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Stress-strain behavior of freshly compressed concrete under axial compression with a practical equation

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HIGHLIGHTS

- The stress-strain behavior of freshly compressed concrete is investigated.
- Empirical formulas for the stress-strain curve of the compressed and uncompressed concrete are developed.
- Compressing the fresh concrete increases the amount of energy absorption.
- Compressing the fresh concrete increases the linear stage of the stress-strain curve.

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ABSTRACT

One of the ways to enhance the mechanical properties of the concrete is to compress the fresh concrete and remove the excess water and air from within it; hence knowing the stress-strain behavior of the compressed concrete is essential for the linear as well as nonlinear analysis and design purposes. In order to investigate the stress-strain behavior of the compressed and uncompressed concrete, an extensive experimental study was conducted and then, based on the experimental results, empirical formulas for the stress-strain curve of the compressed and uncompressed concrete are developed. In addition, the effect of compression on the amount of energy absorption as well as the extent to which the stress-strain curve is linear is investigated. In doing so, a total of 90 concrete cylindrical specimens divided into 10 series with the reference compressive strength ranging from 17.9 to 52.6 MPa were produced. The specimens in each series were grouped into three main categories: (1) short-term pressure-compressed concrete (SPCC), (2) long-term pressure-compressed concrete (LPCC) and (3) reference concrete (RC). The obtained results show that the proposed relationship for the actual stress-strain curve of the compressed and uncompressed concrete is not only able to predict the experimental results with high accuracy, but also it is applicable to a wide range of strength values. Furthermore, compressing the fresh concrete increases the amount of energy absorption and the linear stage of the concrete stress-strain curve, although the energy absorbed by the compressed concrete is lower compared to that of the uncompressed concrete with the same strength.

1. Introduction

Despite recent technological advances and production of new construction materials, the concrete is still widely used in buildings and many other structures as a popular construction material [1–4]. In order to perform any nonlinear analysis of a concrete member, stress-strain relationships must first be defined and calculated [5,6]. While some of these relationships are available, defining a relationship capable of capturing the actual behavior of the concrete in both ascending and descending branches under the test conditions is not possible. This is due to the fact that the stress-strain relationship, in particular the descending part of it, is affected by various factors including the concrete age at loading, aggregate and cement properties, type and size of the specimens, water to cement ratio, specific weight of the concrete, and type of curing [7–9]. Furthermore, the shape of uniaxial stress-strain curve is significantly affected by the test conditions including testing machine stiffness, relative stiffness between test machine and specimen, loading rate, type of strain gauge and displacement transducer and loading type (pre-loading, cyclic loading, etc.).

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Nomenclature

E_0	secant modulus of elasticity at the peak stress
E_{cR}	initial modulus of elasticity of RC specimen
E_{cS}	initial modulus of elasticity of SPCC specimen
E_{it}	initial modulus of elasticity of concrete
f_c	compressive strength of concrete
f_{cL}	compressive strength of LPCC specimen
f_{cR}	compressive strength of RC specimen
f_{cS}	compressive strength of SPCC specimen
LPCC	long term pressure-compressed concrete
m	ratio of E_{it} to E_0
M	error coefficient
N	number of observations
n	a factor for concrete stress-strain curve
n_a	a factor for ascending branch of concrete stress-strain curve
n_d	a factor for descending branch of concrete stress-strain curve
RC	reference concrete
SPCC	short term pressure-compressed concrete
U_r	relative energy absorption
x	dimensionless strain
X_m	measured values
$\bar{X}_m$	average of measured values
X_p	predicted values
y	dimensionless stress
α	a factor for concrete stress-strain curve
α_a	a factor for ascending branch of concrete stress-strain curve
α_d	a factor for descending branch of concrete stress-strain curve
ε	axial strain
ε_0	strain at peak stress
σ	axial stress

Hognestad [10] investigated simple approximate expressions for obtaining a proper ultimate capacity for design purposes, and also, developed a general theory aiming at predicting the behavior of reinforced concrete members subjected to eccentric loading across the entire loading range from the lowest applied load to the failure load, including the failure mode. Wang et al. [8] proposed an analytical relationship with four constant parameters which were dependent on the characteristics of the ascending and descending parts of stress-strain curves. They used two sets of coefficients; one for the ascending branch and the other for the descending branch which could be calculated by having four key points of the curve. The coordinates of the four key points were expressed as functions of compressive strength of concrete, thus the whole curve could be calculated by possessing only the compressive strength. Carreira and Chu [9] proposed an equation to demonstrate the complete stress-strain relationship of the conventional concrete under compression. The parameters defined in the equation were either estimated based on empirical relationships or determined experimentally. The proposed equation was applicable to a wide range of testing conditions and concrete properties for both the ascending and descending branches of the concrete stress-strain curve. Ali et al. [11] presented simple equations in the polynomial form to capture the stress-strain relationships of the concrete made from local materials under uniaxial compression. A very good agreement was found by comparing the results obtained by the proposed equations with those of the experiments. An empirical equation to capture the complete stress-strain behavior of the permeable concrete with the compressive strength and porosity ranging from 10 to 35 MPa and 15 to 25%, respectively, was developed by Hussin et al. [12], in which the only required parameters to be used in the model were the ultimate compressive strength and density. Comparing the proposed empirical stress-strain equations with the test results revealed that the model gave a good representation of the actual stress-strain response behavior. Van Gysel and Taerwe [13] investigated some of the available formulas for the complete stress-strain curve of the high strength concrete under uniaxial compression, and compared the results with the load-controlled tests performed on the high strength concrete cylindrical specimens. In addition, they proposed a new analytical formula for the complete stress-strain curve with emphasis on the softening branch, which was based on the curve developed by Sargin et al. [14] and was approved in the CEB-FIP code [15] for concrete structures with proper parametric values. Tsai [16] proposed a new formula capable of considering both ascending and descending parts of the uniaxial compressive stress-strain relationships. The formula includes two parameters, one of which governing the ascending part's slope and the other governing that of the descending part, both expressed in terms of the concrete compressive strength.

Table 1
Stress-strain relationships in the first group with constant m.

Researcher	Relationship
Hognestad (1951) [10]	$ly = [2x - x^2],\ 0 \leqslant x \leqslant 1$ $y = \left[1 - 0.15\left(\frac{x-1}{k-1}\right)\right],\ 1 \leqslant x \leqslant k$ $\varepsilon_0 = 0.002;\ k = \frac{\varepsilon_{cu}}{\varepsilon_0}$
Smith and Young (1955) [20]	$y = x.exp(1 - x)$
Desayi and Krishnan (1964) [21]	$y = \frac{2x}{1+x^2}$
Tulin and Gerstle (1964) [22]	$y = \frac{3x}{2+x^3}$
Yip (1998) [23]	$y = \frac{2.7182x}{1+x+\frac{1}{2}x^2+\frac{1}{6}x^3}$

Chen et al. [17] examined the mechanical properties of the concrete with the compressive strength in the range of 10–50 MPa, and also conducted an experimental investigation as well as an analytical study to develop a mathematical model in order to predict the stress-strain curve of the concrete under a compressive load. The model was controlled with the experimental results and a good agreement was found between the two. Cui et al. [18] presented an analytical model for the pre-peak stress-strain curve of the light-weight aggregate concretes (LWAC), then, in order to investigate accuracy of the model, it was compared with the test data and a difference of less than 1.5% was observed between the two.

In this paper, first, the various models developed by the other researchers in the literature for the concrete stress-strain curve are investigated, and then, the experimental program is described. The tests are performed on the normal concrete specimens with the compressive strength ranging from 17.9 to 52.6 MPa. The test specimens are divided into the three groups of compressed concrete under short-term pressure, compressed concrete under long-term pressure, and uncompressed concrete. Based on the data obtained through experiments, relationships for the strain at the peak stress for both the compressed and uncompressed concrete specimens are proposed. Finally, a simple but accurate model in order to capture the complete stress-strain curve of concrete based on the empirical equations suggested for the peak stress, initial modulus of elasticity, and strain at peak stress is proposed, which is in good agreement with the experimental results of both the current study and the works of other researchers in the literature.