The International Symposium on Refractories

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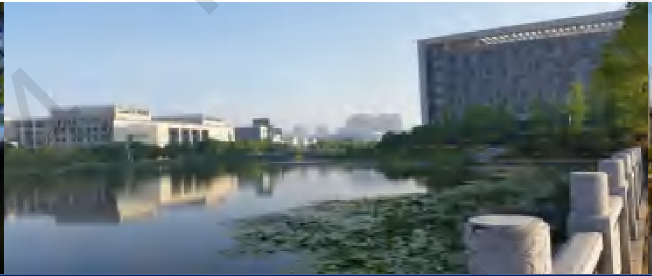
Preparation and Properties of Oriented Steel Fiber Reinforced Refractory Castable

取向钢纤维增强耐火浇注料制备及其性能

2024.10 Cheng Du · China



Introduction

钢纤维增强耐火浇注料，广泛应用于钢铁冶金、石油化工等高温工业的关键服役部位，工作环境恶劣，冲刷、磨损严重。

Steel fiber reinforced refractory castables are widely used in steel metallurgy and other high-temperature industries in critical service parts, where the working environment is very serious.

将钢纤维加入到耐火浇注料中会大幅提高材料的断裂韧性，改善材料的抗热震、抗机械震动和抗冲击性，延缓和减少材料的裂纹扩展和剥落。

Adding steel fibers to refractory castables will substantially increase the fracture toughness of the material, improve its resistance to thermal shocks, mechanical vibration and impacts, delay and reduce cracks expansion and spalling.

Introduction

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钢纤维对材料的增强增韧作用在不考虑温度影响下可以通过复合材料理论或纤维间距理论来解释。

The reinforcing and toughening effect of steel fibers on the material can be explained by composite material theory or fiber spacing theory without considering the effect of temperature.

$$\boxed{\sigma_c=\sigma_m(1-V_f)+\eta_l\eta_\theta\tau\frac{l}{\mathrm{d}}V_f}$$

式（1）中：σ_c-钢纤维复合材料强度；σ_m-基体材料强度；V_f-钢纤维体积率；η_l-钢纤维有限长度系数；η_θ-钢纤维方向系数；τ-钢纤维与基体粘结强度；l-钢纤维长度；d-钢纤维直径。

Where σ_c represents the strength of the steel fiber composite material, σ_m is the strength of the matrix material, V_f is the volume fraction of steel fibers, η_θ is the orientation factor of steel fibers, η_l denotes the effective length coefficient of steel fibers, τ is the bond strength between steel fibers and the matrix, l is the length of steel fibers, and d is the effective diameter of steel fibers.

除了钢纤维长度、直径与体积百分比外，**钢纤维的方向分布也是影响钢纤维增强增韧效果的关键因素**。

In addition to the length, diameter and volume percentage of steel fibers studied above, **the directional distribution of steel fibers is also a key factor affecting the reinforcing and toughening effect of steel fibers.**

Introduction

在实际服役条件下，载荷和工况一般固定，耐火浇注料的受力方向基本一致，浇注料中钢纤维仅有少部分取向于载荷或热应力方向，导致钢纤维增强增韧功效未充分发挥，影响钢纤维浇注料的使用性能。

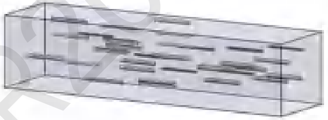
Under the service conditions, the load and working conditions are generally fixed. The stress direction of refractory castables is basically the same, and only a small part of the steel fibers in the castables are oriented in the direction of load or thermal stress, which results in the enhancement of toughening effect of the steel fibers not being brought into full play, thus affecting the performance of the steel fiber castables.

Introduction

RSFRRC

Random steel fiber reinforced mullite castable

OSFRRC



Oriented steel fiber reinforced refractory castable

然而，目前关于耐火浇注料中钢纤维分布方向对材料性能的影响的研究还未见任何文献报道。本工作以莫来石钢纤维浇注料为研究对象，**成功制备了取向钢纤维浇注料**，并研究了其性能。

However, there are few studies on the influence of steel fiber direction distribution in refractory castables. This work took mullite steel fiber castable as the research object, **successfully prepared oriented steel fiber reinforced castable**, and studied its properties.

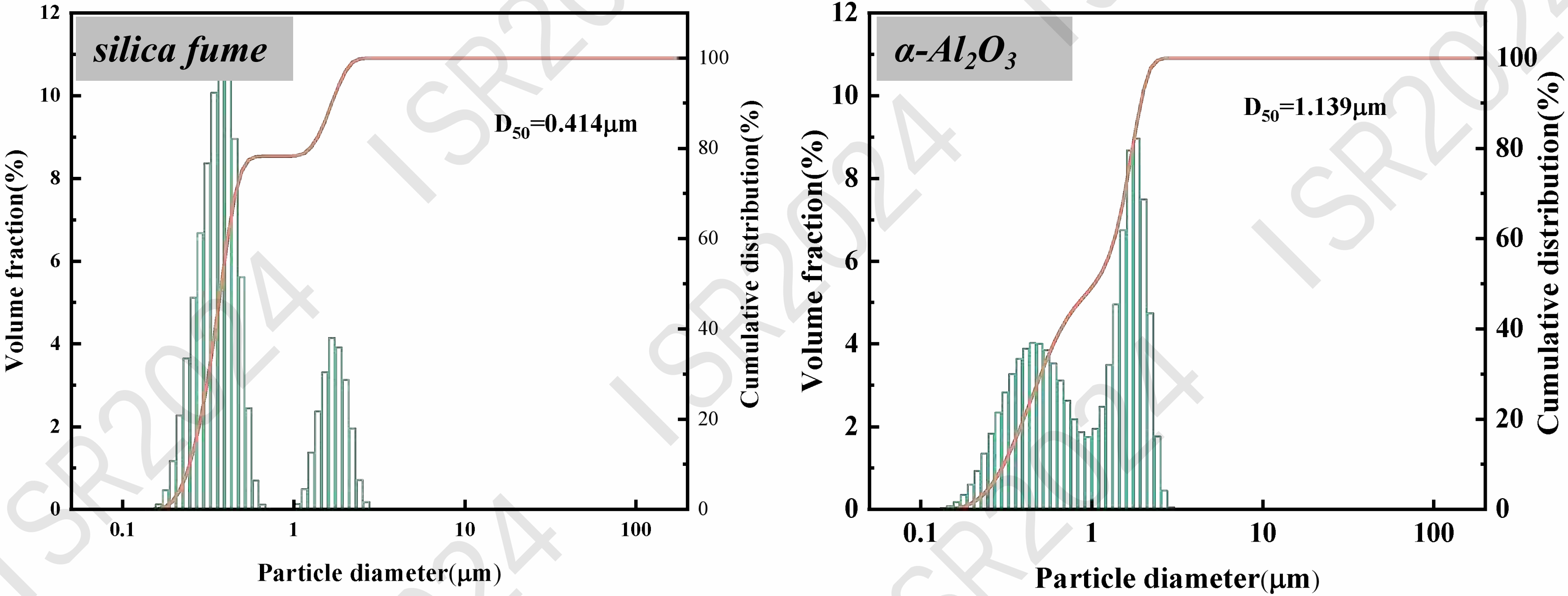
Materials and methods

钢纤维增强莫来石浇注料配方

Compositions of Steel fiber reinforced mullite refractory castables

raw material	S0/wt.%	S2/wt.%	S4/wt.%	S6/wt.%	S8/wt.%
Mullite aggregates (5-3mm, 3-1mm, 1-0mm)			43		
Andalusite aggregates (3-1mm, 1-0mm)			21		
Silicon carbide			2.5		
Mullite powder			6		
Alumina powder			9		
α-Al_2O_3	11	9	7	5	3
Silica fume	0	2	4	6	8
Secar 71			5		
FS20			0.075		
steel fiber			2.5		
DI water			4		

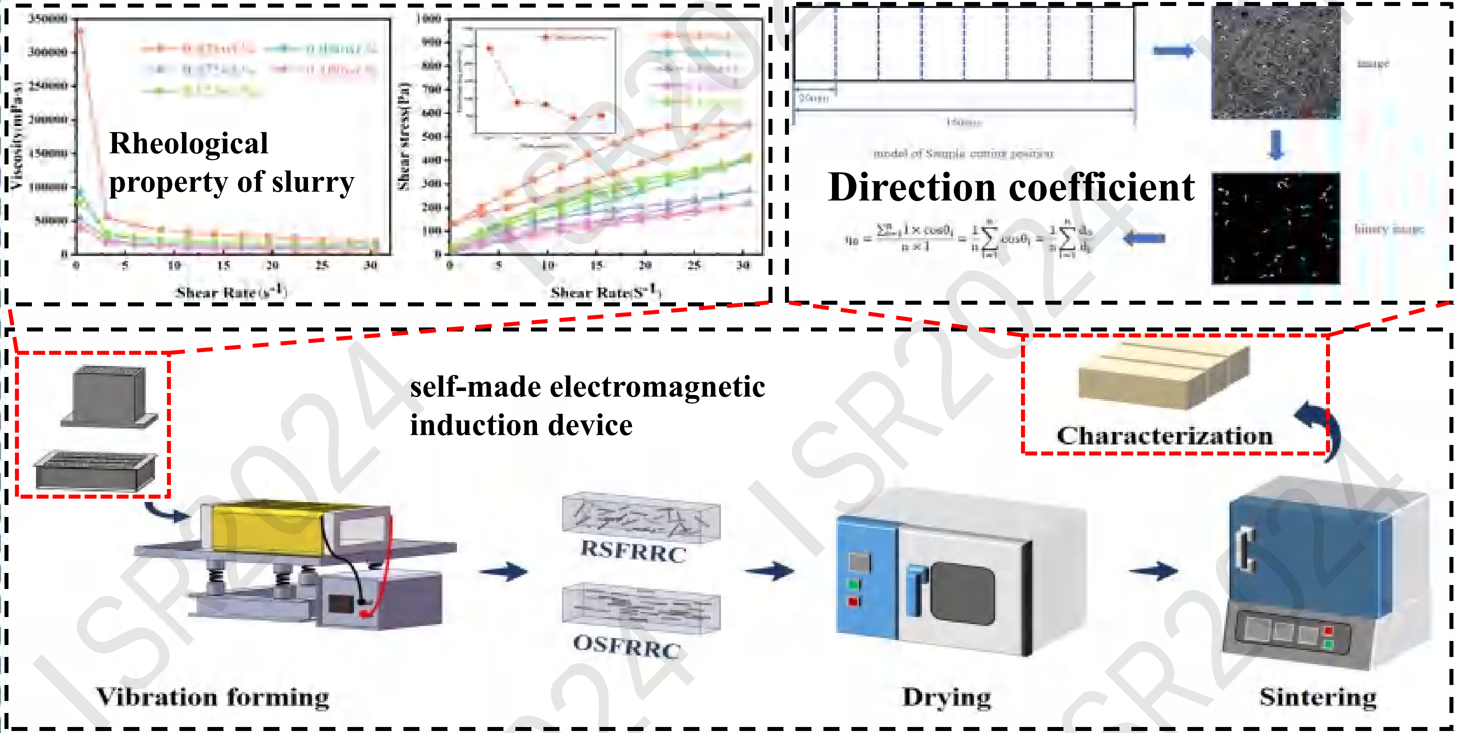
Materials and methods



硅微粉及α-Al_2O_3粒径分布

Particle size distribution of microsilica and α - Al_2O_3

Materials and methods



取向钢纤维莫来石耐火浇注料制备流程

Preparation process of OSFFRC

- Steel fibers were oriented by a self-made electromagnetic induction device.
- The viscous force of castable slurry is the main resistance to the orientation of steel fibers.
- The length of the steel fibers on the section plane could be obtained by the method of section image processing.

Materials and methods

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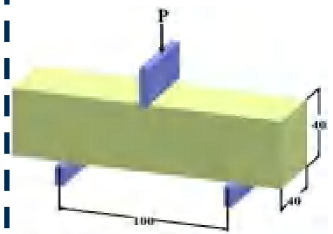
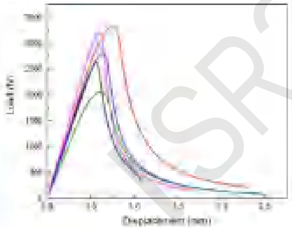
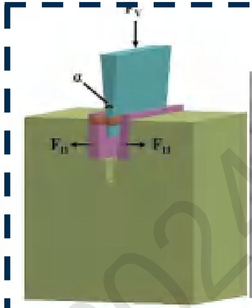
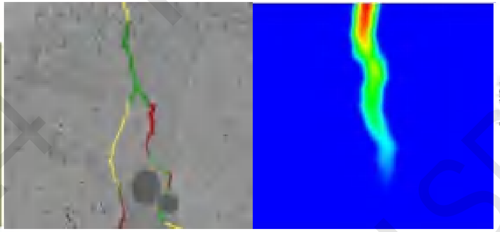
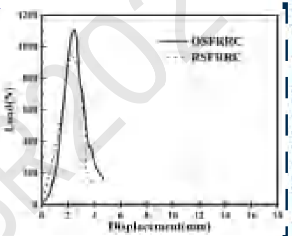




三点弯曲法分析断裂韧性
Fracture toughness analysed by the three-point bending method

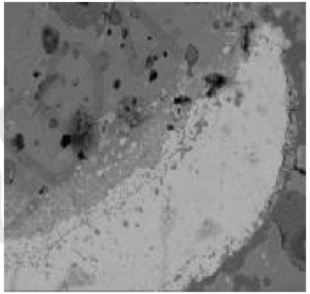


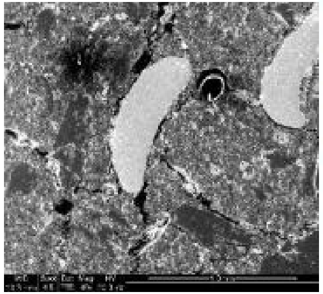




楔形劈裂法结合DIC测试
WST and DIC

物理性能、力学性能与热震稳定性
Physical properties, mechanical properties and thermal shock resistance

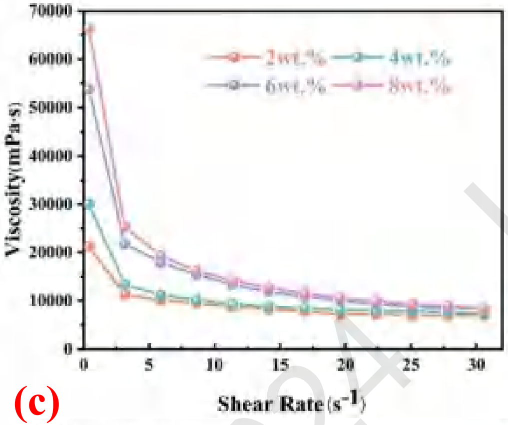




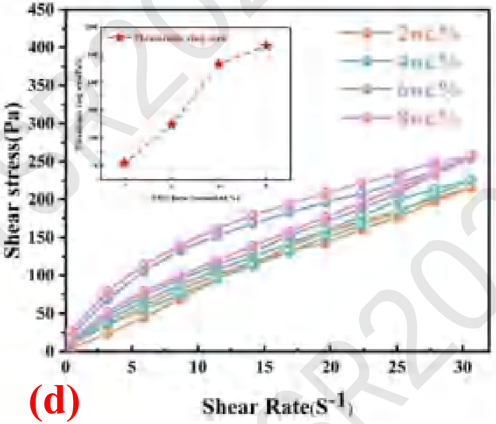
微观结构分析
Microstructure analysis

Results and discussion

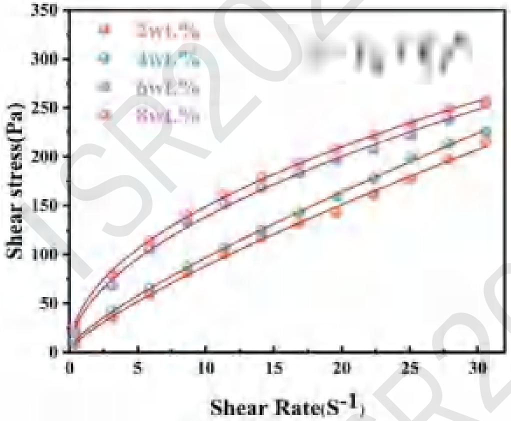
(a)



(b)



(c)



(d)

different contents of silica fume /wt.%	Yield stressτ_0/Pa	K	n	R^2
2	2.60	13.81	0.82	0.9976
4	5.32	14.67	0.76	0.9993
6	6.56	40.68	0.53	0.9970
8	7.86	47.55	0.50	0.9988

不同硅微粉添加量对耐火浆料流变性能得影响：(a)粘度；(b)剪切速率和剪切应力之间的关系；(c)触变环；(d)流变参数。

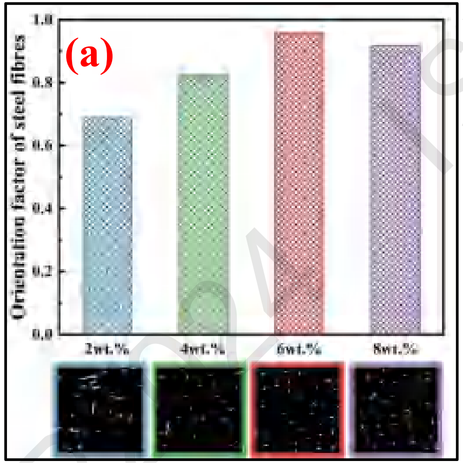
The influence of different amounts of silica fume addition on the rheological properties of refractory slurry: (a) viscosity; (b) relationship between shear rate and shear stress; (c) thixotropic ring; (d) rheological parameters.

随硅微粉添加量的增加，粘度和触变性、屈服应力和剪切稀化程度均呈现增大的趋势。

As the microsilica addition increases, viscosity, thixotropy, yield stress, and shear thinning degree all show an increasing trend.

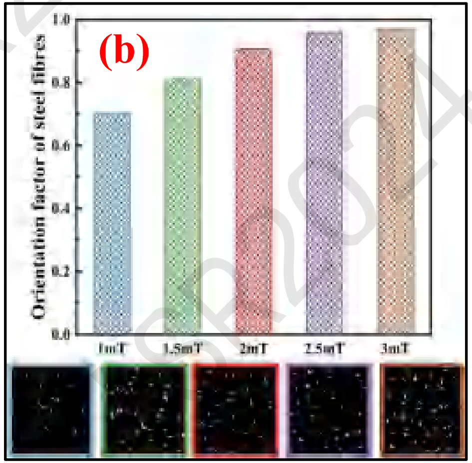
Results and discussion

■ OSFRRC制备 Preparation of OSFRRC



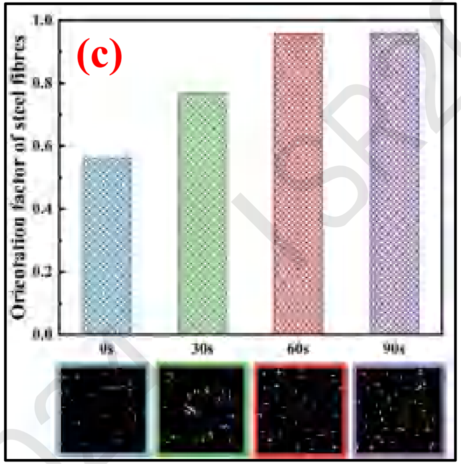
硅微粉添加量对η_θ的影响

Effect of silica fume addition on η_θ



磁场强度对η_θ的影响

Effect of magnetic field strength on η_θ



作用时间对η_θ的影响

Effect of action time on η_θ

The optimum preparation process parameters of OSFFRC are microsilica addition 6 wt.%, magnetic field strength 2.5 mT, action time 60s, while the ηθ reached an impressive value of 0.96, indicating a remarkably high alignment of the steel fibers within the castable.

Results and discussion

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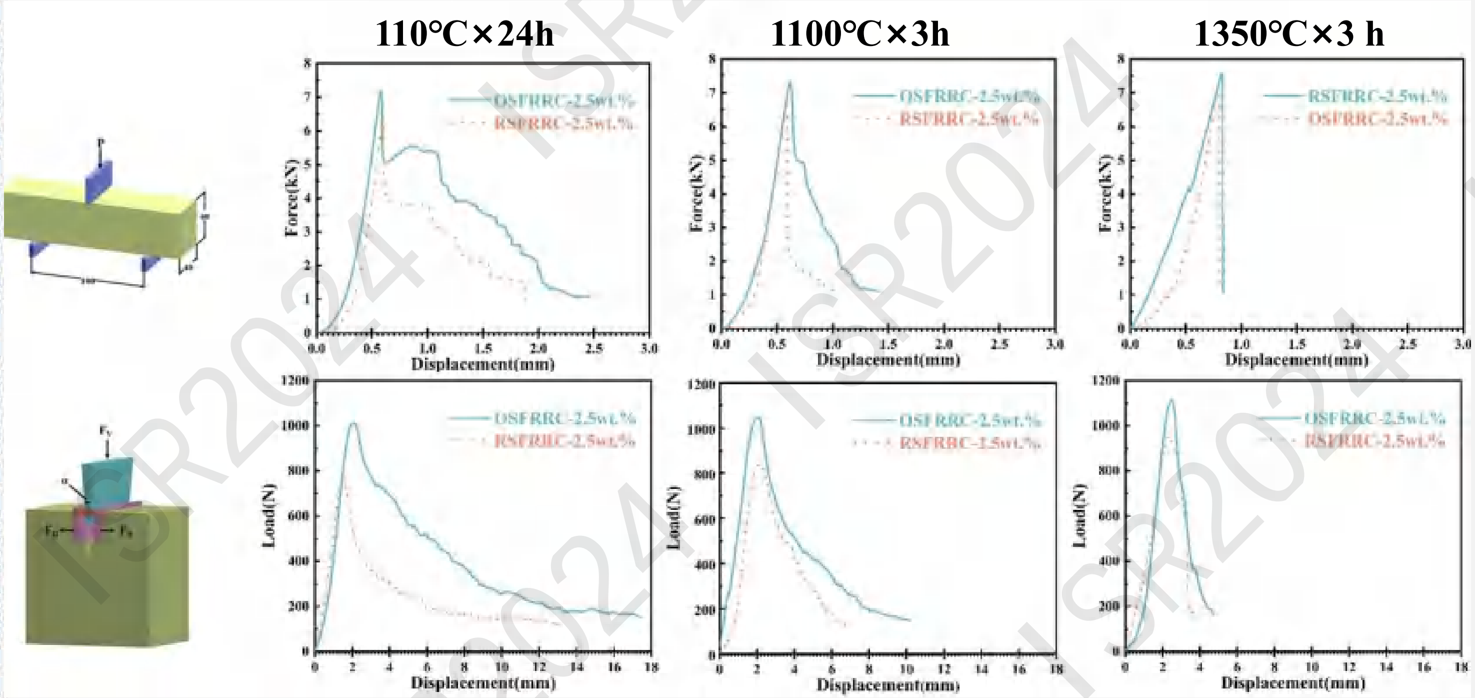
■ 力学性能及其增强增韧机理

Mechanical properties and its strengthening and toughening mechanism



Force-deformation curves for three-point bending test and the WST

It is evident that OSFRRC samples exhibit significantly higher peak loads and maximum displacements.

Results and discussion

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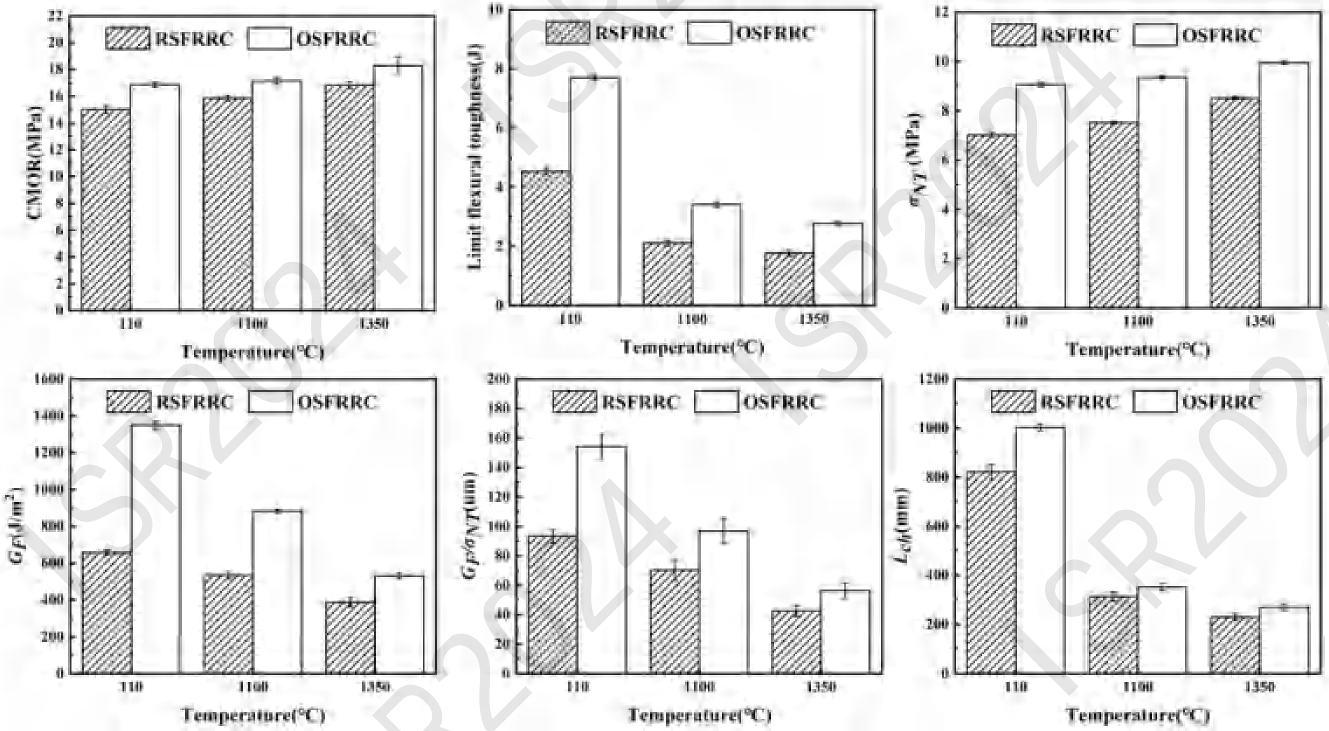
■ 力学性能及其增强增韧机理

Mechanical properties and its strengthening and toughening mechanism



钢纤维取向使浇注料力学性能和断裂能有大幅度的提升。

The OSFRRC samples also exhibit higher CMOR and fracture energy G_F indicating that the orientation of steel fibers significantly improves the mechanical properties and toughness of castables.

Results and discussion

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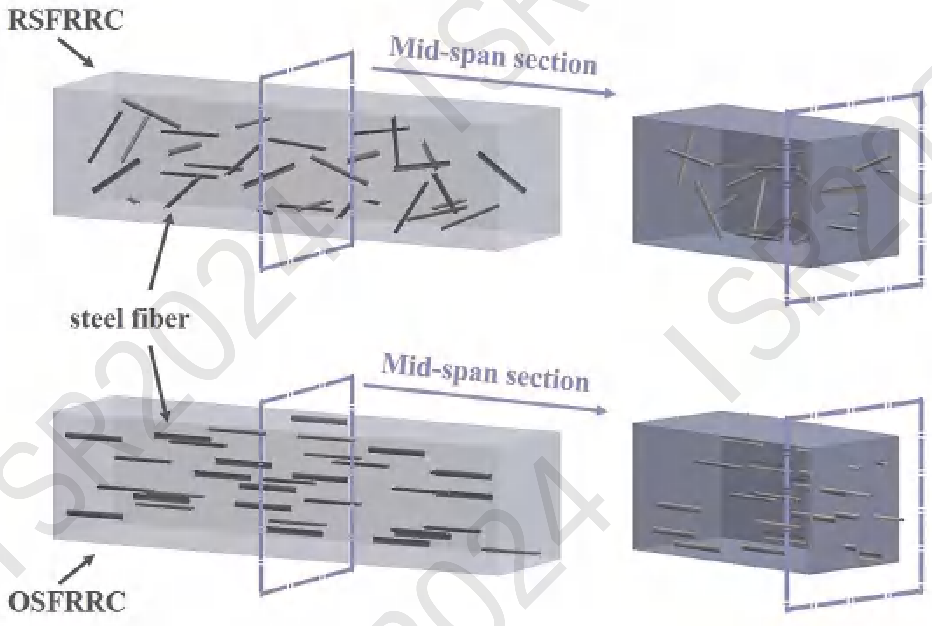
■ 力学性能及其增强增韧机理

Mechanical properties and its strengthening and toughening mechanism



钢纤维的取向增加了桥接浇注料失效面裂纹的钢纤维的数量，能充分发挥桥接裂缝的作用，这极大的提高了OSFRRC试样的强度和韧性。

The orientation of steel fibers increases the number of steel fibers bridging cracks on the failure surface of castables, which can fully play the role of bridging cracks, greatly improving the strength and toughness of OSFRRC samples.

Results and discussion

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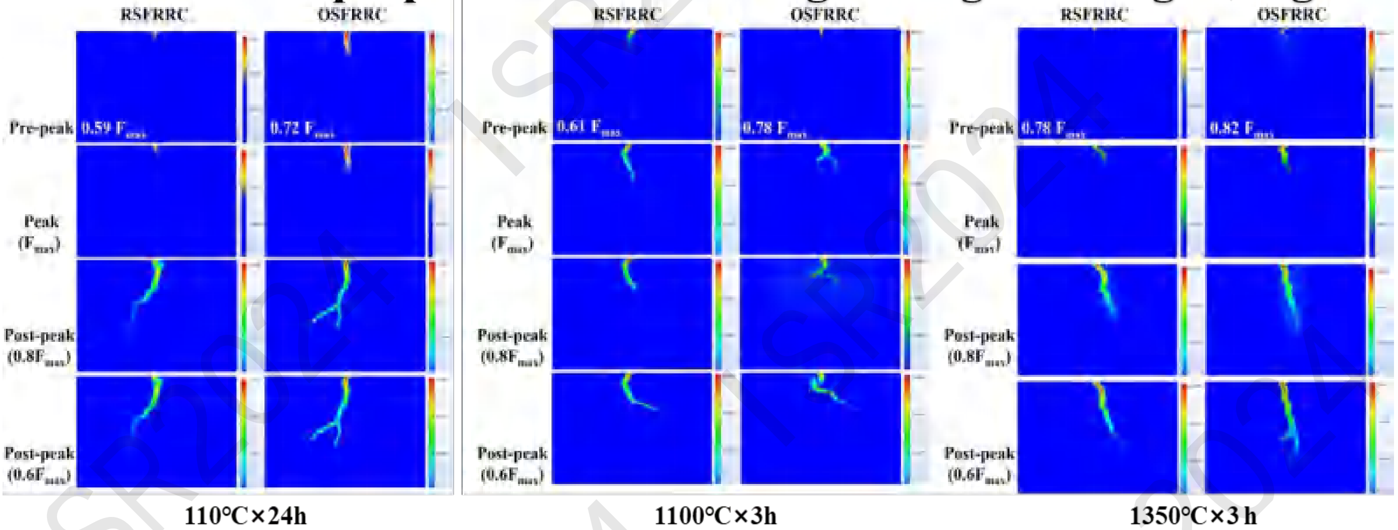
■ 力学性能及其增强增韧机理

Mechanical properties and its strengthening and toughening mechanism



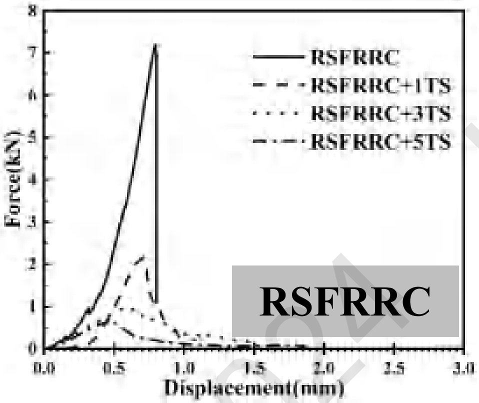
DIC results of the SFRRC tested in the WST

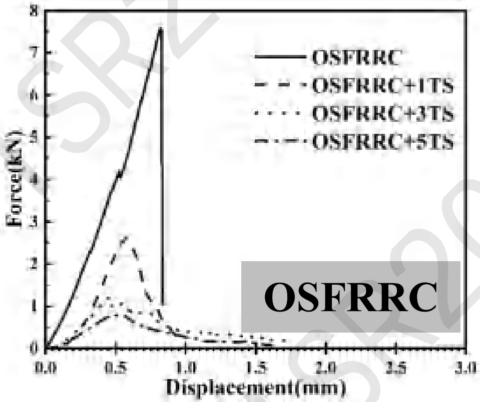
钢纤维取向后试样的E_{XX}显著增加，裂纹偏转更严重且具有裂纹分支，试样抵抗应变能力增强。

OSFRRC samples exhibit more severe crack deflection and branching. The deflection and branching of cracks make the path of crack propagation intricate, thereby enhancing the stress resistance of the samples.

Results and discussion

■ 热震稳定性 Thermal Shock Resistance of OSFRRC





Load-displacement curves before and after thermal shock tests

CMOR retention rate before and after thermal shock tests

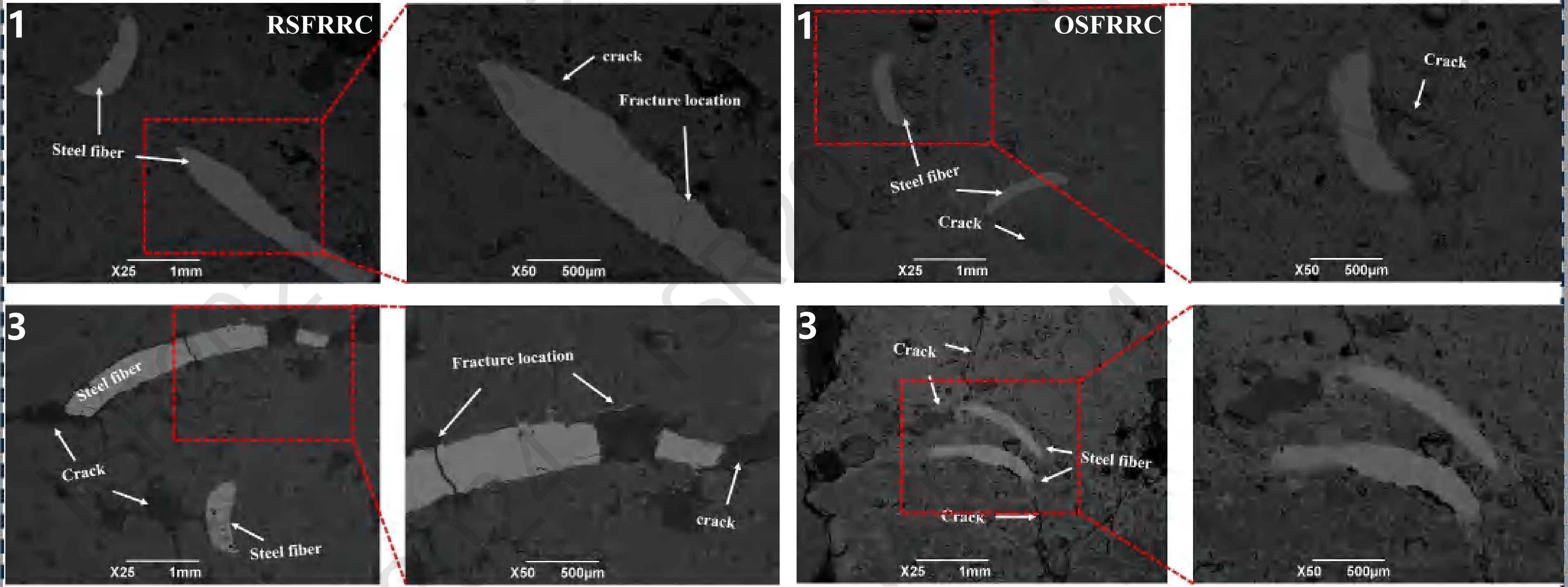
	Number of thermal shock cycles/times	CMOR after thermal shock/MPa	CMOR retention rate/%
RSFRRC	1	6.70	39.69
	3	2.75	16.29
	5	1.91	11.25
OSFRRC	1	7.90	43.92
	3	3.43	19.06
	5	2.51	13.90

钢纤维取向使试样的残余抗折强度保持率有较大提升。随着热震冲击周期增加，试样的断裂行为变得更加非线性。

The orientation of steel fiber greatly improves the retention of the residual CMOR of the samples. With the increase of thermal shock cycles, the fracture behavior of samples becomes more nonlinear.

Results and discussion

热震稳定性 Thermal Shock Stability of OSFRRC



BSE images of samples after thermal shocks

Results and discussion

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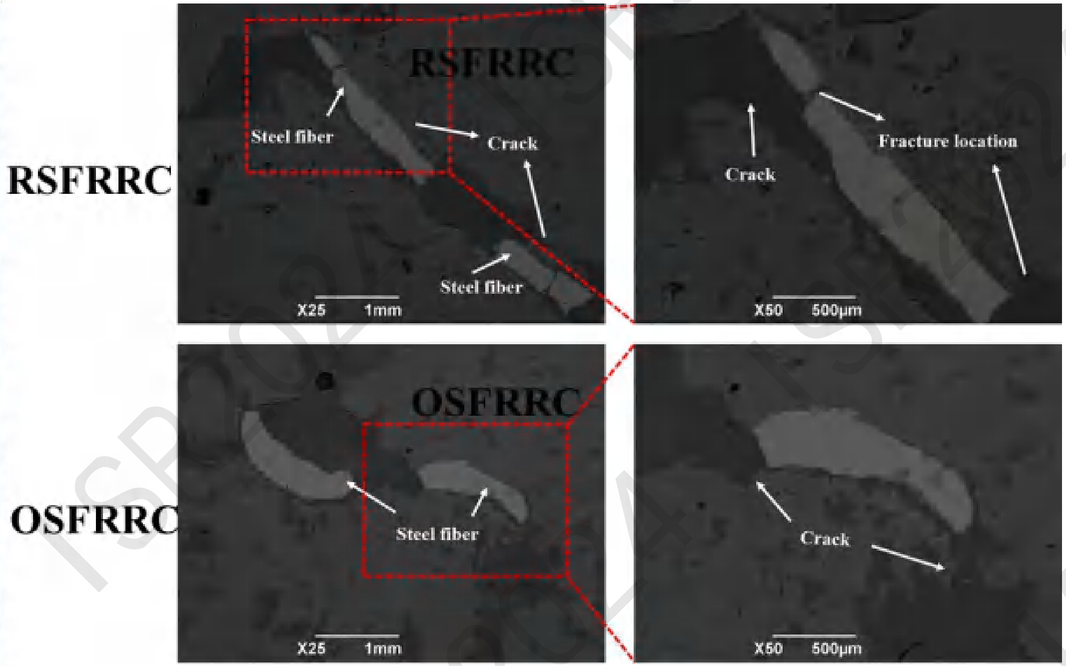
■ 热震稳定性 Thermal Shock Stability of OSFRRC



随着热震次数的增加，RSFRRC中的钢纤维附近出现连续且相对较宽的裂纹，并伴有明显的钢纤维断裂;在OSFRRC中，裂纹在钢纤维周围的扩展显示出明显的偏转或者裂纹消失。

Following thermal shock treatment, continuous and relatively wide cracks become evident near the steel fibers in RSFRRC, leading to significant fracture of the steel fibers. In contrast, in OSFRRC, crack propagation toward the steel fibers shows noticeable deviation and ultimately disappears.

Conclusion

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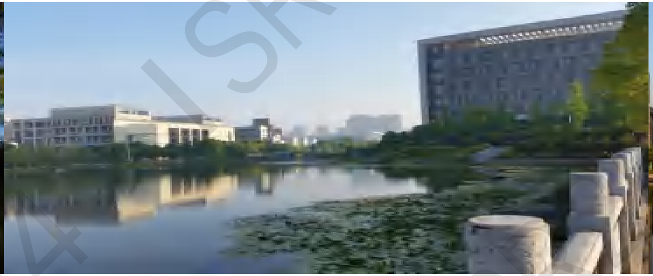
✓ 硅微粉添加量为6wt.%，磁场作用时间≥60s，磁场强度≥2.5mT时，成功制备了η_θ为0.96的取向钢纤维增强耐火浇注料。(When the addtion of silica fume was 6wt.%, the magnetic field action time was 60s and the magnetic field strength is 2.5mT, oriented steel fiber reinforced refractory castables with an η_θ of 0.96 were successfully prepared.)

✓ 钢纤维取向增强了其在浇注料基体内部桥接裂纹和分散应力的有效性,大幅提高了材料断裂韧性；钢纤维取向莫来石浇注料在断裂过程中，裂纹扩展路径变得复杂（分支、偏转），增强了抵抗裂纹扩展能力。(The orientation of steel fibers enhances their effectiveness in bridging cracks and dispersing stress within the castable matrix, and greatly improves the fracture toughness of the material. During the fracture process of OSFFRC, the crack propagation path becomes more complex (branching, deflection), enhancing the ability to resist crack propagation.)

✓ 钢纤维取向可以明显改善浇注料的抗热震性，并优化热震后试样的非线性断裂行为。(The orientation of steel fibers can significantly improve the thermal shock resistance of castables, and optimize the nonlinear fracture behavior of samples after thermal shocks.)

THANK YOU！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