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Understanding failure and stress-strain behavior of very-high strength concrete (>100 MPa) confined by lateral reinforcement

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HIGHLIGHTS

- The use of lateral reinforcement improves the ductility of very-high strength concrete (VHSC).
- The key failure mechanisms of confined VHSC are understood.
- The stress-strain behavior is governed by shear strength of concrete, confinement effect and dowelling action.
- A novel approach is presented to understand the stress-strain behaviour of confined VHSC.

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ABSTRACT

An experimental program is carried out to evaluate the stress-strain behaviour and investigate the failure mechanisms of confined very-high strength concrete (VHSC) with compressive strengths of up to 160 MPa and lower confinement pressures in the range of 0.6–2.7 MPa. Even though post-peak behaviour of concrete is explained and modelled using the confinement effects, the study proposes that it can be explained by superposition of the shear strength behaviour at the failure plane of concrete, confinement effect, and dowelling action of steel. The stress-strain behaviour is further explained through a theoretical approach and it has good agreement with the experimental results.

1. Introduction

High strength concrete (HSC) (50–100 MPa) and very-high strength concrete (VHSC) (>100 MPa) are specified more regularly due to their higher strength, stiffness, lower deformation and durability. Columns made with VHSC should have a ductility that meets seismic demands. Therefore, understanding brittle behaviour and improving ductility using transverse steel is vital for ductility design of VHSC columns because adequate ductility is provided by confining the core using lateral steel reinforcement. The analytical programs, which were developed to predict the flexural and ductile behaviours of HSC and VHSC columns, require a full range of stress-strain curves for confined and unconfined VHSC. Once this stress-strain behaviour is established, the analytical program can predict the flexural behaviour and ductility of the VHSC columns using the full-range moment-curvature relationship [1–7]. Subsequently, suitability and amount of lateral steel for a column can be determined considering the anticipated ductility levels specified in the standards and codes of practice. Therefore, the confined stress-strain behaviour can be considered as an important characteristic to evaluate the suitability of VHSC columns in seismic and non-seismic regions and this is the main focus of the study.

Experimental programs have been conducted by researchers [8–12] to understand the compressive behaviour of confined and unconfined HSC and VHSC columns. There are some experimental programs in the literature which cover strengths up to 125 MPa [8,12–16]. Shin et al. [17] studied the influence of headed crossties on the confinement of ultra-high strength-concrete columns with a compressive strength of 200 MPa. However, experiments from

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125 MPa or greater are scarce in the literature. Analytical models based on extensive experimental programs are well-established to predict the stress-strain behaviour of normal strength concrete (NSC) and HSC. Stress-strain models for unconfined and confined VHSC subjected to uniaxial compressive loads are specified by researchers [1,9,13,14,18]. However, those models are only applicable and experimentally tested for strengths less than or equal to 125 MPa. Thus, the stress-strain behaviour of confined and unconfined VHSC from 125 MPa or more cannot be predicted using state-of-the-art models and has not been captured thoroughly through any experimental program due to scarcity in the experimental results. Therefore, limited information is available to understand the mechanical behaviour and properties of confined VHSC up to 150 MPa, or greater, even though VHSC can be produced up to 150 MPa or more [20]. None of the codes around the world cover VHSC up to this range of compressive strengths [20]. Therefore, understanding the confined behaviour, failure and improvement of ductility due to the confinement of VHSC is vital to increase the strength range of concrete provided by codes and in practice up to 150 MPa or greater.

An experimental program consisting of 22 confined samples with compressive strengths ranging from 120 MPa to 160 MPa was carried out to understand the mechanical behaviour, properties and failure mechanisms of confined VHSC. This paper investigates the mechanical behaviour and presents the properties of confined VHSC, including the failure mechanisms, peak stress, elastic modulus, peak strain, residual stress and stress-strain behaviour. The failure mechanisms of confined VHSC (cover spalling, crushing of the core, buckling of reinforcement and hoop fracture) were investigated using suitable test set-ups and instruments. The samples were confined using lateral stirrups for lower confinements of up to 2.1 MPa, which is consistent with columns used in practice.

2. Experimental program

2.1. Mix design

Three different commercial concrete mixes consisting of two types of aggregates, namely basalt (BAS7) and granite (GRA7), silica fume (SF) and nano-silica fume (NSF) were used to achieve very high strengths. A water-to-binder ratio of 0.22 was used for the three mixes. Superplasticisers were used to obtain the required workability. Due to the higher binder content and lower water-to-binder ratio, VHSC mixes are generally stiff and dry, thereby resulting in a less workable concrete. Therefore, a high-range water reducing admixture, commercially known as Glenium Sky 8379, was used. Table 1 outlines the mix design materials.

2.2. Material properties

2.2.1. Coarse and fine aggregate

Two types of coarse aggregates, granite and basalt, were used to produce VHSC concrete. The size of the coarse aggregates was 7 mm. The apparent particle density and water absorption of granite were 2710 kg/m^3 and 0.6%, respectively. The apparent particle density and water absorption of basalt were 2940 kg/m^3 and 1.1%, respectively. A natural river sand with a fineness modulus of 2.6 and density of 2610 kg/m^3 was used as the fine aggregate.

2.2.2. Steel

Grade 500, deformed (D) and low ductile (L) cold-rolled ribbed 7.6 mm bars (D500L-8) were used as longitudinal reinforcement. Grade 250, round (R) and normal ductile (N) hot-rolled 6 mm bars (R250N-6) were used for the transverse steel. The steel bars comply with AS/NZS 4671 [21]. The steel samples were tested using a tensile testing machine according to ASTM A615/A615M-14 [22] to evaluate the tensile strength and stress-strain behaviour of the longitudinal and transverse reinforcements. Table 2 lists the mechanical properties and characteristics of the reinforcement employed in this study. Fig. 1 shows the stress-strain behaviour of the longitudinal and transverse steel reinforcement.

2.3. Specimen design

2.3.1. Preparation of reinforcement

Twenty-two laterally confined cylindrical samples with a diameter of 150 mm and height of 300 mm were prepared using mixes 1, 2 and 3 (see Table 1). The samples were confined using a reinforcement cage with different spacings (Fig. 2). Six D500L-8 bars were used as longitudinal reinforcement. A longitudinal reinforcement ratio of 0.026 (2.6% of the section area) was set, which is similar to the actual steel ratio of columns used in practice. In general, longitudinal reinforcement ratios varying from 1 to 4% are specified for columns.

Spiral hoops made with R250N-6, with centre-to-centre spacings of 35, 50, 60, 70 and 90 mm (as shown in Fig. 2) were used to confine the concrete core and provide effective confinement of 0.6, 0.9, 1.2, 1.6 and 2.7 MPa, respectively. Providing a volumetric lateral steel ratio of more than 5% is not practical for a VHSC column, considering the construction issues due to small ligature spacing [23]. Therefore, confinement values and volumetric lateral steel ratios were kept to practical and similar values for the VHSC columns. In order to simulate actual behaviour of confined VHSC columns (particularly the spalling), cover of 2.5 mm was maintained for all samples. A cover area equal to 6.5% of the gross section area was selected, which is similar to that of VHSC columns.

Table 1
Mix design.

Materials	Mix No Docket	Mix 1 BAS7 + SF	Mix 2 GRA7 + SF	Mix 3 BAS7 + SF + NSF
	Density (kg/m^3)	Quantity (kg)		
Cement	3110	500	500	500
Fly ash	2290	52	52	52
Slag	2860	187	187	187
Silica fume	2180	60	60	40
Nano-silica	1120	–	–	20
Total aggregate	2940 Bas: 2710 Gra: 2610 Sand	1580	1480	1563
Max water	1000	160	160	160
Design air	100	1.0	1.0	1.0