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An analysis of the microscopic cracking mechanism of hardened alkali-activated slag

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HIGHLIGHTS

- Analyzed the microstructure of the mineral components of the slag.
- Analyzed the effects of thermal stress on the cracking behavior of solidified slag.
- Analyzed the cracking-prone mineral components of the hydration product.
- Analyzed the cause of the propagation of cracks inside solidified slag.

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ABSTRACT

Hardened slag (HS) is prone to cracking at temperatures higher than 70 °C, which prevents it from being widely used as a structural material. In this study, using a strength analysis, HS was thoroughly studied to determine the microstructure of its mineral components, understand its hydration process and determine the microstructure of its hydration products. In addition, a nondestructive testing method, micro-computed tomography, was employed to analyze the cause of cracking of the HS. The results showed that the cracking-prone mineral components of the hydration products of the HS and the alternating thermal stress could induce the formation of micro-cracks in the HS. Air introduced during the paste preparation process promoted further propagation of the micro-cracks. Using an activator that reduced the amount of heat generated from the hydration of slag caused the slag to develop high early strength and led to the formation of hydration products that contain relatively small amounts of cracking-prone components, which effectively reduced the extent of cracking of the HS. This study provides an important basis for developing new activators and extensively applying slag in oil fields.

1. Introduction

Slag is used as a cementing material in the mud-to-cement (MTC) conversion process in oil fields. Slag was once used extensively because the reuse of slag, which is an industrial waste, was favorable for energy conservation and environmental protection. The use of slag has shown that hardened slag (HS) cracks under high temperature conditions. As a result, the popularization and application of slag-based MTC technology in oil fields have been limited in recent years [1].

To solve this “bottleneck” of slag-based MTC technology, numerous researchers have conducted extensive research on the shrinkage stress, thermal stress and bonding performance of the interface. Research has shown that when specimen is under constrained conditions, there is a conflict between local volume shrinkage and macroscopic volume stability, and cracks form when the tensile stress exceeds the ultimate tensile strength [2–5]. HS obtained by placing a prepared paste in a mold and curing it in a water bath exists in a free state, and the constraints are the main factor that causes the HS to crack. Research on the thermal stress has shown that structural cracks induced by the thermal deformation of HS, which is caused by the heat released from the hydration of the paste, are the main cause of cracking of HS [6–10]. Most studies have recommended that slag be used as an external admixture for cement and that cracking be mitigated by reducing the

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Table 1
Main components of the experimental slag.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Other
30.83%	9.86%	2.26%	41.56%	9.02%	6.47%

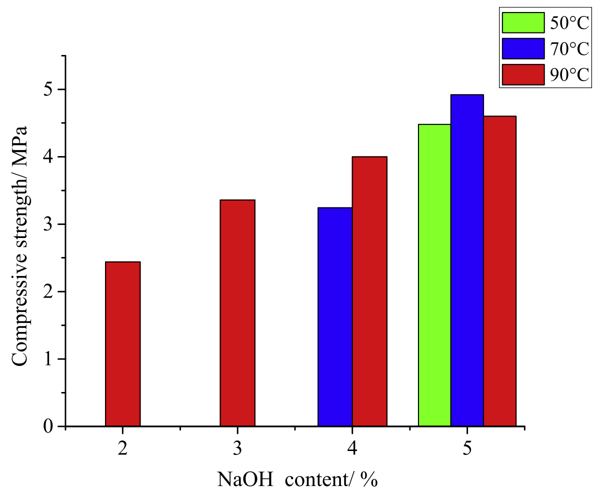

Fig. 1. Compressive strength of the hardened NaOH-activated slag after 24 h of curing.

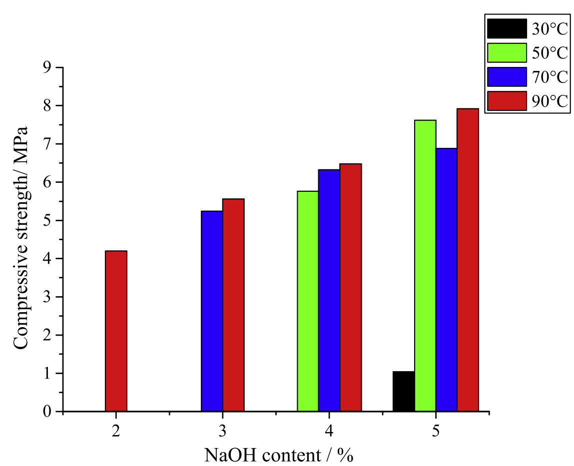

Fig. 2. Compressive strength of the hardened NaOH-activated slag after 48 h of curing.

Table 2
Compressive strength of the hardened Na_2CO_3-activated slag for 24 h at 90 °C of curing.

The amount of Na_2CO_3	4%	5%
Compressive strength MPa	1.88	1.76

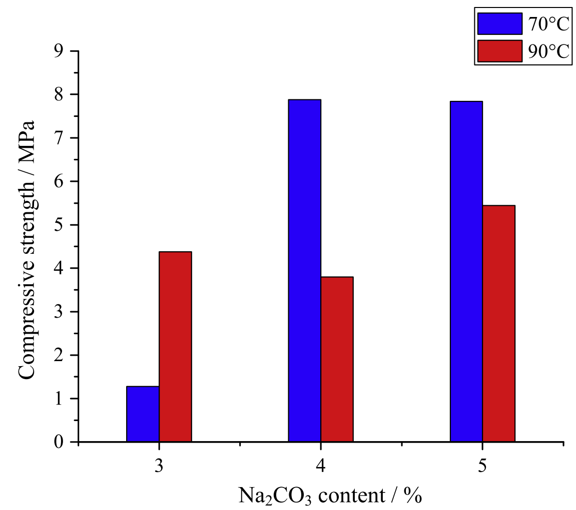

Fig. 3. Compressive strength of the hardened Na_2CO_3-activated slag after 48 h of curing.

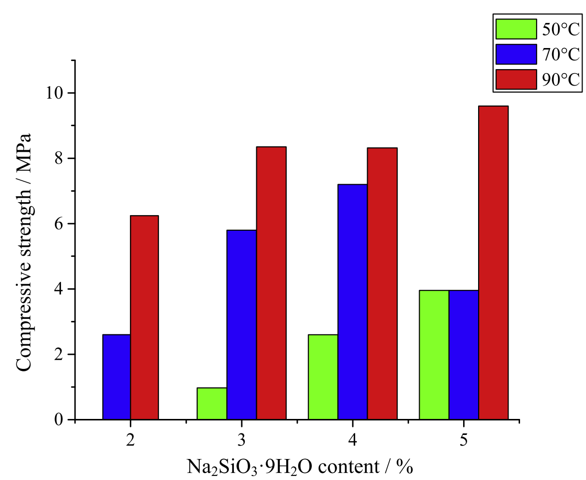

Fig. 4. Compressive strength of the hardened $Na_2SiO_3 \cdot 9H_2O$-activated slag after 24 h of curing.

heat of hydration of the cement by mixing slag at a certain proportion [11,12]. However, little research has been conducted to investigate the effect of the variation in the heat of hydration during the strength development process on the cracking of the HS when pure slag is used as a cementing material. Peng et al. found that the cementing performance of the hydration products of slag was poor when they had a spherical or honeycomb shape and that microcracks formed first at the interface under stress; however, they did not conduct a microscopic analysis of the hydration products [13]. To enhance the mechanical properties of HS, several researchers mitigated the effects of stress on the cracking behavior of HS by adding fiber to the paste [14,15]; however, the applications of their research results in oil fields is somewhat limited because the addition of fiber can affect the rheological properties of the paste.

Previous research has focused more on analyzing the cracking behavior of specimens from a macroscopic mechanical performance perspective. However, little research has investigated the relationship between the microscopic variation mechanism and the structure of HS and to elucidate the cracking behavior of HS from the perspectives of the mineral components, hydration process and components of the hydration products of the cementing material using nondestructive testing methods. The objective of this study is to understand the cracking behavior of HS under high temperature conditions. A high-resolution transmission electron microscope (HRTEM) was used to study the mineral components of the experimental slag and its hydration products. And an