

# 共面双裂隙对砂岩力学性质和破坏特征的影响

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**摘要:** 鉴于岩体内部缺陷对其力学性质和损伤断裂破坏有显著影响的问题,通过单轴压缩试验和 DIC 技术,分析了共面双裂隙类砂岩试样裂隙倾角和岩桥长度对岩石力学性质和破坏的影响。结果表明,随裂隙倾角变化,岩样峰值应力和弹性模量均有明显的变化趋势,相比于岩桥长度,裂隙倾角对岩石的力学性质影响更为显著;随裂隙倾角增加,岩样破坏时表面裂纹数量、主破坏裂纹和表面剥落数量均有减少,掉块面积却有明显增加,而随岩桥长度增加,裂纹扩展和剥落掉块特征基本相同;在裂纹扩展过程中,岩桥的贯通与裂隙倾角和岩桥长度均有关系;在低裂隙倾角时,岩样破坏模式以张拉破坏裂纹为主;随裂隙倾角增加,表现为由张拉破坏裂纹向剪切破坏裂纹转变形成了拉—剪混合破坏模式;同时,随岩桥长度增加,岩桥越难以贯通,裂纹扩展破坏则又由拉—剪混合裂纹向张拉裂纹转变。

**关键词:** 类砂岩; 共面双裂隙; 裂隙倾角; 岩桥; DIC 技术

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## 1 引言

裂隙岩体是水利水电工程中常见的工程介质,这种裂隙缺陷不仅对岩体力学特性产生各种影响,且在外界扰动下内部裂隙会萌生、扩展出更多的裂纹,进而引发工程事故。因此探究裂隙的几何分布对岩体的力学性质和裂纹扩展及破坏的影响具有重要的理论意义。目前,关于双裂隙的研究主要集中于雁形裂隙,且主要是裂隙倾角和岩桥倾角对岩石破坏模式、裂纹扩展和岩桥贯通的研究<sup>[1-5]</sup>,而对共面双裂隙和两裂隙间的岩桥长度的研究较少。为此,本文以共面双裂隙类砂岩试样为例,通过单轴压缩试验和 DIC 技术,探讨了不同的裂隙倾角和岩桥长度对砂岩力学特性与破坏模式的影响。研究成果在工程实际优化设计中具有重要的指导价值。

## 2 试验装置与试验方案设计

试验仪器主要由加载系统和 DIC 系统组成,

其中,加载系统包括 WAW-1000B 型微机伺服控制万能试验机和数据采集系统;DIC 系统包括拍摄系统与数字图像计算系统。

由于现场找样、取样很难得到具有相同尺寸的共面双裂隙砂岩试样,需要人工制作。岩样质量配合比为 32.5R 普通硅酸盐水泥:石英砂:纯净水:聚羧酸早强减水剂:消泡剂 = 1:1:0.28:0.002:0.003。共面双裂隙分布示意图见图 1。其中, $a$  为裂隙长度; $2b$  为岩桥长度; $\alpha$  为裂隙倾角; $\beta$  为岩桥倾角;且  $\alpha = \beta$ 。试验中,压力机加载速率为 0.2 mm/min, DIC 照相机拍摄速

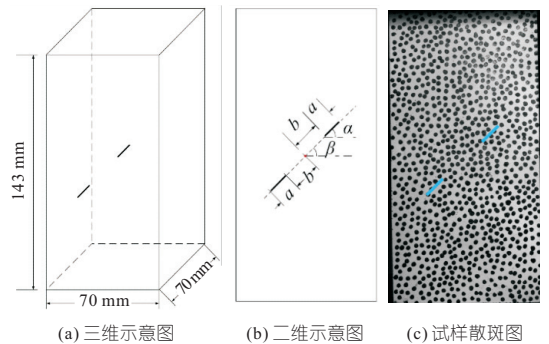


图 1 共面双裂隙分布示意图

Fig. 1 Distribution diagram of coplanar double fissures

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率为 1 帧/s。

为探讨裂隙倾角和岩桥长度对共面双裂隙砂岩力学强度特性和破坏模式的影响,岩样中预制的两条裂隙长度  $a$  均为 10 mm,裂隙倾角  $\alpha$  依次取值为  $0^\circ$ 、 $30^\circ$ 、 $45^\circ$ 、 $60^\circ$ 、 $90^\circ$ ,岩桥长度  $2b$  依次取值为 7、14、21、28 mm,且岩样编号以  $\alpha$ - $2b$  格式进行命名,试验方案和试样编号见表 1。

表 1 试验方案和试样编号

Tab. 1 Test plan and specimens number

$2b$ /mm	$\alpha / (^\circ)$				
	0	30	45	60	90
7	0-7	30-7	45-7	60-7	90-7
14	0-14	30-14	45-14	60-14	90-14
21	0-21	30-21	45-21	60-21	90-21
28	0-28	30-28	45-28	60-28	90-28

### 3 试验结果与分析

#### 3.1 裂隙倾角和岩桥长度对岩样力学性质的影响

按照表 1 所设计的试验方案,对每个岩样进行单轴压缩试验,得到岩样的应力应变曲线,见图 2。由图 2 可知,试验所得应力应变曲线包含压密阶段、弹性阶段和屈服阶段三个阶段,在应力应变曲线的峰值应力前无明显塑性变形,表现出较长的弹性阶段,表明岩样具有较强的脆性特征,有部分曲线在达到峰值应力之前的阶段会有轻微应力下降出现,即斜率突变,这表明岩样内部预制裂隙间萌生了新的裂纹。

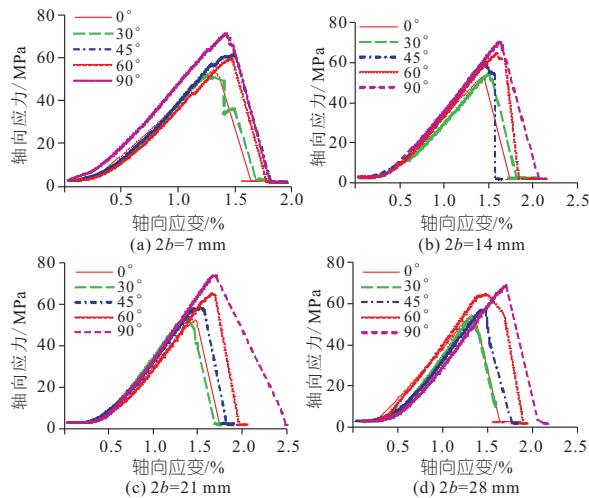


图 2 不同裂隙倾角下的岩样应力应变曲线

Fig. 2 Axial stress-strain curve of rock specimens with different fissured angles

对试验数据进行统计分析,可得到各岩样的峰值应力和弹性模量随裂隙倾角及岩桥长度的变化规律,见图 3、4。由图 3(a)可知,在相同岩桥长度下,峰值应力随裂隙倾角增加有明显增长的趋势,

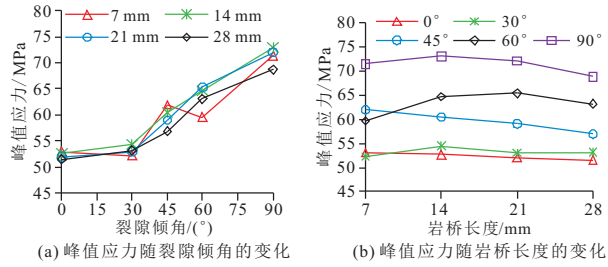


图 3 峰值应力随裂隙倾角和岩桥长度的变化规律

Fig. 3 The variation of peak stress with fissured angles and rock bridge lengths

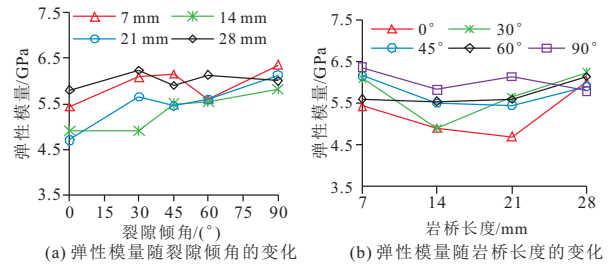


图 4 弹性模量随裂隙倾角和岩桥长度的变化规律

Fig. 4 The variation of elasticity modulus with fissured angles and rock bridge lengths

势,其中,当  $\alpha = 0^\circ$  时,岩样峰值应力在 51.5 ~ 53.1 MPa 之间,相比于完整岩样的 74.0 MPa,岩样力学强度削弱最为严重。当  $\alpha = 90^\circ$  时,岩样峰值应力在 68.7 ~ 73.0 MPa 之间,与完整岩样的强度非常接近。由图 3(b)可知,在相同裂隙倾角下,峰值应力随岩桥长度增加,其值大小较为接近,表现为先增大后减小或小幅递减的规律。由图 4 可知,岩样弹性模量随裂隙倾角增加呈现递增的趋势,但增幅相差较大,其中最大增长率为 30.4%,最小增长率为 3.4%;岩样弹性模量随岩桥长度增加表现为先减小后增大的下凹型趋势,弹性模量变化率在  $-8.8\% \sim 10.5\%$  之间。综上所述,共面双裂隙试样的力学性质随裂隙倾角增加而提高,且岩桥长度对岩样影响程度弱于裂隙倾角。

#### 3.2 裂隙倾角和岩桥长度对岩样破坏特征的影响

在单轴压缩试验中,通过 DIC 系统生成的应变云图来辅助分析岩样表面裂纹的扩展过程,记录不同应力水平下相机拍摄的岩样裂纹产生的先后顺序,以编号为 0-14 试样为例,见图 5。图 5 中数字①、②、③、④代表着不同应力水平下的裂纹产生的先后批次,破坏时主破裂裂纹用黑色实粗线表示,表面剥落用向上倾斜的线条阴影表示。

岩样表面裂纹扩展规律表现为:在低应力水平时(图 5(a)),第①批裂纹出现在岩样上端面 and 左侧边附近,在裂隙尖端区域未出现,该批次裂纹属于远场裂纹,主要因岩样上下端面不平整或端

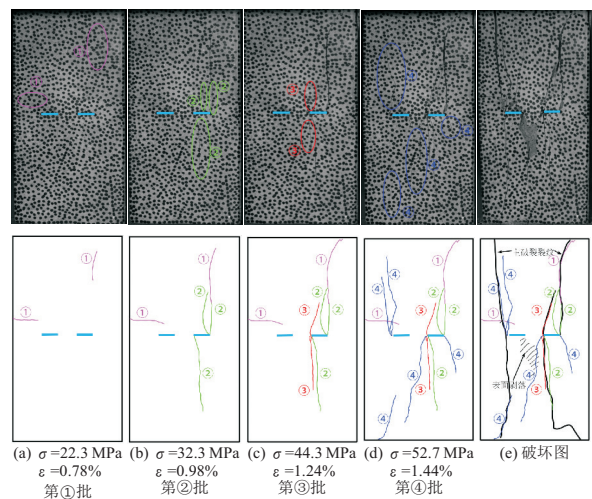


图 5 岩样表面裂纹扩展与分布

Fig. 5 Propagation and distribution of surface cracks on the specimen

面受力不均匀所致。在中等应力水平时,预制裂隙尖端开始产生裂纹并向岩样端部扩展,如图 5 (b)、(c)中均为翼裂纹的第②批裂纹和包含翼裂纹和反翼裂纹的第③批裂纹,且与第①批远场裂纹产生融汇,其主要集中在右侧预制裂隙两端,也说明了端面受力不均匀。在高应力水平时,两个预制裂隙尖端均产生裂纹,并快速向岩样端部扩展并与其他批次裂纹融汇贯通,形成明显的以翼裂纹和反翼裂纹组成的主破坏裂纹和剥落掉块,如图 5(d)第④批裂纹和图 5(e)破坏图所示,产生的第④批裂纹仍是以翼裂纹和反翼裂纹为主,此时应力突降,岩样破坏。

从岩样破坏图中标注的每批次的裂纹可知,在压密阶段由于应力较小达不到起裂的应力,随着应力增加,在弹性阶段出现第①、②批裂纹。达到屈服破坏阶段时,是裂纹产生最多的阶段,裂纹迅速扩展贯通形成③、④或⑤批裂纹。最后达到峰值强度,岩样破坏。从各岩样破坏图可看出,产生的第①、②批裂纹,易为靠近端部的远场裂纹和裂隙尖端的翼裂纹;而产生的第③、④批裂纹易为第①、②批裂纹路径上扩展的新裂纹和使岩样更加破碎的远场裂纹及裂隙尖端的翼裂纹和中部产生的张拉裂纹。

图 6 为在不同岩桥长度下,岩样破坏模式随裂隙倾角变化规律。由图 6 可知:①裂隙倾角对岩样破坏特征影响。在相同岩桥长度下,随裂隙倾角增加,裂纹数量有明显减少趋势,主破坏裂纹由两条变为一条,表明试样破坏模式由张拉破坏向剪切破坏转变;表面剥落掉块数量减少,掉块面积明显增加,其原因是在高裂隙倾角下,试样表面产生裂纹数量较少,裂纹与裂纹间或与试样边缘

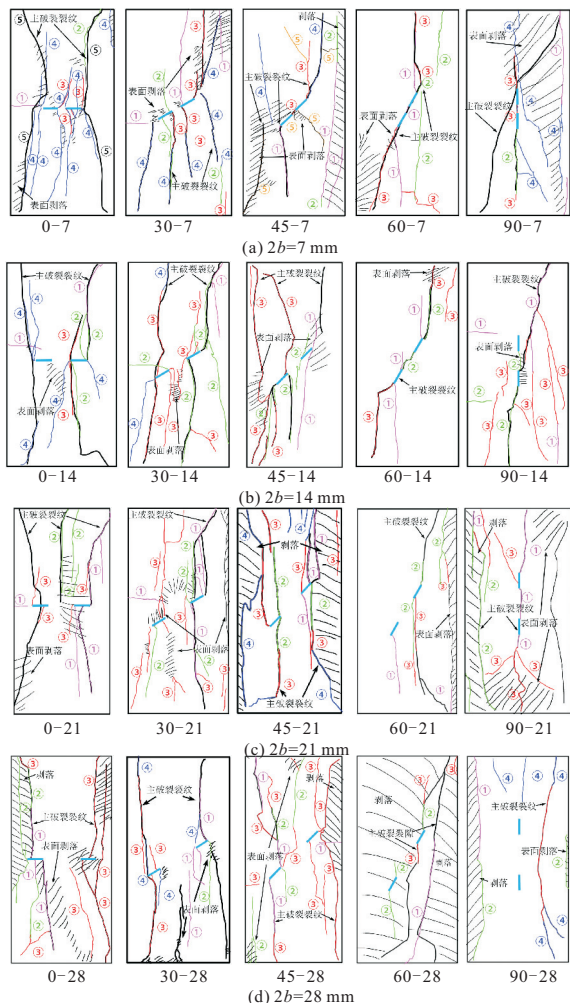


图 6 在不同岩桥长度下,岩样破坏模式随裂隙倾角变化规律

Fig. 6 At different rock bridge lengths, the law of rock specimen failure mode changing with fissured angles

包围形成的块体区域较大,所以掉块面积较大,也表明了试样破坏模式由张拉破坏向剪切破坏转变。岩桥贯通表现为在低裂隙倾角( $\alpha = 0^\circ$ 、 $\alpha = 30^\circ$ )时不会发生岩桥贯通;在高裂隙倾角( $\alpha = 45^\circ$ 、 $60^\circ$ 、 $90^\circ$ )时才发生岩桥贯通。②岩桥长度对岩样破坏特征影响。在相同裂隙倾角下,随岩桥长度增加,岩样表面裂纹扩展、剥落块体等破坏特征基本相同。岩桥贯通表现为在岩桥能够贯通的裂隙倾角下,岩桥越长越难贯通。③从细观破坏机理来看,在低裂隙倾角( $\alpha = 0^\circ$ 或  $30^\circ$ )时,岩样表面产生的裂纹主要为张拉裂纹,鲜有剪切裂纹,表现为张拉破坏,其原因是低裂隙倾角时,在局部无法形成较大的剪应力,而裂隙尖端应力集中形成局部张拉应力,引起张拉裂纹,并向着最大主应力方向扩展,即裂纹由裂隙尖端向试样端部延伸,并在其表面形成两条主破坏裂纹的“蝶形”状的破坏,而随岩桥长度变化破坏模式较为接近。当  $\alpha = 45^\circ$ 、 $\alpha = 60^\circ$ 时,在岩桥长度较小时,岩桥发生

贯通,形成一个修长的剪切带,增加试样剪切破坏的比重,表面产生的裂纹为剪切和张拉的混合裂纹,表现为拉一剪混合破坏,岩样表面形成一条主破裂裂纹的“单翼蝶形”状的破坏。在  $\alpha = 60^\circ$  时,由于与试样的破裂面  $45^\circ + \varphi/2$  处 ( $\varphi$  为内摩擦角)接近,剪应力更大,在  $2b = 14 \text{ mm}$  时,相比于裂隙倾角为  $\alpha = 45^\circ$  时,岩桥能够贯通,与摩尔库伦准则分析结论相符;随岩桥长度增加,岩桥不发生贯通,张拉裂纹比重增多,表现为多张拉破坏少剪切破坏,其表面又形成两条主破裂裂纹的“蝶形”状的破坏。在  $\alpha = 90^\circ$  时,岩样表面产生的裂纹为剪切和张拉的混合裂纹,二者比重相近,同样,随岩桥长度增加,岩桥不发生贯通,表现为拉一剪混合破坏和多张拉少剪切破坏。

将各岩样破坏特征和破坏机理分析汇总,见表 2。由表 2 可知,裂隙倾角与岩桥长度共同影响着岩样的岩桥贯通及破坏模式。岩桥贯通只发生在高裂隙倾角。且随裂隙倾角增加,岩样破坏时,两条预制裂隙之间的岩桥由不贯通向间接、直接贯通转变,这种转变也说明了岩样破坏机理由张拉裂纹向拉一剪裂纹转变。岩桥长度控制着裂隙贯通的难易程度,随岩桥长度增加,两条预制裂隙之间岩桥越难以贯通,特别是在  $\alpha = 45^\circ、60^\circ、90^\circ$  时,岩桥间由直接贯通变化为间接贯通或无贯通,这种变化也说明了岩样破坏机理由拉一剪混合裂纹向张拉裂纹增多转变,与岩样力学性质变化规律相符。

表 2 岩样破坏特征和破坏机理

Tab. 2 Failure characteristics and mechanism of rock samples

2b /mm	$\alpha/(\circ)$				
	0	30	45	60	90
7	岩桥无贯通张拉破坏	岩桥无贯通张拉破坏	岩桥直接贯通拉一剪混合破坏	岩桥直接贯通拉一剪混合破坏	岩桥直接贯通拉一剪混合破坏
14	岩桥无贯通张拉破坏	岩桥间接贯通多拉少剪破坏	岩桥间接贯通拉一剪混合破坏	岩桥直接贯通拉一剪混合破坏	岩桥直接贯通拉一剪混合破坏
21	岩桥无贯通张拉破坏	岩桥无贯通多拉少剪破坏	岩桥无贯通多拉少剪破坏	岩桥无贯通拉一剪混合破坏	岩桥直接贯通多拉少剪破坏
28	岩桥无贯通张拉破坏	岩桥无贯通多拉少剪破坏	岩桥无贯通多拉少剪破坏	岩桥无贯通拉一剪混合破坏	岩桥无贯通多拉少剪破坏

相较于单裂隙,双裂隙岩样的裂隙倾角对于岩样力学特性的影响与其相似,但对于裂纹扩展及破坏模式存在着差异。在裂隙长度相同的情况

下,两条裂隙意味着缺陷比重更大,其次两条裂隙的外尖端更靠近试样端部,在裂纹向端部扩展时更容易形成张拉裂纹。岩桥的贯通与否影响着试样的破坏模式,而单裂隙岩样不会发生破坏模式的转变。

### 4 结论

- a. 随裂隙倾角增加,峰值应力、弹性模量呈递增趋势。随岩桥长度增加,岩样峰值应力变幅较小,弹性模量表现为先减小后增加的趋势,变幅较小。岩桥长度对岩样影响程度弱于裂隙倾角。
- b. 岩样破坏特征规律为在相同岩桥长度下,随裂隙倾角增加,裂纹数量有明显减少趋势,主破坏裂纹由两条变为一条;表面剥落掉块数量减少,掉块面积增加;只有在高裂隙倾角时岩桥才发生岩桥贯通;在相同裂隙倾角下,随岩桥长度增加,岩样表面裂纹扩展、剥落块体等破坏特征基本相同;在岩桥能够贯通的裂隙倾角下,岩桥越长越难贯通。
- c. 破坏机理主要表现为在低裂隙倾角时,以张拉破坏裂纹为主,鲜有剪切破坏裂纹;随裂隙倾角增加,破坏模式由张拉破坏裂纹向剪切破坏裂纹转变成拉一剪混合破坏模式。同时,随岩桥长度增加,岩桥由直接贯通变化为间接贯通或者无贯通,岩样破坏机理由拉一剪混合裂纹向张拉裂纹增多转变。

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## Study on Hydraulic Connection Characteristics of Local Open Channel and Pressurized Tunnels in Water Transfer Project

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**Abstract:** The local open channels play a certain role in regulating and storing water, but the water flow in the junction section with open channel variation and pressure is relatively complex, which may cause adverse water flow phenomena such as air intake, whirlpool and surges. In order to study the hydraulic pattern of the connecting section between the open channel and the pressurized tunnel, based on the water conveyance tunnel of Wenzhou Oujiang water diversion project, a 30:1 large scale normal local hydraulic model was built according to the gravity similarity criterion. The hydraulic pattern, water surface line distribution, velocity distribution and wave characteristics under different conditions were observed through hydraulic model tests. The flow trend, depth, velocity and wave characteristic parameters under different working conditions were obtained. The research results show that the flow in the open channel and the pressurized junction section through the gradual transition is in good shape, and there is no air intake, backflow and surge, which provides support for the safe operation of the project.

**Key words:** water transfer project; open channel flow; free water tunnel; pressurized tunnel; hydraulic pattern; model test

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## Effect of Coplanar Double Fissures on Mechanical Properties and Failure Characteristics of Sandstone

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**Abstract:** The internal defects of rock mass have a significant effect on its mechanical properties and damage and fracture. The influence of fissure angles and bridge lengths on rock mechanical properties and failure was analyzed by uniaxial compression test and DIC technique. The research findings are as follows: The peak stress and elastic modulus of the samples have an obvious change trend with the change of the fissure angle. Compared with the length of the rock bridge, the fissure angle has a more significant effect on the mechanical properties of the rock. With the increase of fissure angle, the number of surface cracks, main failure cracks and surface spalling decreases, while the area of falling blocks increases obviously. However, with the increase of bridge length, the characteristics of crack propagation and spalling are basically the same. In the process of crack propagation, the connection of rock bridge is related to the fissure angle and the length of rock bridge. In the low fissure angle, the failure mode of rock samples is dominated by tensile failure cracks; With the increase of the fissure angle, the performance is as follows: the tension damage crack to shear damage crack transformation to form a mixed tensile shear damage mode; At the same time, with the increase of bridge length, the more difficult the rock bridge is to penetrate, and the local crack expansion failure changes from tensile-shear crack to tensile crack.

**Key words:** sandstone-like; coplanar double fissures; fissure angle; rock bridge length; DIC technique

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## Effect of Temperature and Salinity on Shear Mechanical Properties of Coral Sand

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**Abstract:** Coral sand is an important material for island and reef engineering construction. Its physical and mechanical properties in different marine environments directly affect the design, construction and long-term operation of island and reef structures. In order to study the shear mechanical properties of coral sand under the influence of temperature and salinity, the triaxial drainage shear tests of coral sand in the South China Sea were carried out at different temperatures and salinity by using the self-developed temperature controlled pile-soil interface triaxial tester. The results show that similar to ISO standard sand, the shear stress-strain curves of coral sand have peaks, presenting its characteristics of strain softening; The shear strength of coral sand is not significantly affected by temperature, but it is sensitive to salinity. Compared with fresh water environment, the peak shear strength of coral sand in salt water environment decreases by 2.5%-8.5%, and the lower of confining pressure, the greater of decrease range; Salinity has a deterioration effect on the cohesion of coral sand, and its reduction range is about 30%, but the effect on the internal friction angle of coral sand is not obvious.

**Key words:** coral sand; shear strength; temperature; salinity; cohesion