement was used. The sea sand was collected from a beach in the South China Sea (location: 21°27′28″N, 109°22′36″E). The apparent morphology of the fine aggregate sample is shown in Fig. 1.

The physical properties of both types of fine aggregate were measured according to Chinese Code for Pebble and Crushed Stone for Construction (GB/T 14685-2011) and shown in Table 1. The test measured the sea sand fineness modulus of 2.456, classified by particle thickness belonged to the middle sand. The natural river sand fineness modulus was 3.0, also belonged to the middle sand. The sieve analysis of sea sand and natural river sand are shown in Fig.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Apparent density (kg·m⁻³)</th>
<th>Bulk density (kg·m⁻³)</th>
<th>Fineness modulus</th>
<th>Cl⁻ (%)</th>
<th>Shell content (%)</th>
<th>Mud content (%)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sea sand</td>
<td>2619</td>
<td>1650</td>
<td>2.456</td>
<td>0.0335</td>
<td>0.34</td>
<td>0.39</td>
<td>1.50</td>
</tr>
<tr>
<td>natural river sand</td>
<td>2500</td>
<td>1540</td>
<td>3.215</td>
<td>—</td>
<td>—</td>
<td>0.48</td>
<td>0.78</td>
</tr>
</tbody>
</table>

![Fig. 1 Apparent morphology of fine aggregate samples](image)

(a) Sea sand

(b) Natural river sand

Fig. 1 Primary performance of the fine aggregate
2 (sea sand 1 and sea sand 2 in Fig. 2 refer to two test samples of the same batch of sea sand). Coarse aggregate used in this study was 10~25 mm continuous grade crushed limestone. The seawater and freshwater which were used as mixing water came from undisturbed seawater in a sea area of the South China Sea and tap water, respectively. The main chemical composition of the seawater is shown in Table 2.

### 2.2 Mix proportions and specimens design

Freshwater, seawater, sea sand and natural river sand were used to prepare freshwater sea sand concrete (FSC) and seawater sea sand concrete (SSC). The designed strength of sea sand concrete used in trials was C30. The mix proportions of freshwater sea sand concrete (FSC) and seawater sea sand concrete (SSC) were designed following Chinese Code for Specification for Mix Proportion Design of Ordinary Concrete (JGJ 55-2011) and shown in Table 3.

In this study, a total of thirty 150 mm×150 mm×150 mm test cubes were prepared. The test cubes with a replacement rate of 0% were the benchmark. In the test cubes which with the same mixing water, the ratio of cement, water, and crushed stone were exactly the same in the sea sand concrete under different sea sand replacement ratio. The materials were mixed in a concrete mixer in order, and then the fresh concrete was cast in the plastic molds and compacted on a vibration table. Specimens were removed from the molds after 3 days and moved to the place where the temperature was 20±2°C and the relative humidity was above 95%. All the specimens were cured for 28 days in standard curing condition.

### 2.3 Test methods

All the specimens were exerted load by using the RMT-301 rock mechanics and concrete mechanics testing machine according to Chinese Code for Test Method of Mechanical Properties on Ordinary Concrete (GB/T 50081-2019). The experimental setup is shown in Fig. 3. The test loading system adopted the displacement control method and the loading rate was 0.01 mm/s. The test stopped loading when the load dropped to 75% of the peak load. The load-displacement curves of the specimen were obtained through the acquisition system. Before the test, the surfaces of specimens were polished to eliminate the effect of the uneven force and the influence of friction between the specimen and machine. The friction between the concrete and the pressure plate made the concrete test block the strongest restraint on the upper and lower end faces, and the weakest restraint in the middle of the test block. This will cause the concrete near the pressure plate to not be in a uniaxial compression state. Polishing the surface of the concrete test block could eliminate the slight unevenness and inclination of the pressure-bearing surface of the test piece and reduce the influence of friction.

### 3. Test results and analysis

#### 3.1 Failure process

The destruction process of the FSC test blocks and SSC test blocks is basically the same. According to the development of cracks, the test block can be divided into four stages from the beginning of test to the final failure, as shown in Fig. 4. Based on these plots, the following observations can be made:

1. At the early loading stage, no obvious cracks appeared on the surface of the test blocks. There was no obvious change in the macro deformation performance of the specimens at this stage. Fig. 4(a) shows the development stage of micro-cracks.
2. Fig. 4(b) shows the failure mode of the test block at the peak load stage. With the increase of load, the first crack or several longitudinal cracks appeared in the test block, and entered the stage of stable development of macro-cracks. In this stage, the area near the surface cracks of the test block rapidly expanded to form more micro cracks and the cracks morphology remained basically stable.
After the peak load stage, the test blocks entered the stage of macro crack unstable development. When the load dropped to 85% of the peak load, the surface cracks of the test blocks suddenly widened and extended and the skin peeled off. The cracks developments were no longer stable. The longitudinal through cracks were gradually formed, as shown in Fig. 4(c).

When the load decreased to 75% of the peak load,

Table 3 Mix proportion

<table>
<thead>
<tr>
<th>No.</th>
<th>Concrete strength</th>
<th>R (%)</th>
<th>W/C</th>
<th>Cement (kg/m³)</th>
<th>Coarse aggregate (kg/m³)</th>
<th>Mixing water (kg/m³)</th>
<th>Fine aggregate (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>freshwater</td>
<td>Sea water</td>
</tr>
<tr>
<td>FSC-0</td>
<td></td>
<td>0</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>FSC-25</td>
<td></td>
<td>25</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>FSC-50</td>
<td>C30</td>
<td>50</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>FSC-75</td>
<td></td>
<td>75</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>FSC-100</td>
<td></td>
<td>100</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>SSC-0</td>
<td></td>
<td>0</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>0</td>
<td>185</td>
</tr>
<tr>
<td>SSC-25</td>
<td></td>
<td>25</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>0</td>
<td>185</td>
</tr>
<tr>
<td>SSC-50</td>
<td>C30</td>
<td>50</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>0</td>
<td>185</td>
</tr>
<tr>
<td>SSC-75</td>
<td></td>
<td>75</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>0</td>
<td>185</td>
</tr>
<tr>
<td>SSC-100</td>
<td></td>
<td>100</td>
<td>0.45</td>
<td>415</td>
<td>1205</td>
<td>0</td>
<td>185</td>
</tr>
</tbody>
</table>

Notes: FSC is short for freshwater sea sand concrete. SSC is short for seawater sea sand concrete. R represents sea sand replacement rate. W/C represents water-cement ratio, where W stands for water and C stands for cement.

Fig. 4 The failure process of concrete test block

(a) Initial stage of loading (b) Peak load stage (c) The load drops to 85% of the peak load (d) The load drops to 75% of the peak load (destruction stage)

Fig. 5 Typical failure patterns of cube modes

(a) Longitudinal crack (b) Square pyramid

(3) After the peak load stage, the test blocks entered the stage of macro crack unstable development. When the load dropped to 85% of the peak load, the surface cracks of the test blocks suddenly widened and extended and the skin peeled off. The cracks developments were no longer stable. The longitudinal through cracks were gradually formed, as shown in Fig. 4(c).

(4) When the load decreased to 75% of the peak load,
that was the final failure stage, the surface of the test block was covered with network cracks and the concrete peeled off. At the same time, the integrity of the test block was further damaged and the bearing capacity was lost, as shown in Fig. 4(d).

3.2 Failure pattern

Fig. 5 shows the section shapes of the sea sand concrete blocks after failure. The failure pattern of SCC test blocks and FSC test blocks under uniaxial compression were basically similar. Their final failure pattern was also similar to ordinary concrete.

Generally speaking, there are mainly two typical failure patterns of sea sand concrete. One was longitudinal split failure, which was characterized by obvious longitudinal split cracks, as shown in Fig. 5(a). During the loading process, the longitudinal cracks continued extending to the middle of the test blocks until they penetrated. Because the concrete test block was made in the horizontal direction, the coarse aggregate sank to the bottom when the concrete was vibrated, and the large surface faces down, and the pores might accumulate under the surface to form a relatively weak surface. During the loading process of the test block, the lower bonding strength of the aggregate was most likely to cause cracks. The cracks will develop up and down along the loading direction, and finally form longitudinal cracks.

The other was quadrangular cone failure, which was characterized by positive and reverse quadrangular cone shape, as shown in Fig. 5(b). Through careful observation, it was found that the cracks of the two failure patterns mainly appeared in the interface between the aggregate and the cement-based material and the interior of the mortar base layer, that was cement stone failure. This showed that the replacement of river sand with sea sand had little effect on the failure mode of concrete. However, it was worth noting that the higher the replacement rate of sea sand, the more obvious the brittle failure characteristics of sea sand concrete.

3.3 Stress-strain whole process curves

Load displacement data obtained by automatic acquisition of test machine. The stress-strain whole curve of the test block is obtained through the conversion of Eqs. (1)-(2).

$$\sigma = \frac{N}{A} \quad (1)$$

$$\varepsilon = \frac{\Delta l}{l} \quad (2)$$

where N is the axial pressure of the test block, A is the sectional area of the test block, \(\Delta l\) is the compression deformation value for the test block, l is the height of the test block.

The stress-strain (σ-ε) curves of freshwater sea sand concrete (FSC) test blocks and seawater sea sand concrete (SSC) test blocks under different replacement rates are shown in Fig. 6.

As can be seen from Fig. 6, the trend of the stress-strain curves of sea sand concrete was similar to that of ordinary concrete, going through the elastic stage, the elastoplastic stage, the peak point, and the descending section. The ascending section and descending section of the curves were basically the same as ordinary concrete, but the SSC in the descending section was steeper than the FSC. The overall trends of stress-strain curves under the different replacement rate were close, which could truly reflect the force deformation and failure characteristics of the test block under each sea sand replacement rate. At the beginning of loading, the strain was approximately proportional and the test block was in the elastic stage. With increasing stress, concrete plastic deformation and micro-cracks continued developing, strain growth accelerates. When approaching peak stress, the stress increase was smaller. The 25% replacement rate of FSC had a most favorable particle gradation, so its peak stress was the highest. The stress-strain curve of the SSC test block was less affected by the sea sand replacement rate. But the falling section of the SSC curve was steeper than the FSC. Therefore, the ductility of freshwater sea sand concrete was better. After the test block underwent peak stress, the crack continued expanding, the strain continued increasing, and the curve appeared to decrease.

3.4 Numerical stress-strain relation

The numerical stress-strain relationship of FSC and SSC
ical expression for \( x < 1.5 \), so it is feasible to extend the expression to recycled aggregate concrete. In this paper, the numerical expression for recycled aggregate concrete and ordinary concrete under axial compression suggested by Guo (2013) was adopted. When the expression is applied to recycled aggregate concrete, the effect of replacement rate of recycled aggregate is considered, so it is feasible to extend the expression to sea sand concrete in this study. The normalized expression for the stress-strain curve of FSC and SSC can be approximated by Eq. (3).

\[
y = \begin{cases} 
  ax + (3 - 2a)x^2 + (2 - a)x^3 & 0 \leq x < 1 \\
  x/[b(x - 1)^2 + x] & 1 \leq x
\end{cases}
\]  

(3)

where \( y = \sigma / \sigma_c \), \( x = \varepsilon / \varepsilon_c \), \( a \) represents the initial slope of the stress-strain curve. \( b \) represents the area surrounded by the falling part of the stress-strain curve.

Fitting the test data can obtain the equation parameters \( a \) and \( b \) values of sea sand concrete under different mixing water and sea sand replacement rate. Fig. 7 is a comparison chart of fitting results of freshwater sea sand concrete with
\( \varepsilon / \varepsilon_c \) as the horizontal coordinate and \( \sigma / \sigma_c \) as vertical coordinate. Fig. 8 is a comparison chart of fitting results of seawater sea sand concrete.

It can be seen from Figs. 7-8 that the test result fits well with Expression 1. When the sea sand replacement rate was 0/25/75, a value of freshwater sea sand concrete was greater than that of seawater sea sand concrete. It showed that under this sea sand replacement rate, the elastic modulus of freshwater sea sand concrete was better. When the sea sand replacement rate was 50/100, the elastic modulus of seawater sea sand concrete was better. At the same time, the b-value of seawater sea sand concrete was larger than that of freshwater sea sand concrete. From the fitting curve, the drop section of seawater sea sand concrete was steeper than the freshwater sea sand concrete. It showed that the brittleness of seawater sea sand concrete was large.

4. Analysis of test variation parameters

4.1 Peak stress and peak strain

According to the stress-strain curve of each test block, the peak stress and peak strain of sea sand concrete test block can be obtained under different replacement rates, as shown in Table 4.

In addition to the replacement rate of 25%, the peak stresses of other seawater sea sand concrete under the same replacement rate were higher than that of freshwater sea sand concrete. The main reason was that salt substances such as sodium chloride and potassium sulfate in seawater and sea sand could accelerate the hydration of minerals such as tricalcium silicate in cement and promote the process of cement hydration, which was conducive to early strength development. But with the increase of the replacement rate, the soluble salt content gradually increased and the deterioration of concrete was accelerated by the capillary action penetrates into the concrete interior. Xiao et al. (2018) found that in the early intensity development stage of sea sand concrete, the erosion of sulfate caused sulfate to react with calcium hydroxide and hydrated calcium aluminate in cement to form hydrated calcium sulphoaluminate. The substance produced by this chemical reaction had a certain expansion. It had an adverse effect on the long-term strength development of sea sand concrete.

The influence of substitution rate and mixed water type on the peak stress and strain of sea sand concrete is shown in Fig. 9. Based on these plots, the following observations can be made:

![Fig. 9](image-url)

**Fig. 9** The influence of changing parameters on the peak stress and peak strain of sea sand concrete
Table 5 Strain ductility coefficient of sea sand concrete with different sea sand replacement rate

<table>
<thead>
<tr>
<th>Item</th>
<th>Concrete</th>
<th>R-0%</th>
<th>R-25%</th>
<th>R-50%</th>
<th>R-75%</th>
<th>R-100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>failure strain=$10^{-3}$</td>
<td>FSC</td>
<td>1.993</td>
<td>1.751</td>
<td>2.016</td>
<td>1.880</td>
<td>1.773</td>
</tr>
<tr>
<td></td>
<td>SSC</td>
<td>1.600</td>
<td>1.747</td>
<td>1.813</td>
<td>1.849</td>
<td>1.597</td>
</tr>
<tr>
<td>$\beta$</td>
<td>FSC</td>
<td>2.367</td>
<td>1.990</td>
<td>2.222</td>
<td>2.490</td>
<td>1.989</td>
</tr>
<tr>
<td></td>
<td>SSC</td>
<td>1.948</td>
<td>1.948</td>
<td>2.177</td>
<td>1.818</td>
<td>2.020</td>
</tr>
</tbody>
</table>

As shown in Fig. 9(b), the peak stress of SSC was generally higher than that of FSC, but it was lower than the seawater river sand concrete. The reason for this phenomenon was that the seawater contained chlorine salt to promote the hydration of cement to produce expansive substances, which led to the formation of internal pores and ultimately led to a decrease in concrete strength. When using seawater as mixed water, its overall peak stress was increased by about 10% relative to freshwater. Islam et al. (2012) research showed that when using seawater as mixed water and curing water, the age of 180 days concrete pressure resistance was reduced by 10% compared to freshwater mixing and maintenance. From the peak stress of concrete, the chlorine ions introduced by seawater did not adversely affect the peak stress of concrete. This might be related to the short age of conservation so that chlorine salts had not yet developed harmful mechanisms.

The peak strain of SSC was slightly worse than that of FSC. Compared with the peak strain of SSC, when the replacement rate was 0%, 50% and 100%, respectively, the relative peak strain of FSC increased by 4.3%, 2.6% and 5.6%, respectively. Overall, the relative peak strain of FSC was greater than that of SSC. This was due to the fact that chlorine salt in seawater promotes the early strength of concrete, which made the elastic modulus large and leaded to a decrease in the peak strain of concrete.

4.2 Deformation

In order to quantitatively analyze the force deformation performance of sea sand concrete, the deformation coefficient $\beta$ is cited for analysis, the calculation method is shown in Eq. (4).

$$\beta = \frac{\varepsilon_{0.85}}{\varepsilon_y}$$  \hspace{1cm} (4)

where, $\varepsilon_{0.85}$ is the limit strain, which is the strain value when the peak stress drops to 85%, $\varepsilon_y$ is the initial yield strain, use “energy equivalent area method” to determine the initial yield point, the calculation method is shown in Fig. 10 ($S_{COC} = S_{CAB}$). Under the influence of replacement rate and mixing water, the failure strain and ductility coefficient of sea sand concrete are shown in Table 5.

It can be seen from Table 5 that the failure strain of freshwater sea sand concrete was greater than that of seawater sea sand concrete. This showed that when the mixing water was seawater, the brittle failure characteristics of sea sand concrete were more prominent and the ductility was poor. The failure strain of sea sand concrete was smaller than that of ordinary concrete. The average failure strain was only 50% of ordinary concrete. This showed that sea sand concrete only maintained a lower load-bearing capacity after being destroyed by compression. The load on the test block was resisted by the friction resistance on the inclined plane and the residual bonding force. This should be noticed in the calculation and design of marine concrete structures. The effect of sea sand replacement rate on failure strain had no obvious regularity, which needs further study.

Fig. 11(a) shows the effect of the replacement rate on the ductility of sea sand concrete. With the increase of the replacement rate, the ductility of freshwater sea sand concrete showed the tendency of decreasing first, then increasing and then decreasing. When the replacement rate was 100%, the ductility decreased by about 16%. With the increase of the replacement rate, the ductility of seawater
sea sand concrete showed the tendency of increasing first and then decreasing, finally increasing again. When the replacement rate was 75%, the ductility of the test block was lower. The ductility coefficients of other replacement rates showed greater than ordinary concrete. When the replacement rate was 50%, the increase in ductility was the largest, with fluctuations within 12%.

As shown in Fig. 11(b), the ductility of freshwater sea sand concrete under the same replacement rate was better than that of seawater sea sand concrete. This was also due to the fact that there were more chloride ions, sulfate ions and other salts in the seawater combined with the hydration product of cement calcium-aluminate or monosulfide-calcium-sulphoaluminate to produce the expansive material ettringite. In the short term, it was beneficial to the internal maintenance of concrete and promote the development of concrete's early strength. However, it will cause the expansion of the internal expansion of concrete, change the mechanism of internal hydration of concrete, promote the development of the internal pores of concrete, resulting in its long-term strength reduction.

### 4.3 Damage process analysis

In order to describe the damage development process of the sea sand concrete test block during the loading process, according to the continuous damage mechanics theory, the damage factor $D$ is used to describe the change of the damage degree of the test block during the loading process. The expression for the damage factor $D$ can be approximated by Eq. (5).

$$D = 1 - \frac{E^*}{E_0}$$

where $E_0$ is the elastic modulus of sea sand concrete without damage. $E^*$ is the effective secant modulus of sea sand concrete after damage.

Fig. 12 shows the damage process curves of sea sand concrete test blocks with different sea sand replacement rates. It can be seen from Fig. 12(a) that as the load increases, the damage degree of the test block continued to develop. When $\varepsilon < 4 \times 10^{-4}$, the test block was in the elastic stage with almost no damage and the $D$ value was close to zero. When $\varepsilon$ rose from $4 \times 10^{-4}$ to $12 \times 10^{-4}$, damage occurred and developed at a faster speed. The main manifestation was the appearance of unstable cracks, and as the confining pressure increased, the damage process presented significant changes. Except for the FSC-100 test block, the damage speed of the other concrete test blocks increased with the increase of the sea sand replacement rate. When $\varepsilon > 12 \times 10^{-4}$, the damage rate began to slow down. The final damage factor of all test blocks was closed to 1.

Comparing with the curves in Fig. 12(b), it can be seen that when the sea-sand replacement rate was 100%, the concrete test block mixed with seawater was damaged at $\varepsilon = 2 \times 10^{-4}$. At the same time, the test block of SSC-100 reached the final destruction when $\varepsilon = 12 \times 10^{-4}$. Under the same strain, the damage value of seawater sea sand concrete was greater than that of freshwater sea sand concrete. Therefore, compared with the sea sand concrete mixed with fresh water, the sea sand concrete mixed with the seawater was more brittle. Different mixing water had little effect on the damage rate of concrete test blocks.

### 5. Conclusions

In this paper, the compression properties of freshwater sea sand concrete(FSC) and seawater sea sand concrete(SSC) under axis were studied. The emphasis was the influence of sea sand replacement rate and mixing water type on the compressive performance of sea sand concrete. From the experimental investigation, the following conclusions can be drawn:

- The axial compression failure process of sea sand concrete is similar to that of ordinary concrete. The stress-strain curve of sea sand concrete also presents an elastic stage, an elastoplastic stage and a failure stage. Among them, the failure stage of seawater sea sand concrete curve is steeper, which shows that the seawater sea sand concrete has greater brittleness. The final failure form of sea sand concrete is a pyramid connected upside down.
- Comparing with different mixing water, it is found that using seawater as mixing water can improve the early strength of sea sand concrete. The overall peak stress
can be increased by about 10% compared with freshwater mixing. In general, compared with FSC, SSC has greater peak stress and axial compression stiffness, but its deformability capacity is poor.

- The sea sand replacement rate has no obvious effect on the peak strain and failure strain of the sea sand concrete. The peak stress and deformation of the sea sand concrete fluctuate with the increase of the sea sand replacement rate. When the sea sand replacement rate is 25%, the peak stress of FSC is the largest. When the sea sand replacement rate is 50%, the deformation properties of FSC and SSC are the best. The failure strain of sea sand concrete is smaller than that of ordinary concrete. The average failure strain is only 50% of ordinary concrete.

- The damage rate of sea sand concrete increases with the increase of sea sand replacement rate. When the mixing water is fresh water, the strain at which damage occurs is approximately 6 times that of seawater mixing. Under the same strain, the damage value of SSC is greater than that of FSC.

- The piecewise constitutive equation of ordinary concrete is used to fit the stress-strain relationship of sea sand concrete under uniaxial compression. The curve obtained by equation fitting is in good agreement with the experimental curve. The replacement rate of sea sand and mixing water have certain influence on the stress-strain curve of sea sand concrete. The parameters a and b of the constitutive equation of sea sand concrete with different mixing water and sea sand replacement ratio are given by fitting. The numerical stress-strain relationship of SSC and FSC can be used for theoretical analysis and practical engineering design.

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