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MODEL-SIZED AND FULL-SCALE DYNAMIC PENETRATION TESTS ON DAMPING CONCRETE

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ABSTRACT

Mechanical loading conditions of transport and storage casks for radioactive materials in accidental scenarios are highly affected by the behavior of both: the impact limiters and the footing materials. To minimize potential damages during the handling of casks, a so called damping concrete is frequently used for the footings in interim nuclear facilities. It obtains its shock absorbing properties through admixing of polymer cells.

For a comprehensive mechanical evaluation of casks, advanced material models are also needed for damping concrete. In order to characterize the mechanical properties and to develop numerical material models, penetration tests were carried out at different test facilities of BAM. The tests contain static and dynamic penetration tests on cubic specimen with an edge length of 100 mm as well as mortared specimen with a size of 240 x 240 x 50 cm³. Indenters with different geometries and diameters were used for these model-sized penetration tests. Subsequently a full-scale cylindrical cast-iron indenter with a diameter of 110 cm was dropped of 5 m height on a realistic damping concrete footing.

INTRODUCTION

Due to its mechanical properties damping concrete is particularly suitable for areas in interim nuclear facilities where casks are handled. The shock absorbing properties are obtained by polystyrene parts which are added to the concrete. The resulting concrete-polymer composite is characterized by a long plateau of nearly constant pressure vs. strain under compressive loads. Therefore it is feasible to absorb a large amount of kinetic energy in an accident scenario.

In order to analyze the mechanical behavior of the damping concrete under compressive loads numerical simulations have been conducted. Basis for this are mechanical parameters which have been obtained by a series of compression tests with cubic specimens carried out at BAM. The results have been used to develop a material model for damping concrete which takes relevant factors, e.g. strain rate, into account. In such a comprehensive material model it is also necessary to include information about damage behavior under shear stress.

To obtain data about the mechanical characteristics of damping concrete under shear loads, penetration tests were carried out. This paper focuses on the different experimental setups of the dynamic penetration tests using different sizes of test specimens as well as varying indenters, and gives an overview of a full scale drop test with a 23 Mg cylindrical cast-iron indenter on a damping concrete footing. Furthermore, results of different measuring techniques are shown, e.g. the determination of penetration depth by acceleration sensors as well as by optical measurement systems.

EXPERIMENTAL INVESTIGATIONS

In course of a research project ENREA funded by the German Federal Ministry of Education and Research, static and dynamic compression tests with cubic specimens have been conducted. About 100 tests have been performed to get a comprehensive database for damping concrete to understand and quantify the mechanical behavior. In the following the additional penetration tests regarding specimen, test facility and test setup as well as the evaluation of the results will be discussed.

DAMPING CONCRETE

Damping concrete consists of a concrete matrix in which polystyrene parts are admixed. These parts have a spherical shape with a diameter of about 1.5 mm which leads to a density of fresh concrete of about 800 ± 80 kg/m³ (Figure 1). The specimens for the different series of tests were sawed out of bricks with the dimensions 40 x 40 x 23.5 cm³. The specimens for the dynamic penetration tests were made of single bricks of different sizes. Like in reality, only the bed joints were mortared with a mortar, which has got similar properties as the damping concrete.

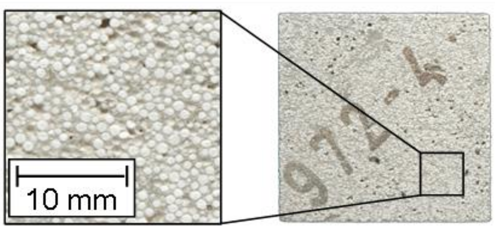


Figure 1: Cubic damping concrete specimen

DISPLACEMENT DRIVEN PENETRATION TESTS

Displacement driven model-sized penetration tests were conducted on specimens with an edge length of 100 mm. These preliminary tests were performed in order to estimate the influence of varying indenters with different geometries.

Test setup and execution

Model-sized displacement driven penetration tests were performed at a hydraulic compression test machine. The cubic specimens were placed in a massive specimen holder to ensure a lateral constraint. Due to instrumentation of the specimen holder with strain gages, lateral forces could be measured as well as forces in load direction by the load cell of the testing machine.
Four different indenter configurations were used: each consists of a penetration element, which is screwed to a base element. In order to estimate the influence of friction by avoiding lateral contact with the damping concrete, two cylindrical base elements with different diameters were used (d =. 45 mm and d = 39 mm). Penetration elements have either a plane or a hemispherical front as shown in Figure 2. The ratio of the penetration elements' diameter and the cube's edge length is similar to the one in dynamic penetration tests with larger specimens which will be presented in the following chapter.
After inserting the damping concrete cube into the specimen holder, the indenter was placed onto it. The loading rate was 0.5 mm/s and penetration depth was 70 mm. For each configuration three tests were conducted. Besides forces measured lateral and parallel to load direction, displacement was measured by a laser triangulation sensor (Figure 3).

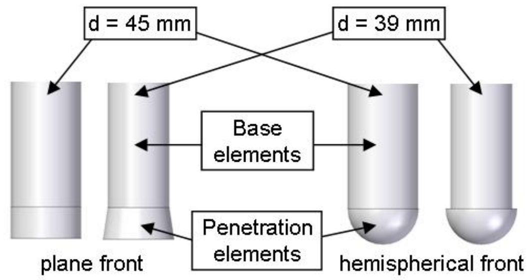


Figure 2: Configurations of indenters

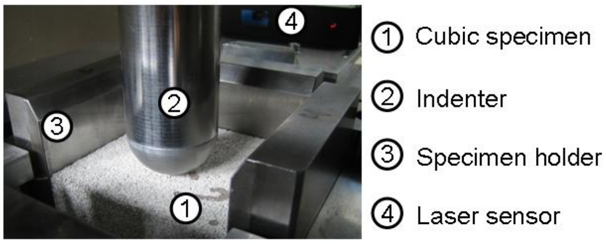


Figure 3: Test setup

Results

The model-sized penetration tests show the influence of penetration elements' geometry as well as the influence of friction on the forces parallel to load direction. Figure 4 illustrates the increase of force caused by friction between indenter and specimen for the indenters with plane front and different diameters. From a displacement of about 20 mm the increase of force over displacement of the indenter with friction is higher than of the one without. This influence of friction is also evident in the penetration tests with a hemispherical front as it is shown in Figure 5. However, these force over displacement curves have a similar curve progression for up to 40 mm deformation.

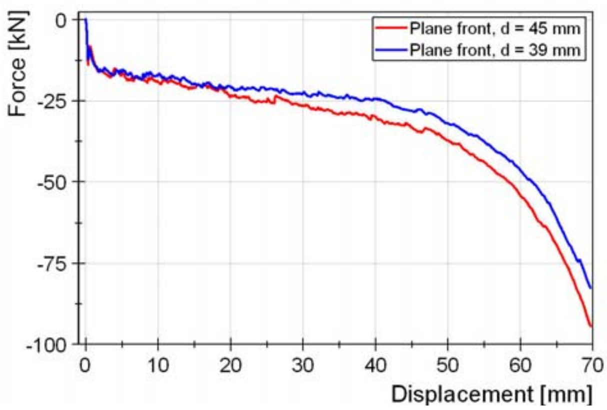


Figure 4: Effect of lateral friction, plane front

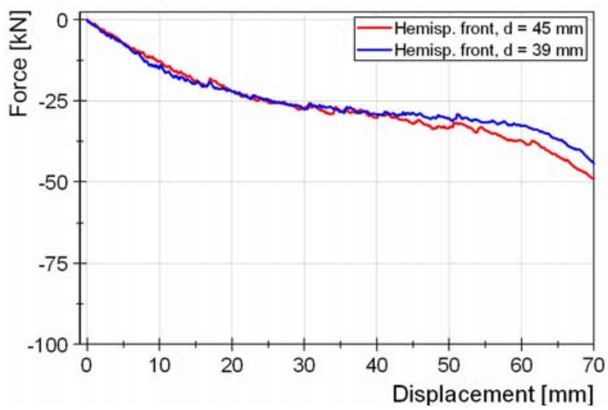


Figure 5: Effect of lateral friction, hemispherical front

The influence of the different penetration elements is shown in Figure 6 for indenter configurations without friction. The force over displacement curve for the indenter with plane front has a steeper increase of force compared to the hemispherical one. At a displacement of about 15 mm up to 50 mm the forces are on the same level. With increasing displacement, the curve for the indenter with plane front shows an eventual compacting with a maximum force of F = -82 kN. The curve for the hemispherical front has a maximum of F = -44 kN, which can be explained by the different compacting zones shown in Figure 7. The load spreading within the cubic specimens is strongly affected by the geometry of the penetration element. Beneath the indenter with plane front a trapeze-shaped compacting zone emerges which is much larger than the compacting zone under the hemispherical indenter. As it is illustrated, the compacting zone has approximately the same diameter like the hemispherical penetration element.

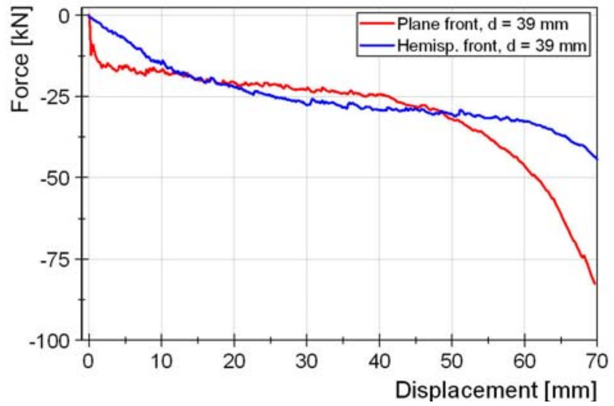


Figure 6: Effect of indenter configurations, plane and hemispherical front

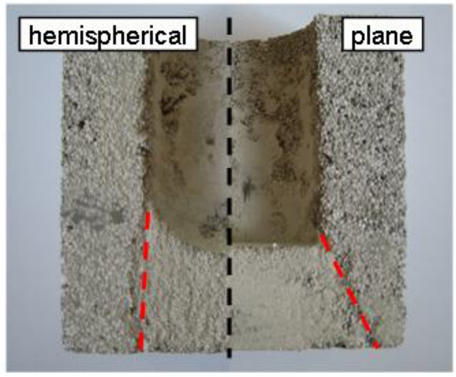


Figure 7: Compacting zone of damping concrete specimens in section

DYNAMIC PENETRTAION TESTS

On the one hand these tests were performed to obtain information about the behavior of damping concrete under shear stress and on the other hand to verify the material model developed by BAM. Just like in the displacement driven penetration tests, different indenters were used. Since higher loading rates were needed, these tests were carried out at BAM test site technical safety (BAM TTS).

Test setup and execution

The model-sized dynamic compression tests were performed on mortared specimens with dimensions of 120 x 40 x 50 cm³. The dimensions of the specimens were specified by the criteria to carry out several penetration tests with one specimen. Two different patterns were mortared to examine the impact of joints; configuration A: drop on a tile spacer of four bricks, configuration B: drop on one brick. As described above, only the bed joints were mortared between the two layers of damping concrete bricks. Conditional to manufacturing, this leads to small gaps of 1 - 2 mm between the bricks. In order to ensure similar conditions to reality, the specimens are laterally constrained by a steel frame, which consists of a base plate and four side parts being screwed together and fixed to the base plate. The side parts are stiffened with U-profiles to minimize bending during the test; additionally, a stiffening plate is screwed on top of the side parts (Figure 8).

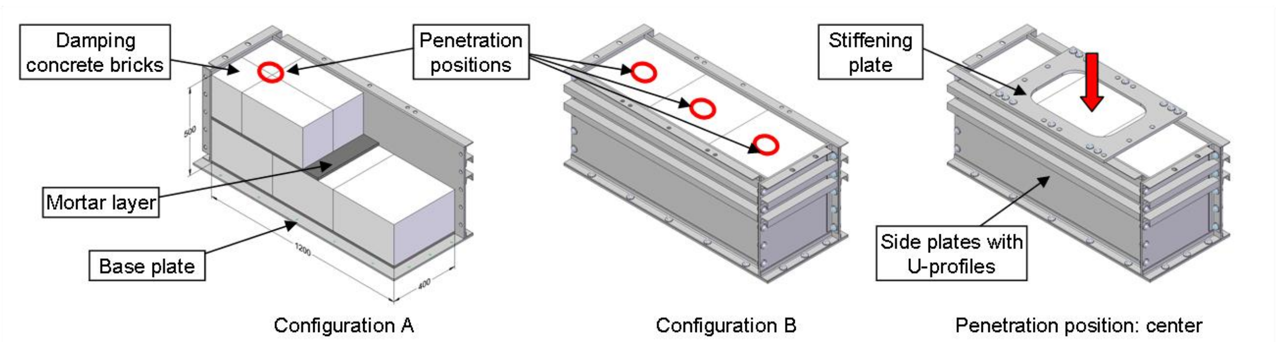


Figure 8: Configurations of mortared damping concrete specimens, steel frame construction

As in the static penetration tests, four different indenters with plane and hemispherical front were used. In order to examine and to quantify the influence of friction between indenter and damping concrete, two cylindrical base elements with different diameters were used as well. Both, the plane and the hemispherical front have a diameter of d = 180 mm. In configuration 1 the diameter of the

base element is as well d = 180 mm, in configuration 2 it is d = 150 mm to avoid contact with the specimen during penetration. Three tests were performed with each configuration.
The dynamic penetration tests were carried out at the BAM drop test machine for guided drop tests [1]. It consists of a 14-metre high steel frame structure and an unyielding impact pad which enables to drop masses up to 1,200 kg from a height up to 12 m. The four different indenters were screwed to the drop mass which is modularly constructed to realize defined drop masses. The construction of the drop test machine enabled the three different penetration positions by moving and fixing the lateral constrained specimen on the unyielding impact pad. The basic construction of the test setup including the test machine and the indenters is shown in Figure 9.

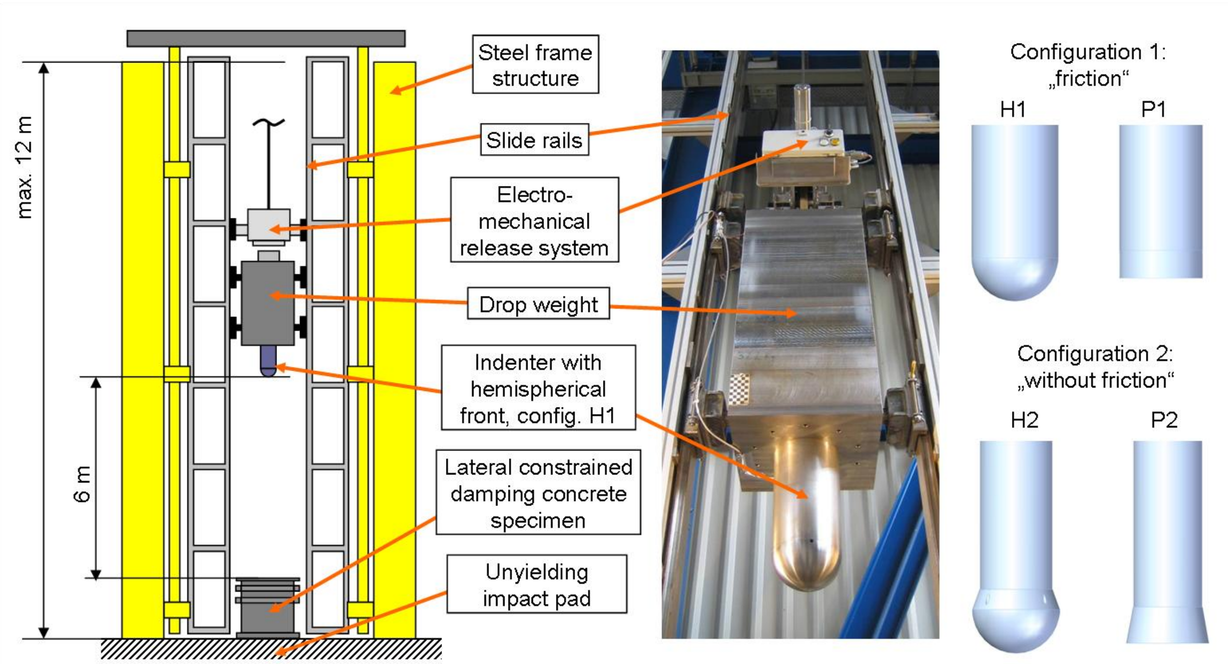


Figure 9: Drop test machine for guided drop tests with test setup for dynamic penetration tests, configurations of indenters with plane and hemispherical front resp. with and without friction

The drop height of the penetration tests was 6 m and the total weight of drop weight and indenter was 1,100 kg. The configuration of drop height and weight was determined analytically with the objective to obtain a specimen's compression of about 30 %. In order to obtain force-displacement curves, the penetration depth was measured by a laser displacement sensor. The occurring forces in load direction were measured by the base element of the indenters, which are instrumented with strain gages in a center bore. Additionally, the deceleration was measured by an accelerometer placed on the drop weight.

Results

In the dynamic penetration tests the influence of different indenters as well as the influence of different joint patterns was examined. The effect of the two different joint pattern configurations 'A' (drop onto tile spacer) and 'B' (drop on one brick) on the force over displacement curves is shown in Figure 10 based on indenter configuration P1 (plane front). A drop onto the tile spacer leads to a softer increase of force and a greater penetration depth at a lower force level compared to the drop on one brick. The reason for this is that the heading joints are not mortared and the small gaps between the bricks reduce the deformation resistance of the specimen.
The effect of the different indenter geometries on the deceleration is shown in Figure 11. The curves show the deceleration over time for drop tests with indenter configuration P1 (plane front) resp. H1 (hemispherical front) on damping concrete specimens configuration 'B'. As expected, the average

deceleration of the plane indenter is significantly higher at the beginning of the impact. Due to the geometry of the hemispherical indenter, the penetration resistance is reduced which leads to a slower increase of deceleration at the beginning of the impact. With increasing penetration depth resp. time, the deceleration level of the hemispherical indenter is higher than the one of the plane one. Penetration time of the two configurations of about 30 ms is comparable.

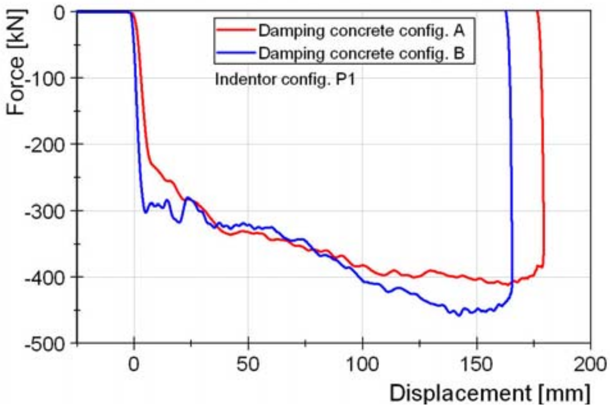


Figure 10: Effect of joint pattern configurations on forces, indenter with plane front (P1)

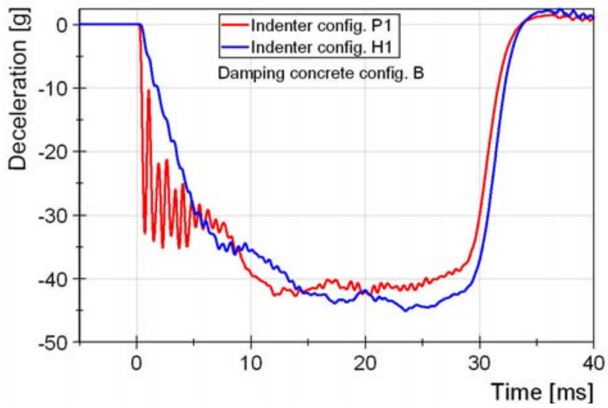


Figure 11: Effect of indenter configuration plane and hemispherical on deceleration, damping concrete config. B

The effects of the indenters with and without friction are shown in displacement over time curves, see Figure 12 and 13. The diagram on left hand side compares the indenters with plane front. Both indenter configurations lead to an average penetration depth of about 166 mm, which means a specimen's compression of about 32 %. The average penetration depth of the indenter with friction is approximately identically to the one without friction. However, the influence of friction is noticeable in the rebound of the indenter, which is significantly higher for configuration P2. Penetration depth over time for the indenter with hemispherical front is shown in the diagram on right hand side. Drop tests with configuration H2 (without friction) lead to a greater penetration depth as well as a higher rebound of the indenter. The average penetration depth for configuration H1 was measured with 174 mm, the one for configuration H2 with 182 mm, which means a specimen's compression of about 35 % resp. 36 %.

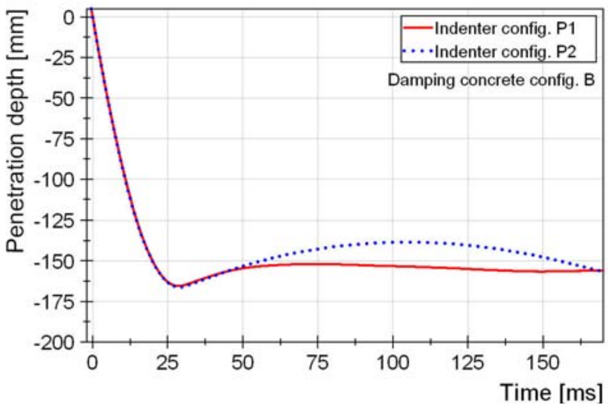


Figure 12: Effect of plane indenter configurations on penetration depth, damping concrete config. B

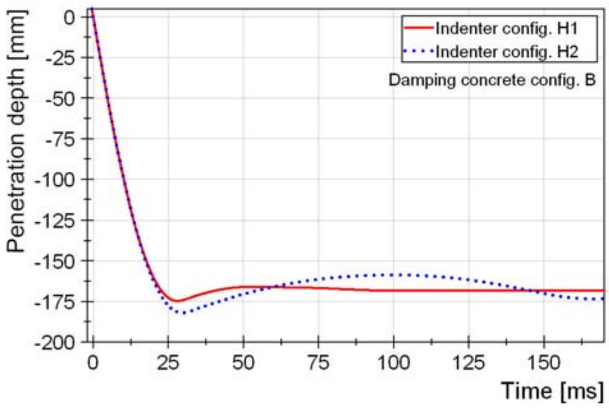


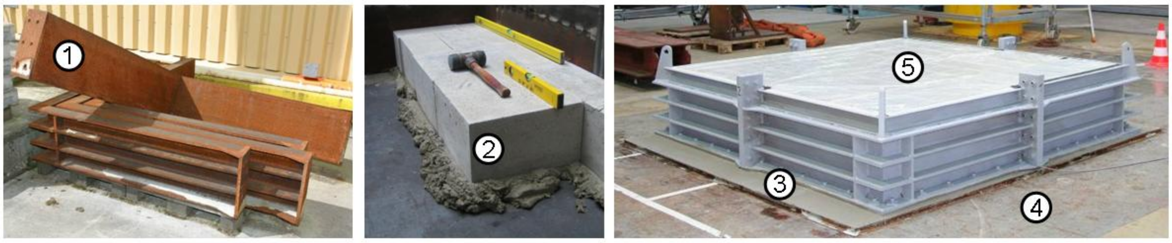
Figure 13: Effect of hemispherical indenter configurations on penetration depth, damping concrete config. B

FULL-SCALE PENETRATION TEST

To verify the advanced FE-model, a drop test was carried out under realistic conditions at the drop test facility of BAM. A full-scale cylindrical cast iron indenter was dropped on a mortared damping concrete footing with the dimensions of 240 x 240 x 50 cm³. The focus was placed on a comparison between calculated penetration depth and experimentally measured values.

<u>Test setup and execution</u>

As in the dynamic penetration tests, the damping concrete footing was laterally constrained by a stiff steel frame. The steel frame itself was built by four massive brackets, which were screwed together with a base plate. The footing consisted of two layers of damping concrete bricks, which were mortared on the base plate as in the model-size tests. The base plate itself was mortared by a 30 mm thick grout onto the unyielding IAEA target of the drop test facility (Figure 14).



① Brackets ② Damping concrete layer ③ Grout ④ Unyielding target ⑤ Damping concrete footing

Figure 14: Steel brackets, mortared damping concrete layer, constrained damping concrete footing

The penetration test was carried out with a cylindrical cast iron indenter with a plane front and a total weight of 23 Mg. The indenter had a height of about 270 cm and consisted of two cylindrical parts: the penetrating one had a height of 20 cm and a diameter of 110 cm, the remaining had a diameter of 138 cm. It was dropped from 5 m height in vertical drop position onto the center of the damping concrete footing. The indenter was instrumented with four accelerometers, which were placed circularly on the top (Figure 15). On the one hand they were used to measure the deceleration during the impact and on the other hand the deceleration data were used to determine the penetration depth. Additionally, the drop test was recorded by two high speed cameras with a recording rate of 3000 frames per second. Subsequently these high-speed recordings were evaluated and used to determine the penetration depth by software for optical tracking.

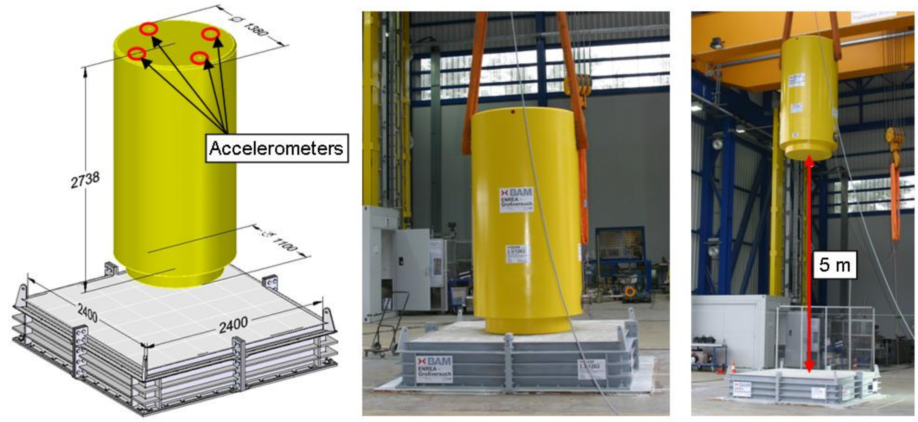


Figure 15: Constrained damping concrete footing with full-scale indenter before drop test and in drop position

Results

The penetration depth of the indenter is calculated from the deceleration data of the drop test. The average maximum deceleration of the four accelerometers, which were placed on top of the cylindrical indenter, was about 43 g (Figure 16). The penetration depth over time curve was calculated by integration of the deceleration data, which is shown in Figure 17. The maximum penetration depth is determined to be 132 mm, which means a specimen's compression of about 26 %.

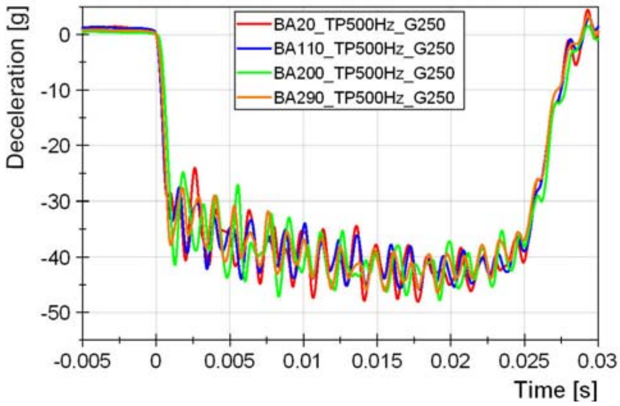


Figure 16: Measured deceleration of indenter

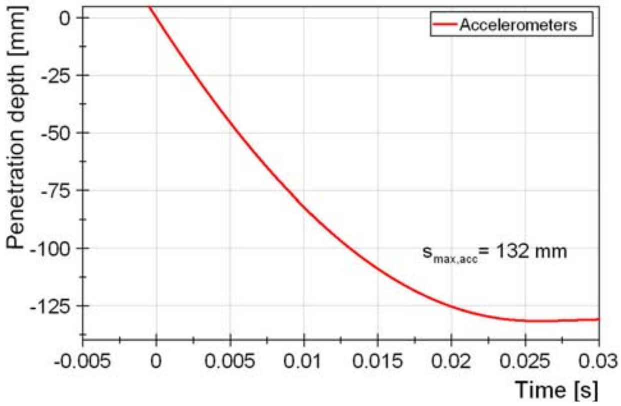


Figure 17: Penetration depth calculated from deceleration data of accelerometers

The test setup for the evaluation of the high-speed recording is shown in Figure 18. The penetration depth s is calculated from the displacement of the indenter (s_1), the displacement of the high-speed camera resulting from shock waves during the impact (s_2) and the yielding of the grout layer (s_3). Taking these three displacements into account, the following formula results:

$$s = s_1 + s_2 - s_3$$

Using software for optical tracking leads to a penetration depth over time curve, which is shown in Figure 19. The maximum penetration depth, measured to be 131 mm, matches almost exactly with the calculations of the deceleration data. The progression of the penetration depth over time curves of the two different methods of measurement coincide very well with each other as it is shown in Figure 20.

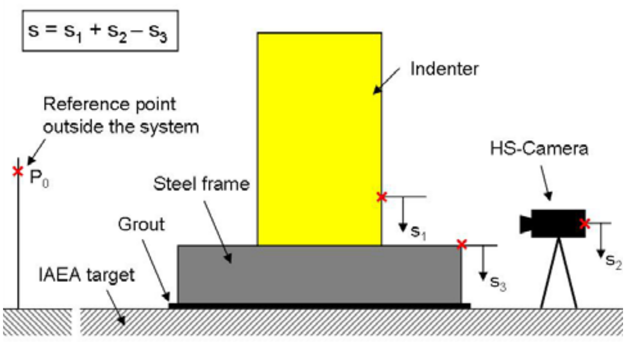


Figure 18: Test setup for optical measurement of penetration depth

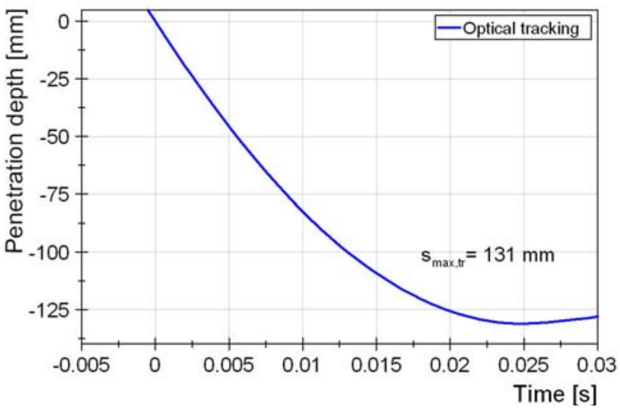


Figure 19: Penetration depth measured by optical tracking

Both, penetration depth and deceleration were calculated by numerical FE-simulation of the whole drop test scenario including cask, damping concrete footing, steel frame, grout layer and IAEA target. As it is described in Ref. [2], the maximum cask body deceleration was calculated as 46 g and the maximum penetration depth as 134 mm, which coincides very well with the results measured experimentally.

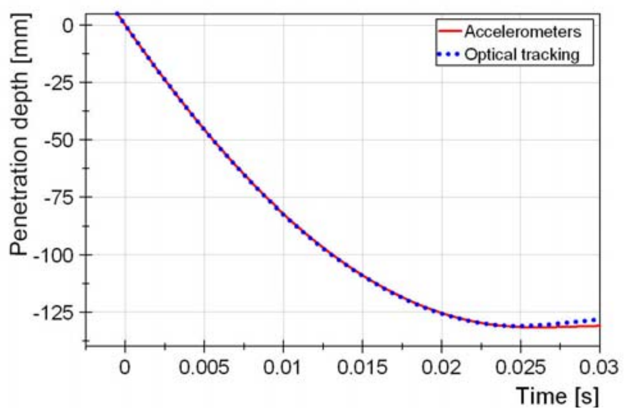


Figure 20: Comparison of measured penetration depth by deceleration data and optical tracking

CONCLUSIONS AND PROSPECTS

A series of different penetration tests on damping concrete was conducted to evaluate an existing material model and to characterize the behavior under shear stress. For this purpose, model-sized tests and a full-scale penetration test were carried out at different test facilities of BAM.

Model-sized penetration tests were performed with cubical damping concrete specimens, which were laterally constrained by a massive specimen holder. Indenters of different geometries and diameters penetrated the specimens with an edge length of 100 mm with a velocity of 0.5 mm/s in order to examine the influence of indenter geometry and friction. The effects of plane or hemispherical indenters as well as friction on the measured forces parallel to load direction were shown as well as the differences in the failure process. Due to the material's behavior, the force level of the hemispherical indenters is lower than of the plane one.

Further penetration tests were conducted with mortared damping concrete specimens at the BAM drop test machine for guided drop tests. The laterally constrained specimens with dimensions of 120 x 40 x 50 cm³ were used to carry out dynamic drop tests with indenter geometries similar to the ones in displacement driven tests. Additionally, two different configurations of joint patterns were examined. Penetration depth, force in load direction as well as the deceleration were measured to characterize the damping concrete by tests with a drop mass of 1,100 kg and a drop height of 6 m. As in the displacement driven tests, the effect of different indenters as well as the influence of friction was determined. Indenters with hemispherical front had greater penetration depths than the ones with plane front. The influence of friction was more significant in the tests with hemispherical indenters. Penetration depths as well as the rebounds of the indenters without friction were greater than of the ones with friction.

To verify the developed material model under realistic drop conditions, a penetration test with a full-scale cylindrical indenter was conducted. The indenter had a drop mass of 23 Mg and was dropped from 5 m height onto a constrained mortared damping concrete footing with dimensions of 240 x 240 x 50 cm³. Deceleration data of accelerometers as well as high-speed recordings were used to determine the penetration depth. Both methods of measurement provide coinciding results, which can be used for verification of numerical calculations of the penetration test [2].

To get a more complete understanding of the complex failure process of damping concrete and to develop more accurate calculation tools, additional systematic material tests are necessary. In particular, further penetration tests are planned at the drop test machine for guided drop tests with drop heights larger than 6 m. Nevertheless, the tests already conducted provide valuable new information about damping concrete properties which can be already used for safety assessments of casks in accidental scenarios.

ACKNOWLEDGMENTS

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