A MATERIAL TESTING PROGRAM TO CHARACTERIZE THE CONCRETE BEHAVIOR UNDER STATIC AND DYNAMIC LOADS

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ABSTRACT

In this paper a comprehensive material testing program is described to characterize a German final repository concrete material (BERB1) subjected to static and dynamic loads. The BERB1 material was developed und specified by the German Bundesanstalt für Materialforschung und -prüfung (BAM) for targets used for drop tests according to the KONRAD requirements.

The testing consists of three concurrent laboratory experimental programs performed in the USA. An extensive preliminary testing program in Germany was performed to assure the required concrete specifications during fabrication and curing.

The first set of data is the static basic material test program consisting of structural tests to quantify macroscopic concrete properties under quasi-static loads. Cubic and cylindrical specimens are investigated under this effort. The second set of test data is from the static complete material test program, where cylindrical concrete specimens are subjected to a variety of quasi-static axial and radial stress and strain paths using a high-pressure hydraulic tri-axial chamber. The material is characterized for confining pressures up to 400 MPa. The third set of data is from the dynamic complete material test program, which uses a modified Split-Hopkinson Pressure Bar to induce dynamic compression and tension waves into cylindrical concrete specimens that generate strain-rates up to 400 s^{-1}.

The ensemble of data generated in these experiments provides a complete set of data that effectively describes the behavior of this concrete and can be used to develop a constitutive calculation model. In addition, the results of the tests show a significant effect of moisture on the strength and rheology of this concrete for quasi-static pressures greater than 50 MPa. Numerical drop test simulations with the developed constitutive model in the Lagrangian finite element code, LS-DYNA, show good agreement with the experimental results from a BAM research project.

INTRODUCTION

The use of a properly verified and validated material model is important to produce reliable physics-based computations. The model should be capable of capturing the materials response for a wide range of behaviors, especially when subject to dynamic loading conditions. The used models are often calibrated on measurements obtained from laboratory experiments designed to mimic the materials response under controlled loading conditions. Concrete is a material used in a wide range of structures that exhibits relatively complex behaviors depending on the loading condition. Laboratory test data for concrete is often generated only on a small subset of the range of behaviors needed to properly characterize concrete response under static and dynamic loads. Other relevant material properties are extracted from separate testing efforts that often use only a notionally similar concrete mix, and then assembled piecewise to fashion a complete material model.

This paper describes a comprehensive material testing and validation program to fully characterize a specific concrete material, designated BERB1 (BAM-Endlager-Referenz-Beton 1), for its behaviors under static and dynamic loads. The concrete constituents, mix proportioning, and fabrication procedures were designed to meet specific strength and hydration requirements. The data generated in these experiments provide a complete set of parameter that effectively describe the behaviors of this concrete under both static and dynamic loads that can be used to derive a constitutive model.

RESEARCH SIGNIFICANCE

Although a majority of basic material property test protocols related to concrete strength and deformability are detailed in national standards (e.g., ASTM and DIN), there is little standardization for the highly specialized laboratory experiments needed to fully characterize concrete for the full spectrum of loading regimes needed for constitutive models. Testing concrete under these conditions is not commonplace because of the specialized laboratory equipment needed to execute these tests.

The dynamic testing of concrete is an active area of research. Using data generated with the Split-Hopkinson Pressure Bar (SHPB) [1], [2] showed that concrete gains strength when subjected to increasing levels of strain-rate. Additional work demonstrates that saturated concrete samples exhibit larger strain-rate sensitivities than identical dry samples. Although the mechanics of this effect is still debated, recent advances in the SHPB provide capabilities to test concrete dynamically while subjected to dynamic confining pressures.

CONCRETE MATERIAL

The German Bundesanstalt für Materialforschung und -prüfung (BAM) is commissioned to assess the mechanical safety of storage containers for final disposal of radioactive waste in the German KONRAD repository. Mechanical tests according to the KONRAD requirements include several cask drops onto a target representative of the ground of the repository. BAM has developed a reference target which meets the repository acceptance criteria and guarantees reproducible test results of high accuracy [3]. The main part of the target is a reinforced concrete slab with exactly defined properties and lying on the IAEA target.

Figure 1. Storage cask at the BAM drop test facilities

Figure 1 shows a 5.55 m drop test of a 16.1 Mg cubic container on the reference target at the BAM drop test facility.

The slab is designed to resist the impact load with only superficial surface damaged allowed. The BERB1 concrete is designed to have a compressive strength as specified in the regulations and satisfy specific concrete strength gain requirements.

TEST PROGRAM DEVELOPMENT

Full characterization of the BERB1 material required three concurrent testing efforts. One of these, the static basic (SB) material test program, consists of structural tests to quantify macroscopic concrete properties. Cubic and cylindrical specimens were investigated under this effort. The second set of test data, from the static complete (SC) material test program, are from cylindrical concrete specimens that were subjected to a variety of controlled axial and radial stress and strain paths using a high-pressure hydraulic tri-axial chamber. The third set of data, from the dynamic complete (DC) material test program, were obtained using a modified SHPB to induce dynamic compression and tension waves into cylindrical concrete specimens.

Testing Laboratories

The University of New Mexico-Department of Civil Engineering (UNM-DCE) executed the SB program, Sandia National Laboratories-Geomechanics Laboratory (SNL-GL) executed the SC program, and the University of California at San Diego-Center of Excellence for Advanced Materials (UCSD-CEAM) designed and executed the experiments needed in the DC program.

Concrete Fabrication and Curing

The cement and dried aggregates were shipped from Germany to the U.S. in special weather independent boxes and held in storage. The concrete was manufactured according to a defined concrete mix and fabrication procedure. All specimens were placed in a curing room under specified temperature and humidity conditions. After 24 hours, the specimens were removed from the molds, and then placed inside curing baths maintained at 20 ºC. Most specimens were tested in the moist-cured surface dry (MCSD) condition.

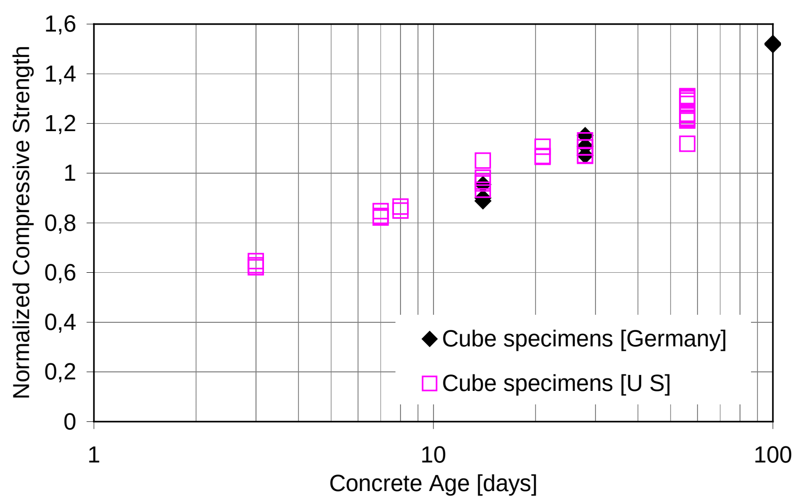


Figure 2: Compressive strength gain of the concrete

A small set of specimens were moist-cured oven-dried (MCOD). Cubic specimens according to DIN were cast in permanent molds for comparison with concrete fabricated in Germany. The compression test results shown in Figure 2 indicate that the concrete fabricated in the U.S. is similar in concrete strength and strength gain as the concrete fabricated in Germany.

STATIC BASIC TESTS

These tests include the unconfined compressive strength test (SB-UC), the modulus of elasticity test (SB-MEL), the flexural strength tests (SB-FLX), the splitting tension strength test (SB-STN), the direction tension strength test (SB-DTN) and the stiff tension test (STT). With the exception of the SB-DTN test, each of the SB tests was performed under DIN standards to remain consistent with tests executed in Germany. The stiff tension test (STT) was run under a draft ASTM specification developed by UNM-DCE, since currently there is no widely accepted test for determining the fracture energy capacity of concrete.

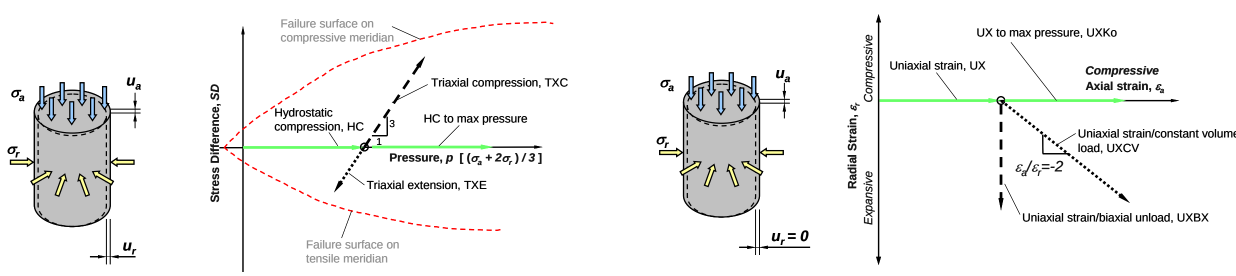
STATIC COMPLETE TESTS

Photographs of the triaxial tests are shown in Figure 3. Axial strain and axial stress are applied to the specimen using a hydraulic actuator placed at the top of the specimen. Radial stresses are applied to the specimen using a hydraulic fluid in the pressure chamber, which applies a uniform confining stress around the surface of the specimen. A variety of stress and strain paths can be induced in the specimen by controlling the loading using an active-feedback control.

(a) Instrumented sample (b) Assembly of pressure chamber (c) Hydraulic actuator

Figure 3. Quasi-static triaxial testing of concrete at the SNL-GL

Of these tests, the hydrostatic compression test (SC-HC), triaxial compression test (SC-TXC), triaxial extension test (SC-TXE) are all load-controlled stress path tests. The uniaxial strain path test (SC-UXKo), the uniaxial strain path followed by biaxial unload test (SC-UXBX), and the uniaxial strain path followed by constant volume strain loading test (SC-UXCV) are all displacement-controlled strain path tests, which are made possible by the active-feedback controls. Each of the stress path tests is illustrated in Figure 4a, which shows the stress path trajectories for each test in terms of pressure versus stress difference. The strain path tests are illustrated on the radial strain versus axial strain plane, which is depicted in Figure 4b.

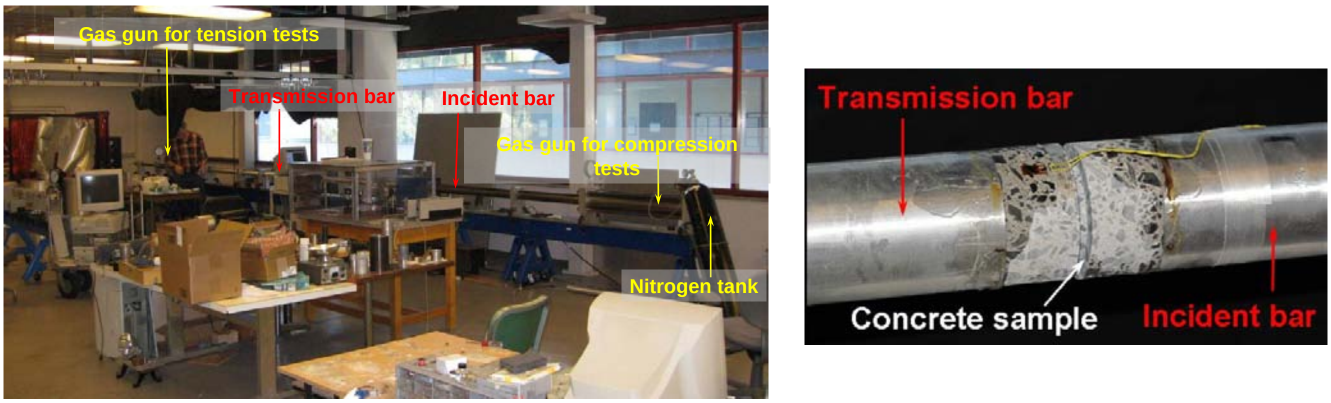


(a) Stress paths (b) Strain paths

Figure 4. Illustration of the SC stress and strain path tests

DYNAMIC COMPLETE TESTS

These material characterization tests provide data needed to quantify the strength and ductility enhancements observed in concrete subjected to rapid rates of deformation. Recent advances in dynamic materials testing have provided a robust capability to perform dynamic TXC tests, but dynamic TXE testing is still in its infancy. Unconfined sets of TXC and TXE tests were performed. The 7.62 cm-diameter SHPB (see Figure 5) at the UCSD-CEAM laboratories was used to perform these tests. The stress pulse and effective strain in the sample is deduced from the incident and transmitter bar strain gages using the known elastic properties of the bars and equations for conserving momentum.

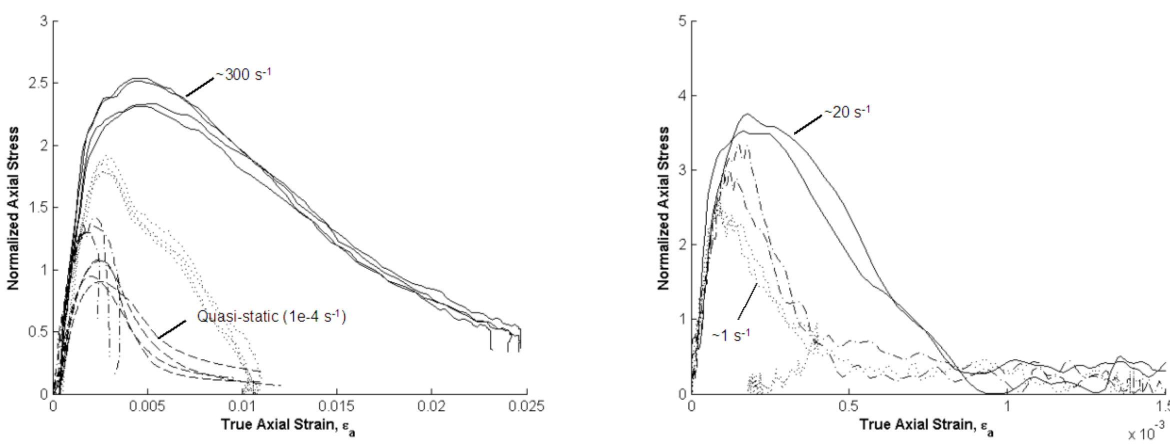


Large diameter SHPB for compression and tension. Tension sample.

Figure 5. Dynamic testing of concrete at the UCSD-CEAM laboratory

TEST RESULTS

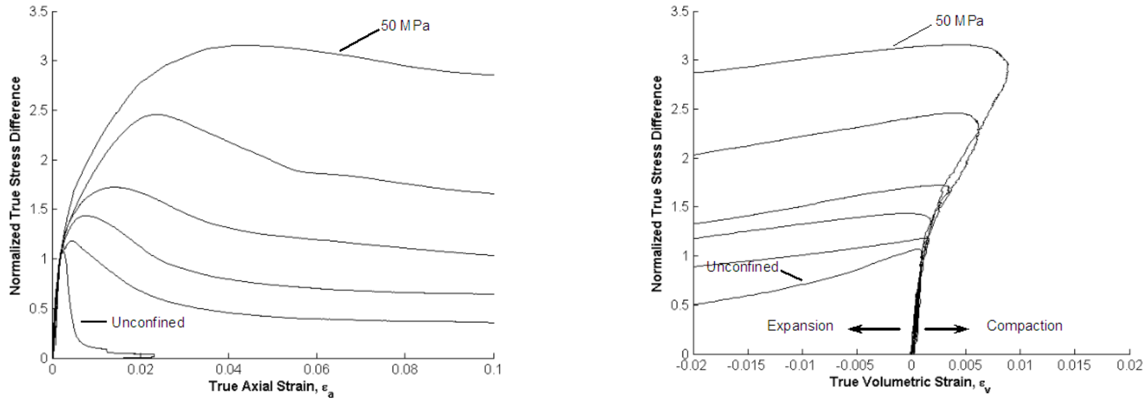
The effect of strain-rate on the unconfined strength of BERB1 is shown in Figure 6. Both the peak strength and the failure strain at the peak strength increase as a function of strain-rate. The tension tests show much more variability than the compression tests, but nevertheless demonstrate the larger sensitivity to strain-rate.



(a) Compression (b) Tension

Figure 6. Normalized strength of unconfined concrete at various strain-rates

As confinement is increased, the material strength and ductility increases. Figure 7 shows this trend with a plot of normalized stress difference versus the axial strain. The material also displays volumetric expansion after reaching its peak compressive strength. This demonstrates another common concrete behavior, where concrete initially compacts in its elastic region, and as it nears its peak shear strength, it transitions to a dilatative material.

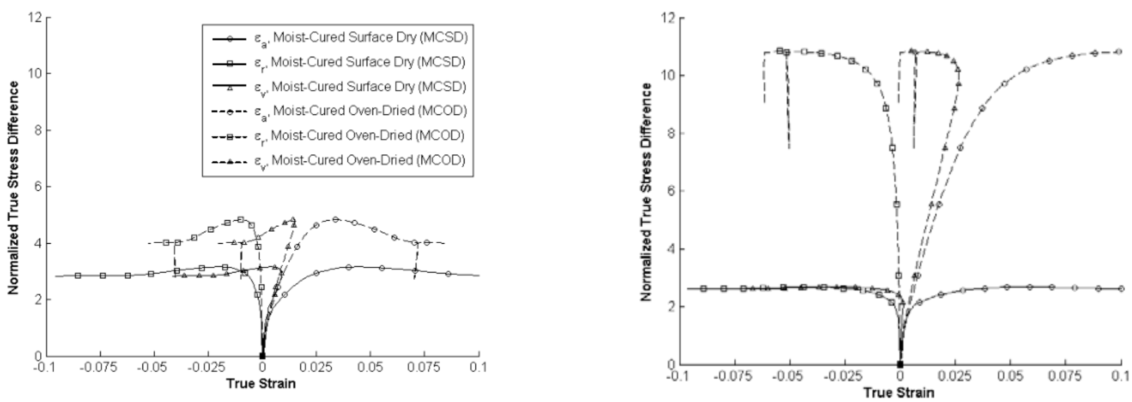


(a) SD versus axial strain

(b) SD versus volumetric strain

Figure 7. Normalized results of triaxial compression tests

The specimen show little increase in strength over a range of confining pressures from 50 MPa to the maximum confining pressure used. The material does retain its ductility throughout this range of pressures, although much less compaction occurs during shearing than is evident at pressures less than 50 MPa.



(a) 50 MPa confining pressure

(b) 200 MPa confining pressure

Figure 8. Comparison of shear strength of MCOD (dashed line) and MCSD (solid line) specimens

Identical curves from the oven-dried MCOD specimens having a negligible degree of saturation are also shown in Figure 8 and indicate a pronounced enhancement in shear strength. The dried BERB1 concrete exhibits a 66% increase in shear strength at 50 MPa and over a 300% increase in shear strength at 200 MPa, when compared with the MCSD samples.

These results indicate that moisture effects play a dominant role on the strength and rheology of BERB1 at quasi-static pressures above 50 MPa.

DERIVATION OF MODEL PARAMETER AND VALIDATION METHODS

The ensemble of data generated in these experiments provides a complete set of data that effectively describes the behaviors of the BERB1 concrete. They were used to develop a constitutive model in LS-DYNA to fully characterize the material response of the BERB1 concrete subjected to static and dynamic loads. The third release of the K&C concrete material model available in LS-DYNA as *MAT_CONCRETE_DAMAGE_REL3 was used to perform the numerical simulations. This material model is a three-invariant plasticity and damage-based constitutive model, uses three failure surfaces, include damage and strain-rate effects and use a method to reduce mesh-dependencies due to strain-softening.

Calibration was performed using combinations of nonlinear least squares regression and the response surface methodology to identify a set of nominal parameters of the K&C concrete model specific to the BERB1 concrete. Two sets of model parameters were derived using this procedure: one for BERB1 under moist-cured surface dry conditions and one for BERB1 under moist-cured oven-dried conditions. The models parameters were then deployed in several validation studies using LS-DYNA models of validation experiments developed to mimic actual test conditions. The validation tests include several experiments conducted in the quasi-static test program and several cask drop tests conducted by BAM onto the BERB1 concrete slabs.

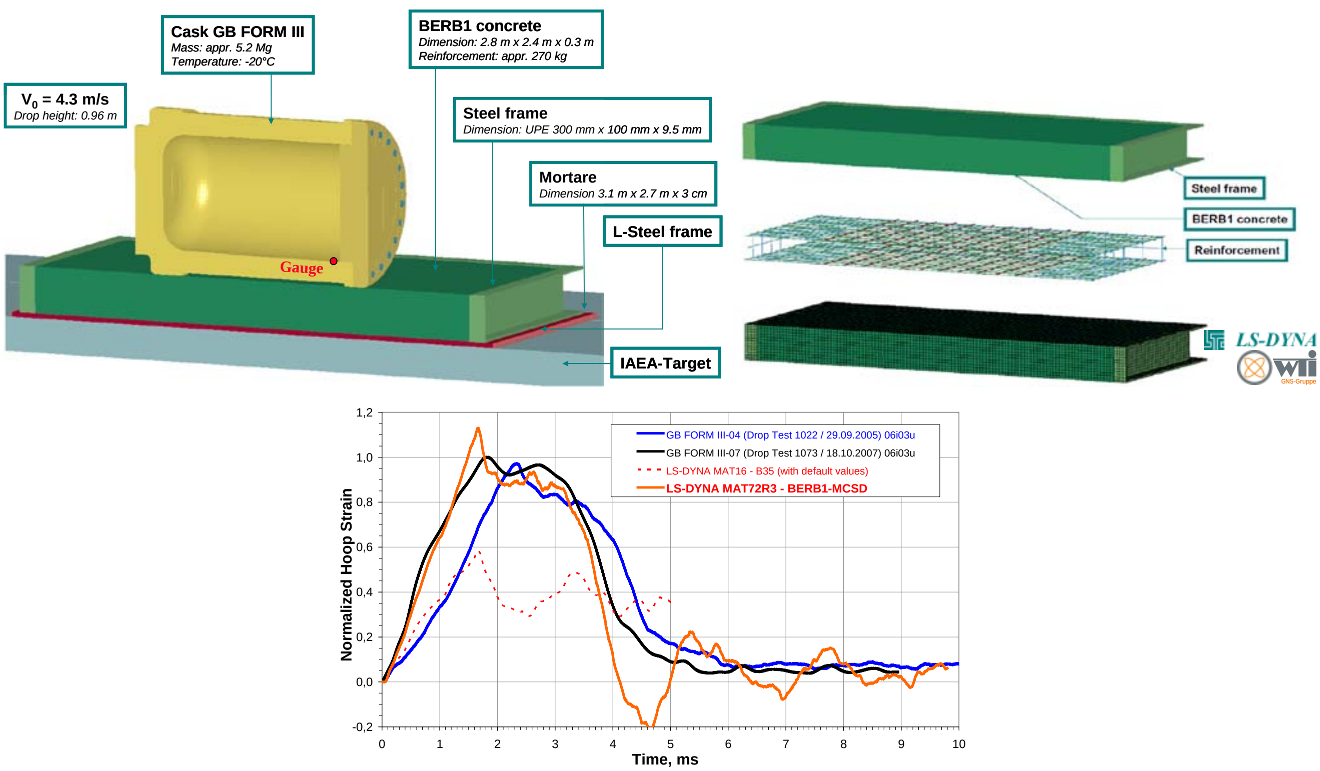


Figure 9. GB-FORM III drop test and measured/calculated hoop strain

The quasi-static simulations include the unconfined compression strength test, the direct tension strength test, the split tension strength test, and the beam flexure test. The model parameters were verified against the complete suite of calibration data by exercising the K&C concrete model in LS-DYNA simulations using single and multi-element models. Each of the key load path tests conducted in the experimental program were performed and obtained very good results. The two dynamic simulations included drop tests performed by BAM regarding the EBER III and GB-FORM III cask drops. Numerical results are shown in Fig. 9 for drop tests with the GB-FORM III cask. The strain-histories and the peak strains obtained with the BERB1-MCSD model compared the most favourably with the experiments, both quantitatively and qualitatively.

SUMMARY AND CONCLUSIONS

This paper describes a comprehensive material testing program to fully characterize a concrete material subjected to static and dynamic loads. The data generated under these efforts provides sufficient data from which to develop a constitutive model.

The results demonstrate that BERB1 exhibits common concrete-like behaviors including confinement effects, strain-rate enhancements in compression and tension, shear-dilation, and fracture energy absorption in tension. In addition, comparison of data obtained with oven-dried concrete samples with saturated surface dry samples shows the significant effect that moisture has on the quasi-static strength and rheology of the concrete for confining pressures greater than 50 MPa. The K&C material concrete model in LS-DYNA with the derived parameter sets can thus be used for the numerical simulation of drop tests on the BERB1 concrete target.

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