Construction and Building Materials 169 (2018) 403–413

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of curing humidity on the fracture properties of concrete

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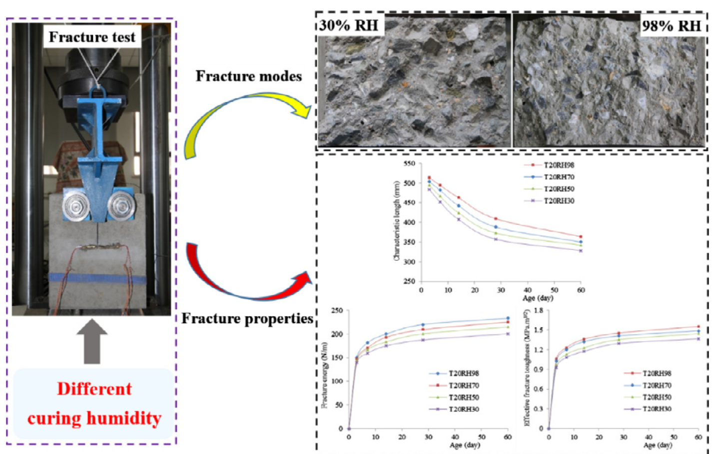
HIGHLIGHTS

- Fracture properties of concrete were investigated under different conditions.
- At early age, fracture parameters remained almost constant during drying.
- At later age, fracture parameters decreased markedly with decreasing curing humidity.
- Fracture mode changed from ductile to brittle with reduction in curing humidity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 November 2017
Received in revised form 24 February 2018
Accepted 1 March 2018
Available online 20 March 2018

Keywords:
Fracture properties
Wedge splitting test
Relative humidity
Failure mode

ABSTRACT

This study investigates the influence of curing humidity on concrete fracture properties. Concrete fracture energy, effective fracture toughness, and characteristic length were tested at five different ages using wedge splitting specimens exposed to four different relative humidity values (30%, 50%, 70% and 98%). Four environmental chambers capable of automatically controlling temperature and relative humidity were constructed. A data averaging method for companion specimens was introduced. The test results show that at the early age, fracture energy, effective fracture toughness, and characteristic length remained almost constant during drying. As time elapsed, however, the influence of curing humidity on the concrete fracture properties became increasingly pronounced; larger values of fracture energy, effective fracture toughness, and characteristic length were measured by concrete specimens kept at high humidity. The concrete fracture mode also gradually changed from ductile to brittle with curing humidity decreasing and hydration time elapsing.

1. Introduction

Concrete is the most common structural material used in the modern times. It is often poured and operated in different environments. Therefore, concrete structures face continuously changing curing conditions owing to climatic variations. This results in the formation of moisture gradients in concrete structures because of water evaporation to the surroundings at lower relative humidity levels. The extent and severity of moisture gradients depend on many factors, such as ambient air relative humidity, temperature, local rainfall, wind speed, and age at exposure. The properties of concrete are also impacted by curing conditions [1,2].

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https://doi.org/10.1016/j.conbuildmat.2018.03.025
0950-0618/

Many studies investigated the effect of moisture gradient on the behavior of concrete, and the results show that the reduced curing humidity not only can negatively affect the hydration reaction and microstructural behavior of concrete, but can also seriously deteriorate its mechanical and fracture properties [3–5]. Powers first recognized that cement hydration slows down at low internal relative humidity and almost stops below approximately 80% RH [6]. In other words, due to desaturation and the corresponding reduction of the internal relative humidity in the pores of a cementitious material, cement hydration may nearly come to a halt and the development of concrete properties may be hampered, even though the system still includes considerable amount of water. This indicates that the development of various properties of concrete structure depend on the available water, and if the structure is exposed to very low humidity, its surface hydration will cease and strength and durability will decrease, which may cause surface cracking and may not afford the desired protection. This will gradually hamper the hydration of the internal parts of concrete structures, as the pore water is also lost through the drying surface. Later, other researchers also observed a similar phenomenon. For instance, Snyder and Bentz [7] found that the hydration of a cement paste at 90% RH was lower than that under saturated conditions. In particular, Jensen's experimental results [8] revealed that the hydration degree of C_3S was about 67% after 365 days at 98% RH, but only about 4% when kept at 85% RH for 365 days. The hydration degree was even smaller at a lower relative humidity, and nearly no hydration took place below 43% RH. On the other hand, Flatt et al. [9] theoretically proved why C_3S cease to hydrate below 80% RH, and showed that this phenomenon is caused mainly by the reduced water activity, which changes the solubility of C_3S so that it is in equilibrium with the pore fluid. Du et al. [10] simulated the reduction in the reaction rate caused by decreased humidity, in which the hydration rate reduction factor independent of temperature and hydration degree was 1.0 at 100% RH and it decreased to smaller values at lower humidity levels.

Regarding the influence of reduced relative humidity on concrete microstructure, Cong and Kirkpatrick [11] observed that the polymerization of C-S-H does not change when the relative humidity was varied from 9% to 100%; however, its local structure becomes more disordered with decreasing relative humidity. Using nuclear magnetic resonance spectroscopy, Aparicio et al. [12] observed that the samples cured at 70% RH presented more tetrahedral coordinated aluminum than those cured at 98% RH because more aluminum was taken up by the C-S-H gel and the transformation of AFt to AFm was promoted. Furthermore, the mean chemical reaction chain length of the C-S-H gel formed increased with decrease in curing humidity, and longer chains correspond to lower hydration degree. In addition, Sellevold and Bjøntegaard [13] claimed that the thermal expansion coefficient of concrete during maturation increase with decreasing humidity, where the reduction in humidity is owing to self-desiccation and/or drying of the environment.

In general, the mechanical properties of concrete, both in term of strength and elastic modulus, decrease monotonically as a function of its curing humidity. Cebeci [14] showed that the compressive strength of concrete reduced by 30% in 75% RH; and by 45% in 33% RH as compared to the specimens cured in water. Saengsoy et al. [15] found that the compressive strength of concrete cured in water and at 95% RH rapidly increased and became almost steady after 28 days. However, at 80% RH, the concrete strength develops slowly; especially at 60% RH, the strength hardly increased after 7 days, leading to a loss of approximately 41% in the ultimate strength compared to those cured in water. It must be noted that Un and Baradan [16] concluded that the flexural strength is more sensitive to curing humidity than compressive strength, and the smaller values of flexural strength are measured by the specimens cured at decreased relative humidity. With regard to the elastic modulus, Beaudoin et al. [17] observed that the static elastic modulus in compression decreases significantly with reducing relative humidity, especially below 20% RH. Furthermore, they also reported that the elastic modulus shows a non-linear response with respect to the relative humidity and that it depends on the drying history. This is also confirmed by Alizadeh et al. [18], who also reported that concrete would lose elastic modulus if exposed to reduced humidity and hypothesized that such reduction could be attributed to micro-cracking and other micro-scale phenomena such as high porosity. Moreover, Yalcinkaya and Yazici [19] studied the effect of relative humidity on the drying strain and showed that the shrinkage of concrete, compared to that at 100% RH, was increased by 33%, 46%, and 52% under 70% RH, 60% RH, and 50% RH, respectively.

However, very limited information is available on the fracture properties of concrete exposed to low humidity. Bazant et al. [20] and Lau et al. [21] investigated the effect of moisture on the fracture properties of hardened concrete. They showed that both the fracture energy and fracture toughness decrease with the increasing moisture, and they supposed that the degradation of fracture properties of concrete under moisture can be attributed to internal pore water pressure, which would cause a very high disjoining pressure between the contacting cement pastes. In particular, data about the effect of curing humidity on the development of concrete fracture parameters over time and long-term fracture properties have been barely reported to date.

Therefore, the objective of this study is to investigate how curing humidity affects the development of fracture properties of concrete with age. Four different curing conditions were considered with a constant temperature of 20 °C under different relative humidity levels. The fracture parameters were measured after 3, 7, 14, 28, and 60 days.

2. Experimental program

2.1. Materials

The concrete mix proportions are listed in Table 1. The cement used was type I ordinary Portland cement with a density of 1450 kg/m^3. The fine aggregate utilized was natural river sand with a fineness modulus of 2.52, conforming to ASTM C33/C33M No.2. The crushed basalt passing the 20 mm sieve was applied as the coarse aggregate. Physical properties and gradations of the coarse aggregate were examined using the test standards of ASTM C33/C33M No.67. The ratio of fine to total aggregate was 39% for all concrete mixtures. The substitution rate of fly ash (ASTM Class A) was 25% for the total binder content, which was in order to reduce the heat of hydration for applications and save the cement. Potable water was used for mixing concrete constituents and curing of the specimens. No further additive was employed. In order to achieve better uniformity, the concrete was mixed for 6 min. In addition, an external vibrator was used for concrete compaction.

2.2. Specimen preparation and test set-up

Fracture tests were carried out on notched wedge splitting specimens. These specimens are characterized by a negligible influence of their self-weight on test results and by a considerably large fracture area to the specimen volume ratio, which is approximately 4.6 times greater than that of a commonly used three-point bending beam of equal volume [22]. However, compared to a conventional wedge splitting test with one line support, two hinge roller supports located at the center of the half section of the specimens were utilized to improve their stability and to avoid