Effect of Temperature-Specimen Geometry on Pure Shear Crack Resistance of Cemented Rock-Like Materials

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ABSTRACT

Fracture toughness is considered a key parameter for evaluating the mechanical behavior of rock-like materials, particularly when they are subjected to temperature variations. Since many engineering structures, such as tunnels and underground structures, operate over a range of temperatures, investigating the combined effects of temperature and specimen geometry on the fracture behavior of these materials is of particular importance. In this study, the effects of temperature and specimen geometry on the Mode II fracture toughness of cement mortar were experimentally investigated. To this end, tests were conducted on three different specimen geometries, including a centrally cracked Brazilian disc, a modified semi-Brazilian specimen with a pre-existing notch, and a Brazilian disc with a double diagonal crack, at four temperature levels of −10, 25, 50, and 100 °C. In addition to fracture toughness, uniaxial compressive strength and P- and S-wave velocities were measured to evaluate changes in the internal quality of the specimens under the influence of temperature. The results indicate that decreasing the temperature below the reference temperature improves the internal quality of the specimens and increases fracture toughness, whereas increasing the temperature leads to deterioration in internal quality, a reduction in ultrasonic wave velocities, and, ultimately, a decrease in the resistance capacity against crack propagation. Furthermore, comparison of the different specimen geometries revealed that the sensitivity of fracture toughness to temperature variations depends on the stress distribution and crack-tip conditions associated with each geometry.

KEYWORDS

crack growth resistance, temperature effect, specimen geometry effect, quality index, ultrasonic pulse velocity

1. Introduction

Natural and artificial structures are subjected to various loading conditions that influence their mechanical properties and stability. Understanding how these materials respond to different loads is crucial for stability analysis, failure prediction, and optimal design in civil and geotechnical engineering. The initiation and propagation of cracks in rock materials depend on the stress state and can occur in three primary fracture modes (Modes I, II, and III) or their combinations. Under mixed-mode conditions, failure results from multiple fracture modes interacting, affecting crack propagation paths, growth rates, and load-bearing capacity. Thus, a systematic understanding of mixed-mode fracture behavior is vital for slope stability analysis, safe underground structure design, and enhancing engineering efficiency and safety [1–3].

In fracture mechanics, crack behavior in materials depends on specimen geometry, boundary conditions, and applied loading. The stress intensity factor is a key parameter that characterizes the stress field near a crack tip and is crucial for understanding crack initiation and propagation in linear elastic fracture mechanics and advanced nonlinear models. Stress intensity factors are classified into three components based on fracture modes. Fracture toughness, the critical value of the stress intensity factor, quantitatively measures a material's resistance to crack initiation or propagation, making it essential for evaluating the mechanical performance of brittle and quasi-brittle materials, such as concrete and rocks [4–6].

Thermal conditions significantly influence the fracture behavior of materials. Temperature fluctuations, from daily variations to extreme events like fires, can induce damage in rock-like materials, particularly those with inherent defects like microcracks and discontinuities. Differences in thermal expansion among the material phases can increase stress concentrations, promote crack propagation, and reduce resistance to crack growth.

The study investigates how temperature and specimen geometry jointly affect Mode II fracture toughness, considering the roles of microstructural quality, thermal damage, stress distribution, and crack propagation. It aims to clarify thermal damage mechanisms and provide a basis for designing structures exposed to variable thermal conditions.

2. Methodology

This study evaluates the impact of thermal conditions on the mechanical performance of cement mortar using a uniform mix design. The primary mixture comprised Type II Portland cement, fine-grained sand, and water, with all materials kept identical to eliminate secondary factors. The main variable was the addition of 5% micro silica by weight as a cement replacement to enhance microstructure and early-age strength. Specimen preparation followed ASTM C305 standards.

In this study, cylindrical specimens were prepared to examine the effects of thermal conditions on their physical and mechanical behavior. They underwent a single thermal cycle at four temperatures: −10, 25, 50, and 100 °C, each for 24 hours, followed by 24 hours in a laboratory environment. Ultrasonic tests measured P-wave and S-wave velocities to assess microstructural changes, and uniaxial compressive strength tests evaluated the material's strength. This approach linked nondestructive testing results to destructive tests and analyzed the fracture behavior of the cement-based material under the same thermal conditions. This study prepared three types of specimens: the centrally cracked straight-through Brazilian disc (CSTBD), the modified semi-circular Brazilian specimen with a notch (MSCB), and the double-notched Brazilian disc (DNBD). These geometries were designed to investigate fracture response and crack propagation under indirect loading, as well as temperature sensitivity. A total of 36 specimens were tested across different temperature and geometry combinations. For the specimens with pre-existing cracks, a 1-mm blade created the initial notch. The mortar was compacted, and after 24 hours, the specimens were demolded and cured for 28 days in a lime-saturated water bath to standardize conditions.

3. Results and discussion

Mode II fracture toughness of the centrally cracked Brazilian specimens showed a significant temperature dependence. The mean fracture toughness increased from 0.6879 $\mathrm{MPa\cdot m^{0.5}}$ at 25 °C to 0.7822 $\mathrm{MPa\cdot m^{0.5}}$ at −10 °C, representing a 13.7% increase. In contrast, it decreased to 0.6305 and 0.5724 $\mathrm{MPa\cdot m^{0.5}}$ at 50 and 100 °C, corresponding to reductions of 8.3% and 16.8%, respectively. This decrease is mainly attributed to thermal damage, microstructural deterioration, and the development of thermally induced microcracks. The modified semi-Brazilian specimens showed a similar trend. Fracture toughness increased from 0.6928 $\mathrm{MPa\cdot m^{0.5}}$ at 25 °C to 0.7675 $\mathrm{MPa\cdot m^{0.5}}$ at −10 °C, an increase of 10.8%. At 50 and 100 °C, it decreased to 0.6497 and 0.5954 $\mathrm{MPa\cdot m^{0.5}}$, corresponding to reductions of 6.2% and 14%, respectively. For the Brazilian specimens with double-edge cracks, fracture toughness increased from 0.6388 $\mathrm{MPa\cdot m^{0.5}}$ at 25 °C to

0.6691 MPa·$m^{0.5}$ at −10 °C, representing a 4.8% increase. At 50 and 100 °C, it decreased to 0.5775 and 0.5206 MPa·$m^{0.5}$, corresponding to reductions of 9.6% and 18.5%, respectively (See Figure 1).

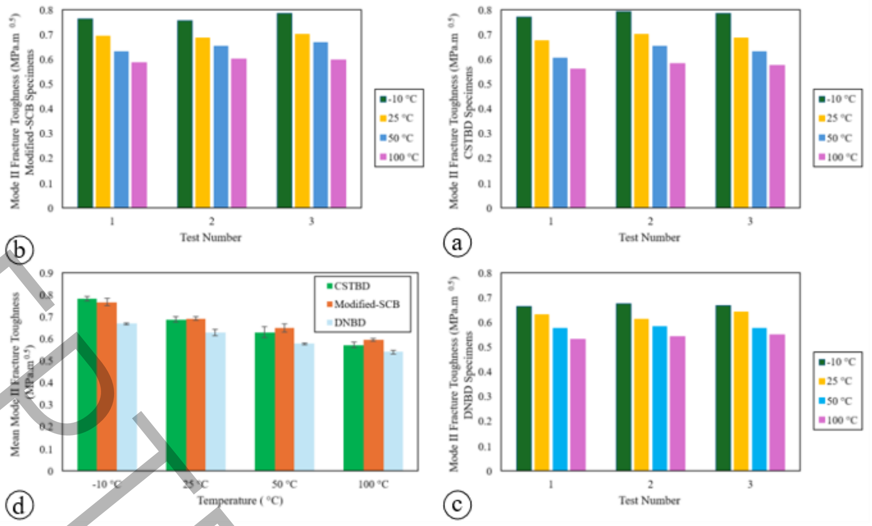

Figure 1. Overall experimental results for Mode II fracture toughness: (a) centrally straight notched Brazilian disc specimens, (b) modified semi-Brazilian specimens, (c) Brazilian disc specimens with double-edge cracks, and (d) average values.

Overall, the reduction in fracture toughness at elevated temperatures is mainly associated with moisture loss, thermal stresses, differential thermal expansion between aggregate and cement paste, and the development of microcracks. Conversely, the increase at −10 °C can be attributed to freeze-induced strengthening, reduced crack-tip stress concentration, and improved aggregate–cement interfacial bonding.

4. Conclusion

Temperature had a significant effect on Mode II fracture toughness. Lowering the temperature to −10 °C increased fracture toughness by about 10–15%, whereas increasing it to 100 °C reduced it by more than 25% in some geometries. The MSCB geometry was more sensitive to high temperatures than CSTBD and DNBD, highlighting the role of crack-tip stress distribution. Uniaxial compressive strength decreased from about 41 MPa at −10 °C to 33 MPa at 100 °C, indicating microstructural deterioration. P and S-wave velocities also decreased with increasing temperature, confirming the development of thermally induced microcracks. The ultrasonic quality index showed a positive correlation with fracture toughness, suggesting that ultrasonic measurements can be used to assess thermal damage and predict changes in fracture toughness. Overall, shear fracture behavior is controlled by the combined effects of temperature, microstructural quality, loading conditions, and specimen geometry.

5. References

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