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Determination of tensile strength of concrete using a novel apparatus

Vahab Sarfarazi [a], Hadi Haeri [b,*], Pouyan Ebneabbasi [c], Alireza Bagher Shemirani [d], Ahmadreza Hedayat [e]

[a] Department of Mining Engineering, Hamedan University of Technology, Hamedan, Iran
[b] Young Researchers and Elite Club, Bafgh Branch, Islamic Azad University, Bafgh, Iran
[c] Hamedan Branch, Islamic Azad University, Hamedan, Iran
[d] Department of Civil Engineering, Sadra Institute of Higher Education, Tehran, Iran
[e] Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO 80401, USA

HIGHLIGHTS

- The concrete specimens are experimentally tested under indirect tensile loading using a new load convertor device.
- The effect of the hole diameter on stress concentrations around the hole are studied.
- A formula for determining the tensile strength of concrete is developed.
- The same specimens are numerically simulated by a two-dimensional finite element code FRANC2D/L.

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ABSTRACT

This study presents a new and novel technique for the determination of the tensile strength of concrete specimens. A prismatic concrete specimen with a hole at its centre is placed in a new device, called seesaw, and with the use of a conventional loading machine in compression mode, a tensile stress is applied to the specimen for the determination of the indirect tensile strength. In this study, two types of concrete mixes were used for preparation of specimens. The mixes were made of gravel, sand, cement, water, polypropylene fibre, and admixtures. Concrete specimens were subjected to tensile loading using a new load convertor device and a universal loading machine was used for the application of the load to the specimen. The load was applied at the rate of 0.02 MPa/s. The two dimensional finite element code FRANC2D/L was used for numerical modelling of the specimens and the loading conditions to determine the stress concentrations around the hole as a function of the hole diameter and the specimen width. Based on the results of experiments and numerical modelling efforts, a new formula for determination of the tensile strength of concrete is proposed in this study. Concurrent with indirect tensile tests using this new device, splitting test were performed to confirm the observed tensile strength values for concrete specimens. Both experimental and numerical modelling results show that the tensile failure occurs around the sides of the hole along the horizontal axis.

1. Introduction

Many experimental and theoretical studies have focused on determining the tensile strength of concrete and cementitious materials [26,6,7,1,24,25,31,16,13,29,19,8,27,30,12,28,18,15,34,35,32,11,23,10,22,20,21,39,36,43–50]. The tensile strength of concrete can be measured from different tests with different specimen geometries, such as direct pull tests on briquettes or dumb-bell shape specimens ([2,38,41,12], flexural tests on beams, splitting tests on cylinders or cubes, ring-tensile tests [14] and double-punch test [9]. Swaddiwudhipong et al. [33] studied the strain capacity in direct tension and the tensile strength of concrete produced with different types of cement at early ages. The most accurate and reliable way of measuring the tensile strength is by direct application of uniaxial tensile stress. However, this method requires significant amount of preparation and care compared with the indirect methods. Many experimental efforts for determination of the uniaxial tensile strength have failed because of unexpected crushing that occurs as a result of local stress concentrations in direct tensile tests. Another major drawback of the direct tension methods is that the rotation of the crack (failure) surface is unavoidable. Small load eccentricity, un-symmetry of specimens and imperfection of materials can cause un-symmetric

* Corresponding author.
E-mail addresses: haerihadi@gmail.com, h.haeri@bafgh-iau.ac.ir (H. Haeri).

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deformations in the damage zone [42]. These factors result in application of moment in the damage zone which can affect the obtained tensile strength values and reportedly reduce the tensile strength [42]. By conducting direct tensile stress tests on cylindrical concrete specimens and utilizing finite element and fuzzy image pattern recognition methods, Kim and Taha [18] assessed the stress uniformity along the concrete specimens subjected to direct tension and confirmed that the cracking location on direct tension tests is a function of unit weight distribution along the specimen.

It is known that the simplest and the most reliable method, which typically provides a lower coefficient of variation, is the splitting tensile strength of a cylindrical specimen (ASTM D3967-16 [4]). The splitting tensile strength of a cylindrical sample with radius R and thickness t, is given as:

$$\sigma_t = \frac{P_{max}}{\pi R t} \tag{1}$$

Zain et al. [40] proposed some equations relating the splitting tensile strength of high strength concretes to its compressive strength at different ages. However, most of existing methods suffer from some limitations. Majority of the indirect tests are based on the assumption that concrete is an elastic material. The indirect tests do not produce a uniform tension stress on the failure surface and the induced stresses on the failure surfaces are often not uniaxial [17]. These drawbacks result in an approximation of the value of the tensile strength of concrete. Using the 3- and 4-point bending configurations, one can evaluate the modulus of rupture for the concrete specimens as a measure of resistance to tension cracking. The main objective of this paper is to develop a new, simple, and reliable apparatus, called here in this work the seesaw device, for determination of the tensile strength of concrete specimens by applying a compressive load to the specimen. This paper first describes the specimen preparation and procedure and then focuses on the presentation of the design steps and assembly of the seesaw device. The results of a numerical modelling effort for the determination of the stress concentrations in the specimen are presented and used for proposing an equation for determination of the tensile strength of concrete specimens.

2. Experimental studies

2.1. Materials

Two types of concrete specimens were prepared from a mixture of gravel, sand, cement, water, polypropylene fibre, super-plasticizer and micro silica. The material proportions used for batching of the specimens are shown in Table 1. Crushed-limestone sand and gravel with specific gravity of 2.5 g/cm^3 of and 2.7 g/cm^3, respectively, were used as aggregates.

The reason for using concrete in this study is threefold: (a) concrete is an ideal material that could be representative of a wide range of brittle materials; (b) there is an extensive database of performance and literature exists allowing for comparison of new data with existing data (e.g., [31,15]); and (c) a large number of specimens can be prepared easily with high degree of repeatability. Concurrent with the preparation of specimens for this study, uniaxial compression tests were conducted to verify the strength and the specimen preparation procedure. The ASTM D2938-86 [3] procedure was followed to conduct the uniaxial compressive strength (UCS) tests on specimens of the model material in cylindrical shapes with diameter of 56 mm and height of 112 mm. Table 2 shows the results of the uniaxial compressive strengths on both concrete types.

2.2. Specimen geometry and preparation

A stainless steel mold with the internal dimensions of 12 × 12 × 4 cm was used for preparation of the internally holed specimens. The cast consists of three discrete parts (Fig. 1a–c). Two "L" and "U" shape parts are connected to each other and then cylindrical steel disc is screwed in middle of the main part (Fig. 1d). Diameter and height of steel disc are 6 cm and 5 cm, respectively. The concrete was poured into the mold after mixing and then vibrated on a vibrating table to assist with the removal of entrapped air inside the mix. After vibration, the mix was stored in room temperature for 8 h and then removed from the mold. The ratio of specimen height (12 cm) to diameter (6 cm) was two. The complete procedure of sample preparation and mold assembly is shown in Fig. 1e. Splitting test (BS1881, 1983 [6,7]) was also performed to compare the results with those of indirect tension test. The specimens for this test were 10 cm in diameter and 20 cm in height.

Eight similar cubic samples and eight similar cylindrical specimens were prepared from each mixture (Fig. 2) and kept in water tank for 23 days (Fig. 3).

2.3. Seesaw device

The seesaw device is a new device that allows for the transformation of the compression-to tension loads. The primary design requirement is to be able to convert the compression load applied through a conventional compression loading machine to tensile stresses acting on the failure plane in the concrete specimen. The seesaws device comprises of eight parts made from hardened stainless steel. Fig. 4 shows all components of the seesaw device and Figs. 6–12 show the individual components with the schematic design.

Part No. 1 is made of two semi cylindrical pieces as shown in Fig. 5. Internal dimension of these parts is 4.8 cm and the height is 4 cm and additional dimensions of these pieces are shown in Fig. 5b. Part No. 2 is a stainless steel block with a notch in the upper edge. A hole is drilled in the mold, going through the notch walls (Fig. 6a and b). Part No. 3 is a stainless steel block with a notch at the lower edge. Also, one hole is drilled within the mold and goes through the notch walls (Fig. 7a). Part No. 4 is a stainless steel block with two parallel openings as shown in Fig. 8a. Part No. 5 is a stainless steel bar as shown in Fig. 9a. Part No. 6 is a stainless-steel

Table 2
Materials properties of two type of concretes.

Mechanical properties	Concrete Type 1	Concrete Type 2
Average uniaxial compressive strength (MPa)	55	45
Average Young's Modulus in compression (GPa)	10	8.5
Average Poisson's ratio	0.18	0.2

Table 1
Materials used for preparation of concrete specimens.

Mixture type	Gravel (kg)	Sand (kg)	Cement (kg)	Water (cc)	Polypropylene fibre	Super-plasticizer (high range water reducer)	Micro silica
1	3	10.5	3	1500	14 g	–	–
2	3	10.5	2.8	1500	–	120 g	90 g