Chapter 9
Mechanical Response and Damage Evolution of High-Strength Concrete Under Triaxial Loading

Brett Williams, William Heard, Steven Graham, Bradley Martin, Colin Loeffler, and Xu Nie

Abstract Current weapons effects modeling efforts rely heavily on quasi-static triaxial data sets. However, there are fundamental knowledge gaps in the current continuum modeling approach due to limited experimental data in the areas of dynamic effects and damage evolution. Arbitrary scalar values used for damage parameters have experimentally unverified mathematical forms that often do not scale to different geometries, stress states, or strain rates. Although some preliminary tests have been performed through dynamic triaxial compression experiments, the results are difficult to interpret due to changes in specimen diameter and length-to-diameter ratio. In this study, a high-strength concrete (f'_c ~130 MPa) was investigated under triaxial loading conditions at confining pressures up to 300 MPa. Three cylindrical specimen sizes were used to determine size effects, including 50 × 114 mm, 25 × 50 mm, and 25 × 13 mm. For a limited number of specimens, X-Ray Computed Microtomography (XCMT) scans were conducted. It was noted that size and length-to-diameter ratio have substantial effects on the experimental results that must be understood to determine dynamic effects based on specimen geometries used in dynamic triaxial compression experiments. Additionally, by quantifying pore crushing and crack development under a variety of triaxial loading conditions, future multi-scale modeling efforts will be able to incorporate systematically defined damage parameters that are founded on experimental results.

Keywords Triaxial loading · High-strength concrete · Damage · Aspect ratio · Micro-CT

9.1 Introduction

When developing continuum models, material properties need to be understood for a wide range of stress states. Many concrete modeling efforts rely heavily on a suite of quasi-static confined experiments on 50 × 114 mm cylindrical specimens as detailed by Williams et al. [1]. However, specimen geometries must be substantially different to satisfy diameter restrictions and stress equilibrium requirements for Kolsky bar experiments. For example, prior work has been published with cylindrical specimen sizes of 19 × 13 mm [2]. In future work, 25 × 13 mm specimens will be used to maintain a length-to-diameter ratio of 1:2. Before these data can be used in modeling efforts, additional quasi-static experiments are required to develop a baseline dataset to account for modified specimen geometries. Although the effects of scaling and length-to-diameter ratios have been thoroughly characterized for unconfined compression tests [3], these parameters have not been investigated for confined testing conditions.

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9.2 Experiments

For this study, a high-strength self-consolidating concrete, BBR9, was selected as the material of interest. This concrete was developed by the US Army Engineer Research and Development Center using the following constituent materials: crushed limestone sand, type I/II cement, grade 100 slag, microsilica, and high-range water-reducing admixture. Traditional unconfined compression tests were performed on 75 × 150 mm cylindrical specimens yielding a compressive strength of 130 MPa. The traditional suite of quasi-static confined experiments was conducted using 50 × 114 mm cylindrical specimens to form a baseline for scaled datasets. To investigate the effects of scaling, one triaxial experiment was conducted at 200 MPa confining pressure using reduced specimen dimensions (25 × 50 mm) while maintaining a length-to-diameter ratio of 2:1. Furthermore, effects of changes in length-to-diameter ratios were investigated by performing one triaxial experiment on a scaled specimen (25 × 13 mm) with a length-to-diameter ratio of 1:2. For observation of damage evolution, X-Ray Computed Microtomography (XCMT) was conducted on specimens before and after loading as shown in Fig. 9.1.

9.3 Results

Triaxial experiments were performed on BBR9 using the conventional specimen geometry (50 x 114 mm) as shown in Fig. 9.2a. In these experiments, specimens are first loaded hydrostatically until the desired confining pressure is reached (maintaining a principal stress difference of zero). These experiments are axis-symmetric ($\sigma_2 = \sigma_3$) due to radial confining

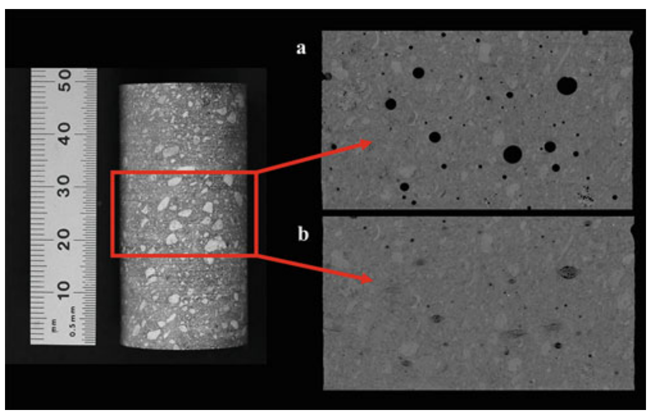

Fig. 9.1 Micro-CT results comparing concrete porosity (**a**) before and (**b**) after triaxial loading (200 MPa confining pressure, 10% axial strain)

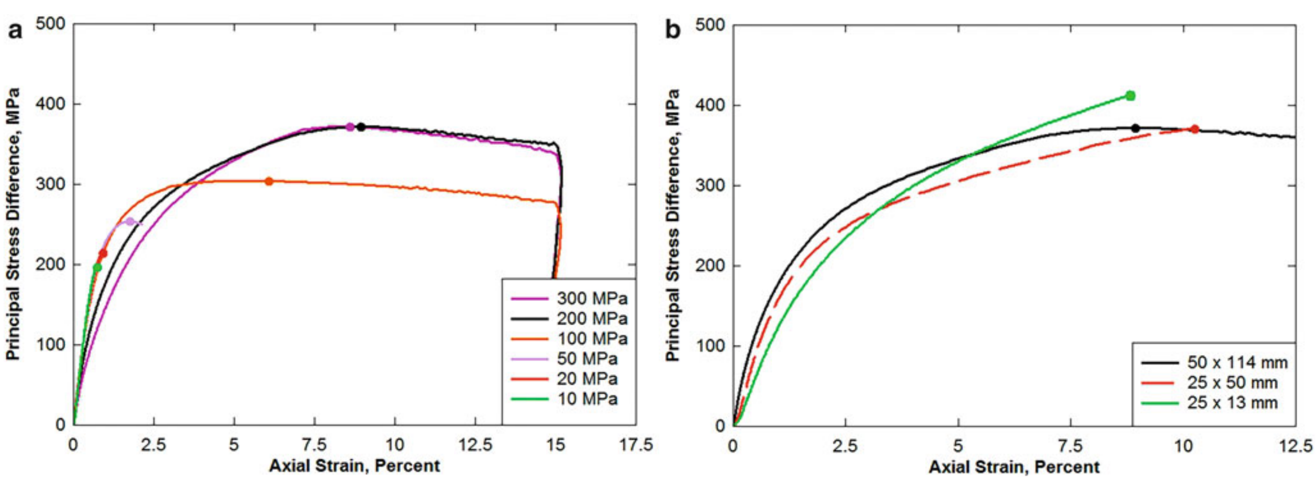

Fig. 9.2 BBR9 triaxial compression results for (**a**) 50 × 114 mm specimens with confining pressures ranging from 10–300 MPa and (**b**) three different specimen geometries with fixed confining pressure of 200 MPa

pressure applied on the outer circumference of the cylindrical specimens. Subsequently, the axial load is increased while radial confining pressure is maintained at a constant value. Axial strain is measured using LVDTs and radial strain is measured using a spring-arm radial deformeter. These tests verify that concrete becomes more ductile as confining pressure increases. After conducting baseline experiments, the results from three different specimen geometries were compared as illustrated in Fig. 9.2b. Examining triaxial data for specimen geometries of 50 × 114 mm and 25 × 50 mm under 200 MPa confining pressure reveals that size effects may be present, even when length-to-diameter ratios are approximately the same (2:1). Testing of the 25 × 50 mm specimen was stopped at the same principal stress difference (deviatoric stress), 370 MPa, to observe damage evolution as previously shown in Fig. 9.1. After going through the specified loading cycle in the ductile failure region, it is noted that pore collapse is prevalent. These damage mechanisms are substantially different from macrocracking observed in a similar material under unconfined loading conditions [4]. An additional triaxial experiment was conducted under 200 MPa confining pressure using a 25 × 13 mm specimen. In addition to size effects noted earlier, this final test indicates that length-to-diameter ratio also has an effect on material behavior under triaxial compression.

9.4 Conclusion

Preliminary studies have revealed that size effects must be considered when interpreting quasi-static triaxial experimental results. Furthermore, effects from length-to-diameter ratios must also be understood when using specimens with non-standard aspect ratios. In order to isolate rate effects in triaxial compression experiments, a series of tests must be conducted both under quasi-static and dynamic (Kolsky bar) testing conditions using the same specimen geometry. Additionally, scaled experiments using 2:1 length-to-diameter ratio are needed to correlate the data to historical datasets that have been used for model calibration. Future work will be focused on conducting additional experiments on 25 × 50 mm and 25 × 13 mm specimens under various confining pressures yielding brittle, quasi-brittle, and ductile failures. Additional XCMT scans will be performed in conjunction with all triaxial experiments so that damage evolution can be quantified for the purpose of informing damage parameters within continuum-based models.

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