Mechanical Properties of High-Strength Concrete

Manish Kumar[1], A.M. ASCE; Zhaoyu Ma[2]; Moses Matovu[2]

1.1 Introduction

Mechanical properties of High-Strength Concrete (HSC) can be divided in two groups as short-term mechanical properties and long-term mechanical properties. A discussion on short-term mechanical properties of concrete which includes, compressive strength, stress-strain behavior, elastic modulus, Poisson's ratio, tensile strength and modulus of rupture, is presented here. The equations and formulations that are used for normal strength concrete (NSC) cannot always be extended to include HSC, and need to be revisited. Important parameters that affect these properties and mathematical formulations that represent the behavior of HSC more appropriately are summarized here from previous research work.

1.2 Stress-strain Behavior in Compression

Stress-strain behavior of concrete for different range of compressive strength is shown in Figure 1. The ascending branch of stress-strain is more linear and steeper for HSC. Strain at maximum strength is greater and descending part becomes steeper compared to NSC.

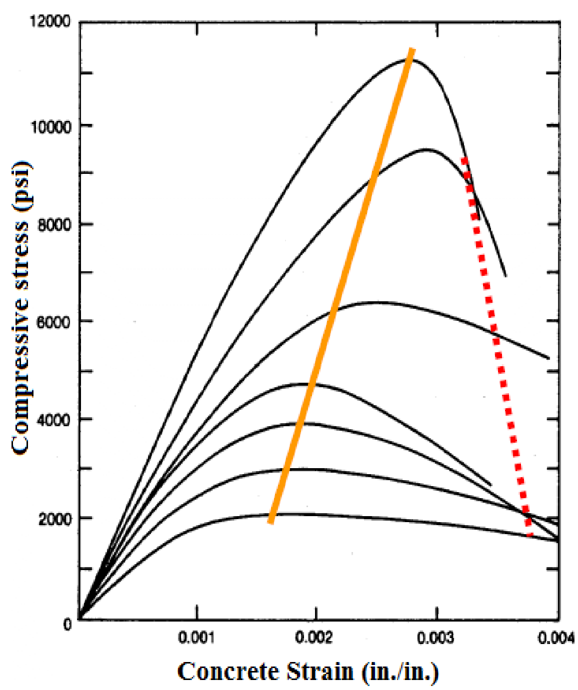

Figure 1: Typical concrete stress-strain curves in concrete (Wight and MacGregor (2009), reproduced from Whittaker (2012))

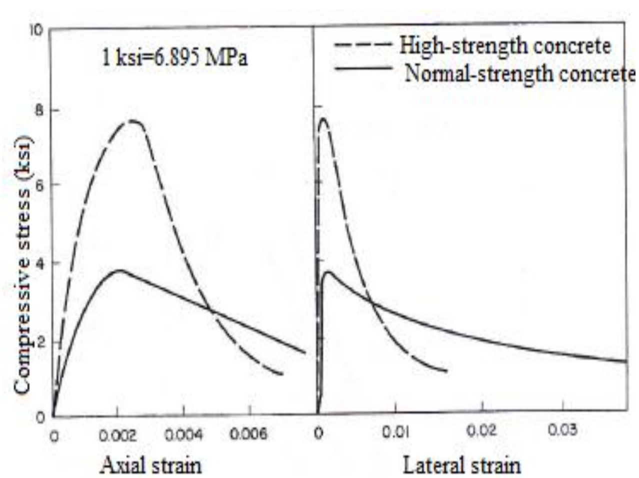

Figure 2: Axial stress vs. axial strain and lateral strain for concrete (from Ahmad and Shah (1982), reproduced from ACI (2010))

[1] PhD Candidate, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York

[2] Graduate Student, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York

Stress-strain behavior of HSC depends on material parameters such as aggregate type and experimental parameters that include age at testing, strain rate and interaction between specimen and testing machine. The stress-strain model used for NSC cannot be extended for use in HSC as the nature of loading curve changes significantly. Steeper rise and sudden drop in strength after maximum value presents difficulty in numerical modeling of stress-strain behavior of HSC. Aītcin (1998) suggests that HSC behaves like a real composite material and parallels can be drawn to the stress-strain behavior used in rock mechanics.

Carrasquillo *et al.* (1981) reported that there is less internal microcracking in HSC than NSC for the same axial strain imposed, as shown in Figure 2. This also implies that HSC experience less lateral strain, and consequently effectiveness of confinement on compressive strength of HSC is often limited compared to NSC.

1.3 Compressive Strength

Decreasing w/c ratio increases the strength of concrete. However, this trend follows only where strength of hydrated cement is low compared to the strength of coarse aggregates. When these two strengths become comparable, decreasing w/c ratio doesn't increase the strength significantly, and to further increase the strength of HSC, strength and quality of coarse aggregates need to be increased, in addition to other factors. Typically, w/c ratios between 0.2-0.4 are used for HSC. Low w/c ratio decreases the workability. Super plasticizers are added to increase the workability in HSC. Shape, texture and maximum size of coarse aggregate affect the compressive strength of HSC. Smooth river gravel produces weaker concrete. Smallest size of coarse aggregate produces highest strength concrete owing to its high specific surface area. Addition of silica fume decreases the requirement of low w/c to achieve high compressive strength. Iravani (1996) noted that effect of silica fume on strength development of HSC is most prominent during 7 to 28 days after mixing.

Measured compressive strength of HSC depends on testing variables, namely, mold type, specimen size, end conditions and strain rate. 4×8 in. (102×204 mm) cylinder specimen have been shown to produce higher compressive than 6×12 in. (152×305 mm) cylinders, and is recommended for specimens in the testing of HSC (ACI, 2010).

When compared to NSC, there is higher rate of strength gain in HSC at earlier stages, as shown in Figure 4 (Carrasquillo *et al.*, 1981). There is notable gain in compressive strength of HSC after 28 days strength. 10-15% increase in strength is obtained at 56 days and 95 days compared to 28 days strength. Curing of HSC has a strong influence on the strength development because of its low w/c ratio. Iravani (1996) investigated the effect of curing conditions on strength gain of HSC at later stages and concluded that drying followed by moist-curing increased the 147-day compressive strength of HSC relative to continuously moist-cured concrete tested under moist conditions. Based on his test results, he also claimed that 3 weeks is a sufficient most-curing period for HSC. Testing age of HSC specimens depend on construction requirements; however, considering notable strength gain at later stages, testing age of 56 days or 90 days is often recommended (ACI, 2010).

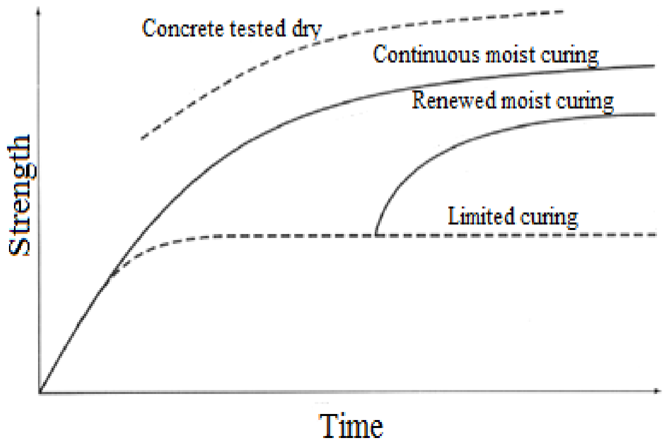

Figure 3: Effect of curing on the strength of concrete (Beushausen and Alexander, 2010)

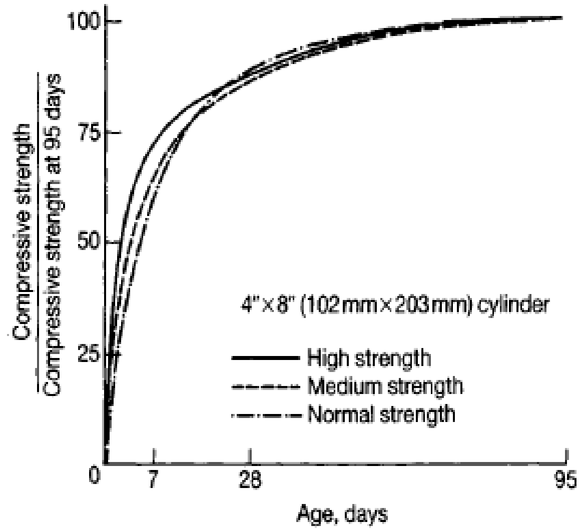

Figure 4: Normalized strength gain with age for limestone concretes moist-cured until testing (from Carrasquillo *et al.* (1981) as reported in Shah and Ahmad (1994))

1.4 Elastic Modulus

ACI-318 (ACI, 2011) defines the secant modulus of elasticity as the ratio of stress and strain at 40% of the compressive strength. As strength of concrete increases, its modulus of elasticity increases as well. The same parameters that influence the compressive strength of concrete are responsible for elastic modulus as well. Hence, most of the empirical formulations express modulus of elasticity as a function of compressive strength. The equation suggested in ACI-318 overestimates elastic modulus of HSC and ACI 363 (ACI, 2010) suggest a different equation for HSC based on studies done by Carrasquillo *et al.* (1981) that have been shown to produce conservative values for normal-density concrete (Shah and Ahmad, 1994):

$$E_c = 3.32\sqrt{f_c^{'}} + 6.9 \ \ (in\, GPa) \tag{1}$$

Numerous equations have been proposed for estimating the modulus of elasticity of HSC; however, due to large variations, most of the equations are representative of only the selected data for that particular expression. Moreover, ACI-363 (ACI, 2010) recommends that a design engineer should verify the elastic modulus through a trial field batching or by documented performance.

Analytical expressions are also available for calculation of elastic modulus that make use of two-phase models involving aggregates and cement paste. Simplest of these models assume either constant stress or strain in both phase. In order to use these expressions, elastic modulus of aggregates and hydrated cement paste are required, making it an unpopular choice.

1.5 Poisson’s Ratio

Data on Poisson’s ratio of concrete is very limited, especially for HSC. Poisson’s ratio of HSC is constant in the linear zone but increases in the non-linear zone as a function of axial strain. In the linear range, Poisson’s ratio is not affected by compressive strength, curing method and age of concrete (Logan *et al.*, 2009). Poisson’s ratios of HSC reported by different studies in the linear range at 40% of ultimate stress are summarized in Table 1.

Table 1: Poisson's ratio of HSC reported by different studies

Study	Strength range (MPa)	Poisson’s ratio	Standard deviation
Perenchio and Klieger (1978), as reported in Iravani (1996)	Not available	0.22	Not available
Carrasquillo *et al.* (1981)	34-73	0.210	0.016
Ibrahim and MacGregor (1994)	73-99	0.18	Not available
Iravani (1996)	64-125	0.17	0.023
Logan *et al.* (2009)	34-120	0.17	0.07

Poisson’s ratio of HSC in its linear range varies around 0.2, which is comparable to the range of values obtained for NSC (0.15-0.25). As presented in Figure 2, HSC experience less lateral strain in non-linear zone due to less microcracking, and is expected to have lower Poisson’s ratio than NSC.

1.6 Tensile Strength

Tensile strength of concrete is measured by direct and indirect tensile tests. Direct tensile tests, which include testing HSC specimen under pure tension, are difficult to perform due to testing limitations. Indirect tests include flexure and split-cylinder tests, and are used popularly to measure tensile strength of concrete.

1.6.1 Modulus of Rupture

Modulus of rupture is evaluated in flexure test as a function of compressive strength. General expression for modulus of rupture is given as:

$$f_r = c\sqrt{f_c^{'}} \quad (2)$$

where c is a constant that takes a value between 7.5 and 12 if f_r is expressed in psi, and between 0.62 to 0.99 if f_r is expressed in MPa, respectively (ACI, 2010). These expressions provide good agreement with experimental data upto strength of 100 MPa, but often underestimate the values for higher strength.

1.6.2 Splitting Tensile Strength

ACI 363R-10 (ACI, 2010) reports a study by Dewar (1964) that claims that for lower strength concrete, tensile strength may go upto 10% of compressive strength; however, for higher strength it reduces to 5%. Expressions used for calculation of splitting tensile strength are:

ACI 318-11: $$f_{ct} = 0.56\sqrt{f_c^{'}} \ \ (MPa) \quad (3)$$

Carrasquillo *et al.* (1981): $$f_{sp} = 0.59\sqrt{f_c^{'}} \ \ (MPa) \quad (4)$$

Iravani (1996) obtained the modulus of rupture and splitting tensile strength of HSC cylinders upto a strength of 125 MPa, and found that equations suggested by Carrasquillo *et al.* (1981) shows good agreement with experimental results within $\pm 10\%$.

1.7 Conclusions

Behavior of HSC in compression differs from NSC significantly, and new equations for compressive strength, elastic modulus, and stress-strain behavior have been suggested by researchers. Mechanical properties of HSC are sensitive to the type of coarse aggregates and curing techniques. Poisson's ratio and mechanical properties in tension, including modulus of rupture and splitting tensile strength do not vary too much from NSC, and equations used for NSC provide a conservative estimate of properties of HSC.

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