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Stress–strain model for normal- and light-weight concretes under uniaxial and triaxial compression

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HIGHLIGHTS

- Two experimental databases of confined and unconfined concretes are reported.
- Parameters defining pre-peak, peak and post-peak conditions of concretes were established.
- A unified stress–strain model for confined and unconfined concretes is presented.
- The model is applicable to concrete specimens with various dimensions, densities and strengths.
- The model provides improved predictions of stress–strain behavior over existing models.

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ABSTRACT

Accurate prediction of stress–strain relationship of concrete is of vital importance to accurately predict the overall structural behavior of reinforced concrete members. The various types of concrete that are available in the construction industry today makes it essential that the models developed for the prediction of their behavior are of high versatility. Review of the existing literature revealed that existing stress–strain models for unconfined and confined concretes are limited in their application domains, defined by the parametric range of the experimental results considered in their development. The review also indicated that a unified model that is applicable to normal- and light-weight concretes is not yet available. The aim of the present study was to develop a unified confinement model that is applicable to various types of concrete, ranging from light-weight to high-strength. To this end, two large databases of experimental results of concrete specimens tested under uniaxial and triaxial compression were assembled through an extensive review of the literature. The databases covered a wide range of concrete properties, thereby allowing detailed observation of the important factors influencing the compressive behavior of concrete. The analysis of the unconfined concrete database resulted in the development of expressions for the prediction of elastic modulus, compressive strength and corresponding axial strain of various types of concrete. In addition, through a comprehensive analysis of the combined test database a unified stress–strain model was developed to predict the peak and residual conditions and the complete stress–strain behavior of unconfined and actively confined concretes.

1. Introduction

It is well established that lateral confinement of concrete enhances its compressive strength and axial deformation capacity [1–6]. A comprehensive review of the literature that was undertaken as part of the current study and those previously reported in Refs. [6,7] revealed that over 500 experimental studies have been conducted on the axial compressive behavior of unconfined, actively confined, and fiber reinforced polymer (FRP)-confined concretes, resulting in the development of over 110 stress–strain models. However, due to the limitations in the parametric ranges of the experimental results considered in their development, the applicability of the existing models are often restricted to specific specimens subsets. The current availability of variety of concrete confinement techniques and reinforcing materials [4,8–21], and the abundance of concretes with different mechanical and material properties [9,22–26] poses a challenge for engineers in finding a suitable model given the possible composite combinations of these materials.

The work presented in this paper was motivated by the need to develop a unified model applicable to various types of concrete

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under unconfined and confined conditions. To this end, firstly two extensive databases of unconfined and actively confined concrete test results, which covered various concrete types, were assembled. The database results indicated significant differences in the stress–strain behavior of different types of concrete, ranging from light-weight (LWC) to normal-weight (NWC), and normal-strength (NSC) to high-strength (HSC). Based on these results, changes in the compressive behavior of concrete with various test parameters were then investigated, and the influential parameters were established. Finally, through a comprehensive examination of the results in the databases, a unified stress–strain model that it is applicable to: i) both LWC and NWC, ii) both NSC and HSC, and iii) both unconfined and actively confined concretes was developed.

2. Experimental test databases

2.1. Database of unconfined concrete

The database of unconfined concrete was assembled from 209 experimental studies and consisted of 4353 datasets. 1167 datasets from 161 studies that reported the specimen axial strain at peak compressive stress of concrete (ε_{co}) are presented in Tables A1–A3 in Appendix, whereas the remaining datasets are presented in Tables A4–A7. The results in Tables A1–A3 and A4–A7 were sorted into seven groups according to the type of concrete (NWC or LWC) and the cross-sectional shape of specimen (circular or square). Out of the 4353 datasets presented in Tables A1–A7, 2279 of the datasets were NWC cylinders, 1167 were LWC cylinders, 864 were NWC prisms, 43 were LWC prisms. In Tables A1–A7, the following information was available for each dataset in the database: the number of identical specimen; the geometric properties (cross-sectional dimension B and height H); the specimen age; the water-to-cementitious binder ratio (w/c); the density of concrete ($\rho_{c,f}$); the type and size of aggregates; the silica fume-to-cementitious binder percentage (sf/c); the mineral additive-to-cementitious binder percentage (ma/c); the elastic modulus of concrete (E_c); and the compressive strength of concrete (f'_{co}). In Tables A1–A3, the axial strain corresponding to the peak compressive stress (ε_{co}) and its measurement method is available in the last two columns. It should be noted that in some of the datasets, details of the aggregate type were not available from the source documents. Given the omission of such details, the aggregate types are noted as either normal-weight or light-weight aggregates in Tables A1–A7, according to the type of concrete (NWC or LWC). Regarding the percentages of mineral additives in concrete mixes of specimens presented in Tables A1–A7, except for silica fume that is presented in the 9th column, details of other mineral additives, such as fly-ash, slag, and hi-fi are presented in the same column in the 10th column. To distinguish their types in this column, these mineral additives are noted with superscripts '*f*', '*s*', '*h*', respectively.

In the database presented in Tables A1–A7 in Appendix, the specimen cross-sectional dimensions (B) varied from 50 to 406 mm, the specimen heights (H) varied from 25 to 1016 mm and the specimen aspect ratios (H/B) varied from 0.25 to 8, the water–cementitious binder ratios (w/c) varied from 0.16 to 1.27, the concrete densities ($\rho_{c,f}$) varied from 666 to 2584 kg/m^3, the concrete elastic moduli (E_c) varied from 9620 to 57,800 MPa, and the compressive strengths (f'_{co}) and the corresponding axial strains (ε_{co}) varied from 5.3 to 171.1 MPa and 0.07 to 0.53%, respectively.

2.2. Database of actively confined concrete

The database of actively confined concrete, presented in Ref. [7], was assembled from 25 experimental studies that consisted of 346 test datasets, and 31 additional datasets from tests recently undertaken at the University of Adelaide [27]. All of the specimens in the database had circular cross-sections, with cross-sectional dimensions (B) varying from 50 and 160 mm. The specimen heights (H) varied from 88 to 320 mm, the specimen aspect ratios (H/B) varied from 1 to 3, and the compressive strength (f'_{co}) and the corresponding axial strains (ε_{co}), obtained from unconfined concrete cylinder tests, varied from 7.2 to 132.0 MPa and 0.15% to 0.40%, respectively. Various instruments were used in existing studies to measure the axial strains (ε_{co}) of specimens, including in-built extensometers of compression machines, linear variable displacement transducers, and axial strain gauges. The unconfined concrete cylinders had the same geometric dimensions as the corresponding confined specimens. The active confinement ratio (f_l^*/f'_{co}), defined as the ratio of the hydrostatic confining pressure of the triaxial cell to the unconfined concrete strength, varied from 0.004 to 21.67.

It is worth noting that, given the limitation of the actively confined concrete database only to specimens with circular cross-sections, for a consistent treatment of the test results, only the specimens with circular cross-sections from both unconfined and actively confined concrete databases were included in the development of the models that are presented later in the paper. However, wherever possible, observations on the influences of the cross-sectional shape on the observed behavior are also supplied. Thereafter, the specimen cross-sectional dimension (B) is referred to as the specimen diameter (D).

3. Elastic modulus and peak condition of unconfined concrete

Based on the observed difference in their compressive behavior, concretes with a density (ρ_c) greater than 2250 kg/m^3 were categorized as NWC, whereas concretes with a density below the limit were categorized as LWC. A same transition boundary between NWC and LWC at concrete density of 2250 kg/m^3 were previously reported in Tasdemir et al. [23] based on the observed difference in concrete heterogeneity and material properties. In the database results, details of fresh concrete density ($\rho_{c,f}$) of specimens are commonly available from source documents, whereas the densities of air dried ($\rho_{c,a}$) and oven dried hardened concretes ($\rho_{c,o}$) are less commonly reported. Given the availability of information about the fresh densities of concrete ($\rho_{c,f}$), this parameter was therefore used in the analysis of the database results. Fig. 1 shows the comparisons of the densities of air dried ($\rho_{c,a}$) and oven dried concretes ($\rho_{c,o}$) to fresh concrete ($\rho_{c,f}$). The slight variations between the densities of fresh ($\rho_{c,f}$), air dried ($\rho_{c,a}$) and oven dried ($\rho_{c,o}$) concretes can be accounted using the expressions given by the trendlines of Fig. 1, of which $\rho_{c,f}$ is in unit kg/m^3.

3.1. Modelling of compressive strength of concrete

Several studies have been reported to date on the modelling of concrete compressive strength (Refs. [28–33]). However, a unified expression to estimate the compressive strength of different types

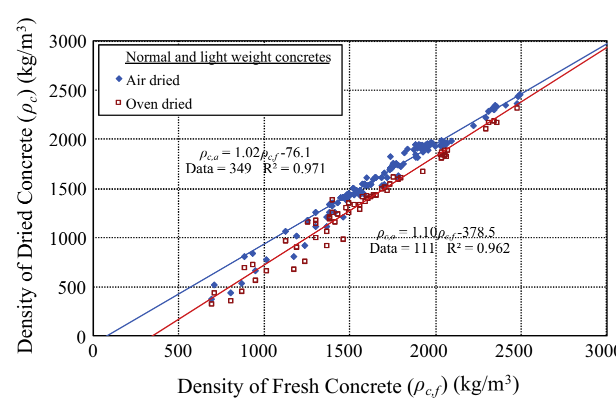

Fig. 1. Variation of densities of air dried ($\rho_{c,a}$) and oven dried concretes ($\rho_{c,o}$) with fresh concrete density ($\rho_{c,f}$).

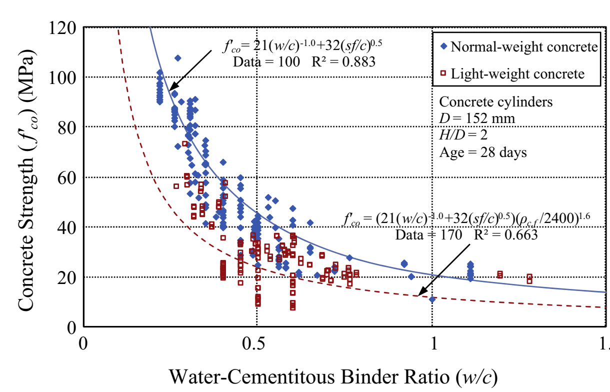

Fig. 2. Variation of concrete compressive strength (f'_{co}) with water-cementitious binder ratio (w/c).