Dynamic Penetration Tests on Shock Absorbing Damping Concrete – 14166

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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 dynamic penetration tests on mortared specimens with a size of 2,400 x 2,400 x 500 mm³. For these model-sized penetration tests indenters with different geometries and diameters were used. Subsequently a cylindrical cast-iron indenter with a diameter of 1.100 mm 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 nuclear facilities where casks are handled. Its shock absorbing properties are obtained by polystyrene parts which are added to the concrete matrix. 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 a crash scenario.

In order to analyze the mechanical behavior of the damping concrete under such impact 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 course of 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 that permits to understand and quantify the mechanical behavior. 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 experimental setups and results of the dynamic penetration tests using different configurations of test specimens as well as indenters varying in geometry and diameter.

Finally an overview of a drop test with a 23 Mg cylindrical cast-iron indenter on a damping concrete footing will be given. In this context, results of the applied measuring techniques are shown, e.g. the determination of penetration depth by acceleration sensors as well as by an optical measurement system. Furthermore, a brief comparison of the numerically and experimentally determined penetration depth will be shown.

DYNAMIC PENETRATION TESTS

These tests were performed to obtain information about the behavior of damping concrete under shear stress as well as to verify the material model developed by BAM. For this purpose indenters with different geometries and diameters were dropped on mortared damping concrete specimens. Since higher loading rates were needed, these tests were carried out at BAM test site technical safety (BAM TTS).

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 400 x 400 x 235 mm³. 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.

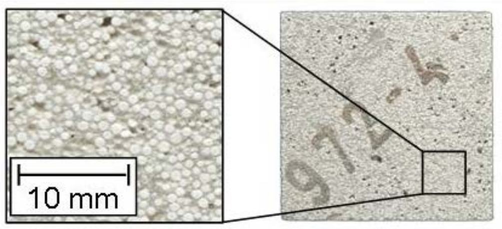

Fig. 1. Cubic damping concrete specimen

Test setup and execution

The model-size dynamic compression tests were performed on specimens with two layers of mortared damping concrete bricks having total dimensions of 1,200 x 400 x 500 mm³. The specimen dimension enabled to carry out several penetration tests with one sample. 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 the middle of 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 and to maximize lateral constraint during the test; additionally, a stiffening plate is screwed on top of the side parts (Figure 2).

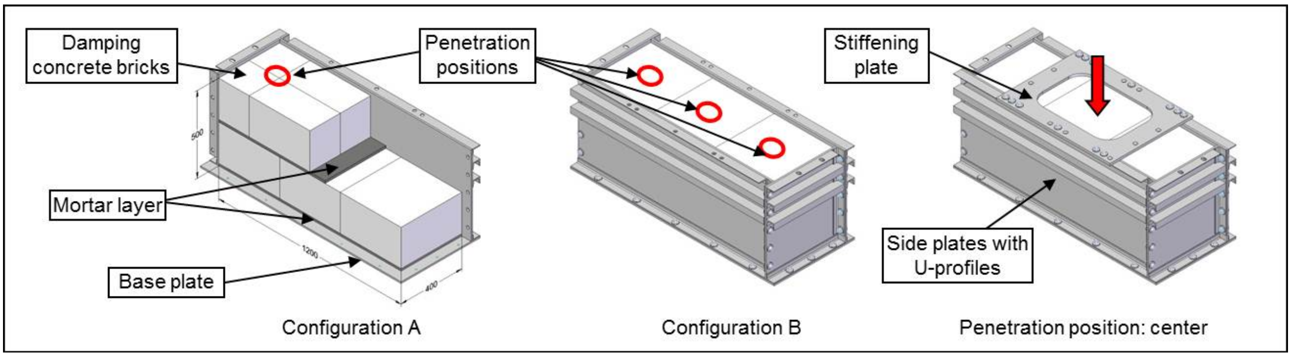

Fig. 2. Configurations of mortared damping concrete specimens, steel frame construction

The penetration tests were conducted with four different indenter configurations in total. Each indenter configuration consists of the combination of a base and a penetration element as it is shown in Figure 3. 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. One with a diameter of d_1 = 180 mm and the other one with a diameter of d_2 = 150 mm to avoid contact with the specimen and to avoid friction during penetration. The base elements were equipped with a plane resp. a hemispherical shaped penetration element, each with a diameter of d = 180 mm.

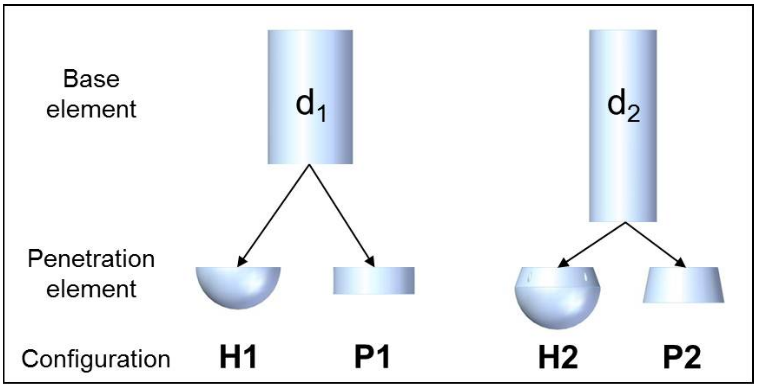

Fig. 3. Indenter configurations: base elements with different diameters and penetration elements with hemispherical and plane front

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 weight which is modularly constructed to realize defined drop masses. The construction of the drop test machine enabled to perform subsequently three different penetration tests with one sample by moving and fixing the steel frame with the lateral constrained specimen on the unyielding impact pad. The basic construction of the test setup including the drop test machine and the drop weight with hemispherical indenter is shown in Figure 4.

The drop height of the penetration tests was 6 m and the total weight of the drop assembly inclusive indenter was 1,100 kg for all different indenter configurations. The combination of drop height and weight was determined analytically with the objective to obtain a specimen's compression of about 30 %. In order to get force-displacement curves, the penetration of the indenter was measured by a laser displacement sensor during the penetration process. The occurring forces in load direction were measured by the base elements 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. For each indenter configuration three tests were performed with one damping concrete specimen.

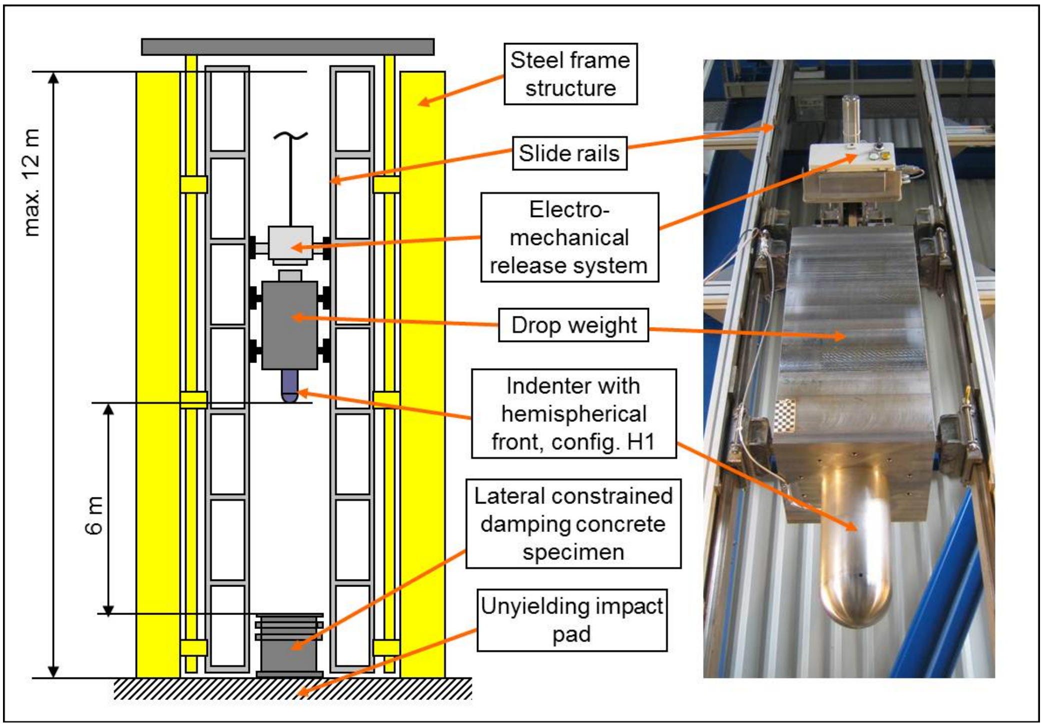

Fig. 4. Drop test machine for guided drop tests with test setup for dynamic penetration tests

Results

In the dynamic penetration tests the influence of different indenters as well as the influence of different joint patterns was examined. For analysis and comparison of the test results the measurement data of the three related tests were averaged.

The effect of the two different joint pattern configurations 'A' (drop onto tile spacer) and 'B' (drop on the middle of one brick) is shown in Figure 5. The force over displacement curves were determined by drop tests with the indenter configuration P1 ("friction" and plane front). A drop onto the tile spacer leads to a slightly softer increase of force during the impact and a greater penetration depth. Maximum force level of about 400 kN is lower than the one of the drop on one brick which is about 450 kN. The reason for this is that the heading joints are not mortared and the small gaps between the damping concrete bricks reduce the deformation resistance of the specimen.

The effect of the indenter on penetration depth is influenced by the geometry of the penetration element and the diameter of the base element. In order to analyze the effect of the penetration element's geometry separately, the base element with the diameter of 150 mm was used to reduce the influence of friction. The force over penetration depth curves for drop tests with indenter configuration P2 (plane front) resp. H2 (hemispherical front) on damping concrete specimens with pattern configuration 'B' are shown in Figure 6. Due to the hemispherical geometry the impact area of the indenter increases during the penetration which influences the penetration resistance and leads to a slower increase of force at the beginning of the impact in comparison to the plane front. With 182 mm the penetration depth is larger than the one of the drop test with plane geometry which is 166 mm. The effect of the different indenter geometries on the force level shows a slightly higher maximum force of 500 kN for the drop tests with hemispherical geometry in comparison to 475 kN due to the larger penetration depth.

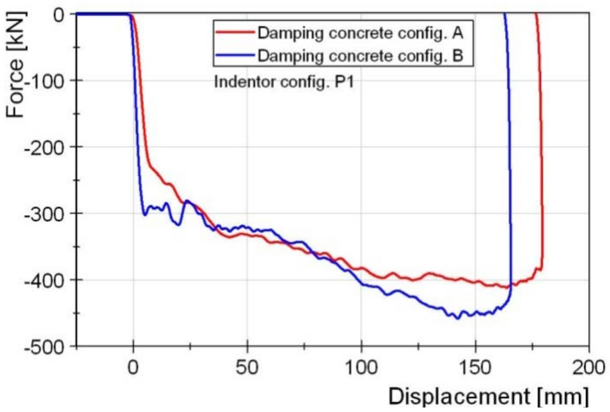

Fig. 5. Effect of joint pattern configurations on forces

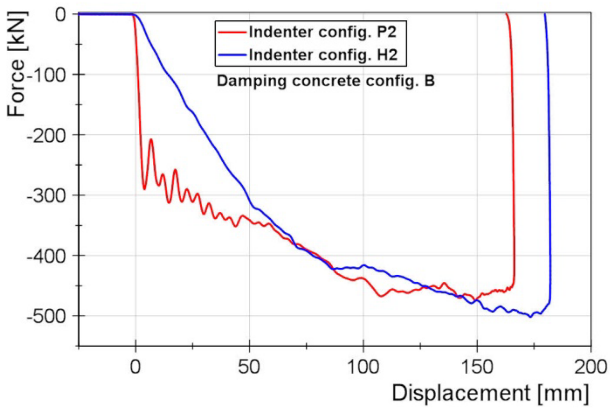

Fig. 6. Effect of indenter configuration plane and hemispherical front

The effects of the indenters with and without friction are shown in displacement over time curves in Figure 7 and 8. The diagram on left hand side compares the indenters with plane geometry. 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 (P1) is approximately identically to the one with reduced friction (P2). However, the influence of friction is noticeable in the rebound of the indenters, which is significantly higher for configuration P2. Penetration depth over time for the indenter with hemispherical geometry is shown in the diagram on right hand side. Drop tests with the indenter configuration H2 lead to a greater penetration depth as well as a higher rebound. 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 %.

The different frictional effects of plane and hemispherical shaped indenters on the penetration depth can be explained by the failure process under shear stress. Due to the plane geometry of the penetration elements P1 and P2, the damping concrete is punched out plastically by the indenters, which minimizes the effect of lateral friction during the penetration leading to similar penetration depths. During penetration of hemispherical shaped indenters, the material is rather displaced laterally. This lateral displacement has an elastic component which leads to higher friction respectively lateral forces and as a consequence to a lower penetration depth for the configuration H1 in comparison to H2.

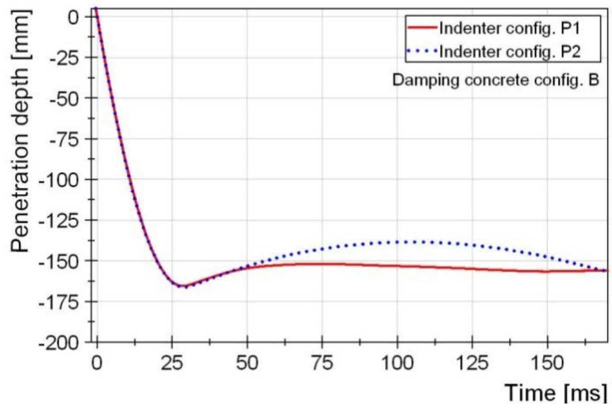

Fig. 7. Effect of friction on penetration depth, indenter configuration P1 and P2

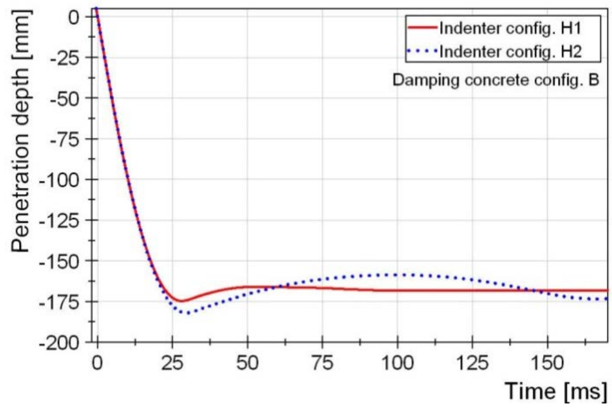

Fig. 8. Effect of friction on penetration depth, indenter configuration H1 and H2

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 cylindrical cast iron indenter was dropped on a mortared damping concrete footing with the dimensions of 2,400 x 2,400 x 500 mm³. The paper focuses on the comparison between experimentally measured and numerically calculated penetration depth.

Test setup and execution

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 9).

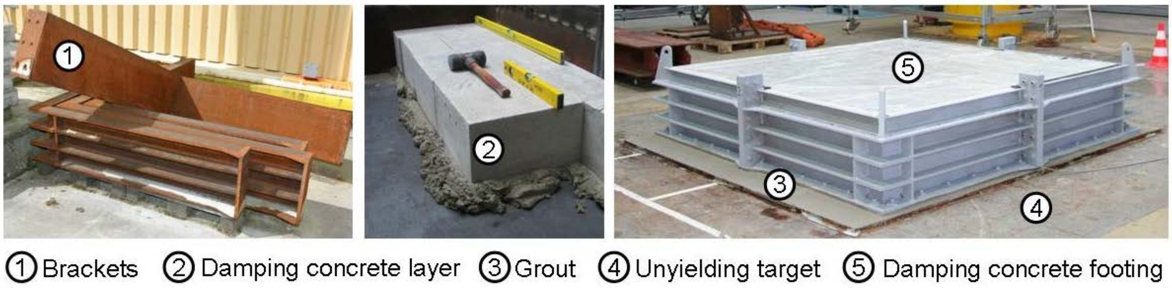

Fig. 9. Steel brackets, mortared damping concrete layer, constrained damping concrete footing

The penetration test was carried out with a cylindrical cast iron indenter with a total weight of 23 Mg. It has a height of about 2,740 mm and a plane penetration area with a diameter of 1,100 mm. The indenter 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 its top (Figure 10). 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 3,000 frames per second. Subsequently these high-speed recordings were evaluated and used to determine the penetration depth by software for optical tracking.

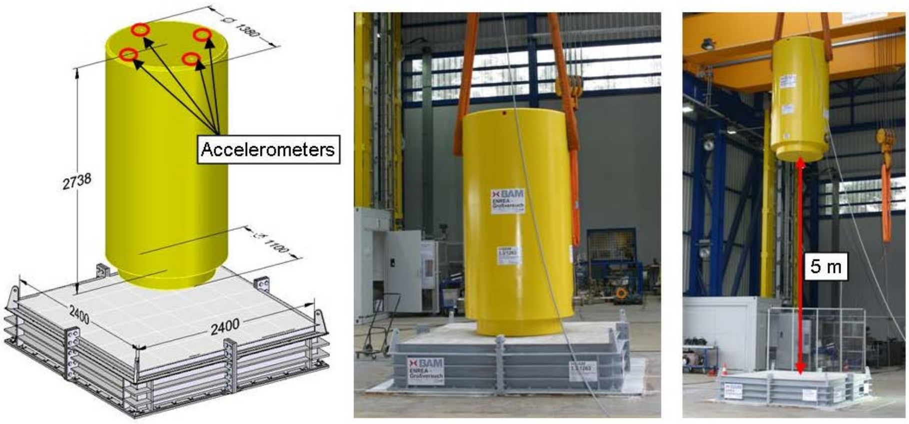

Fig. 10. Constrained damping concrete footing with full-scale indenter before drop test and in drop position

Results

The penetration depth of the indenter has been 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 11). The penetration depth over time curve was calculated by double integration of the deceleration data, which is shown in Figure 12. The maximum penetration depth is determined to be 132 mm, which means a specimen's compression of about 26 %.

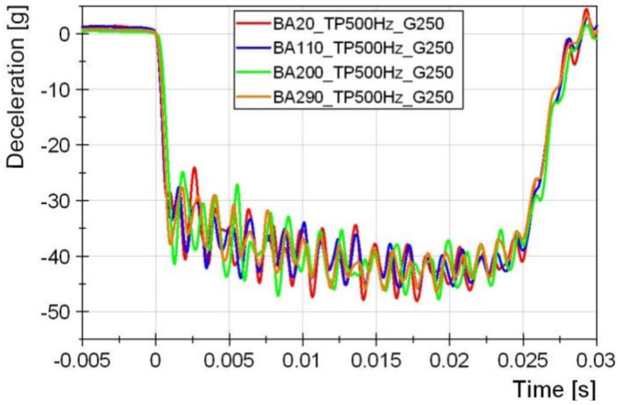

Fig. 11: Measured deceleration of indenter

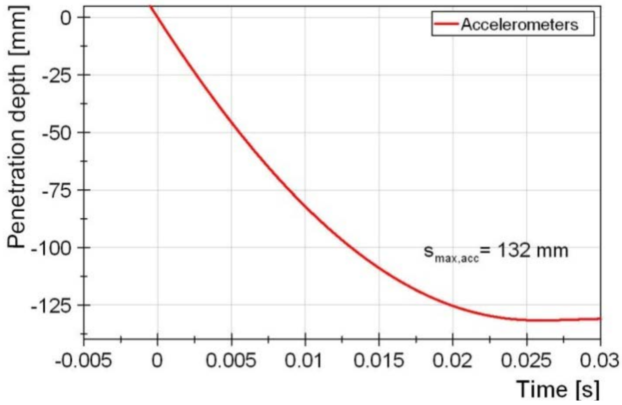

Fig. 12. Penetration depth calculated from deceleration data of accelerometers

The test setup for the determination of the penetration depth by evaluating the high-speed recording is shown in Figure 13. To determine the resulting penetration depth s three different displacements were taken into account: 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). These three displacements were measured in relation to the reference point P_0 by using software for optical tracking. Following formula is used:

$$s = s_1 + s_2 - s_3 \qquad \text{(Eq. 1)}$$

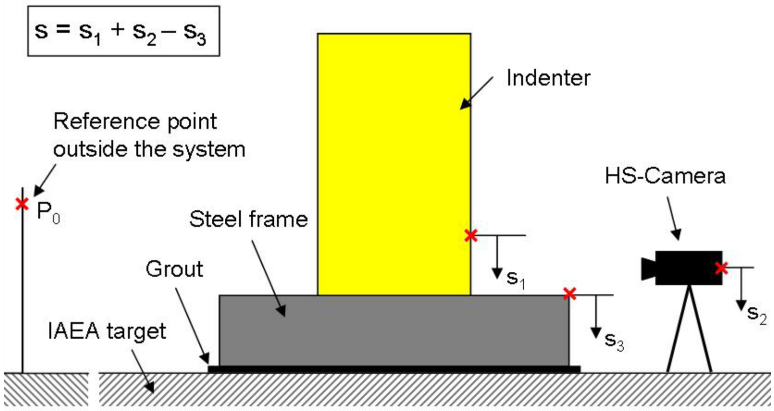

Fig. 13. Test setup for optical measurement of penetration depth

The calculated penetration depth s of the cylindrical indenter is shown in Figure 14. Maximum penetration depth, measured to be 131 mm, matches almost exactly with the calculations of the deceleration data. The progression and maximum of the curves calculated by the two different methods coincide very well with each other as it is shown in Figure 15.

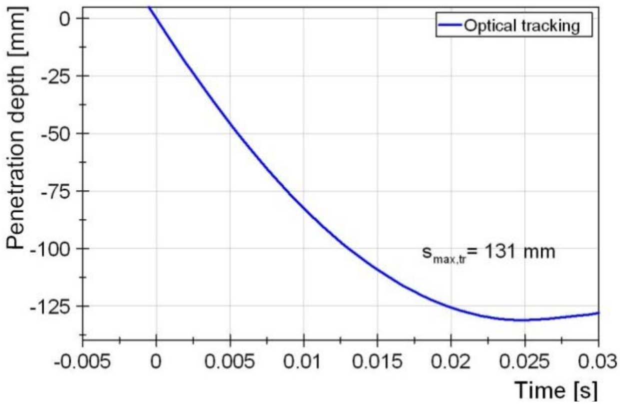

Fig. 14. Penetration depth measured by optical tracking

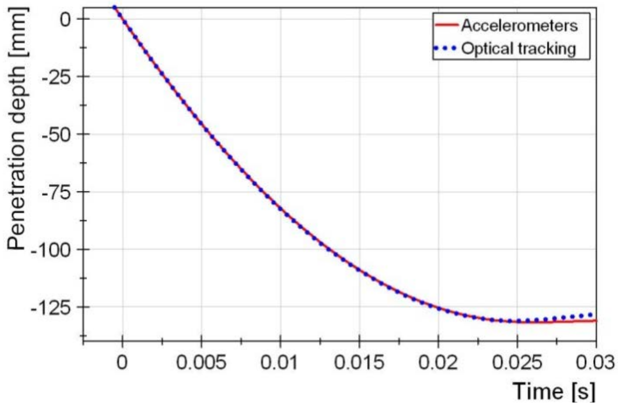

Fig. 15. Comparison of penetration depth by deceleration data and optical tracking

In a further step the experimental results were compared with numerical calculations which take into account the whole drop test scenario including cask, damping concrete footing, steel frame, grout layer and IAEA target. Based on the material model for damping concrete, that was already adapted by the previous tests, the drop test was simulated. The indenter imprint in the damping concrete footing of the experimental drop test and the one numerically simulated are shown in Figure 16. Both, penetration depth and deceleration were calculated by FEM simulation as it is described in Ref. [2]. The maximum cask body deceleration was calculated to be 46 g and the maximum penetration depth to be 138 mm, which coincides well with the results measured experimentally by the accelerometers as it is shown in Figure 17.

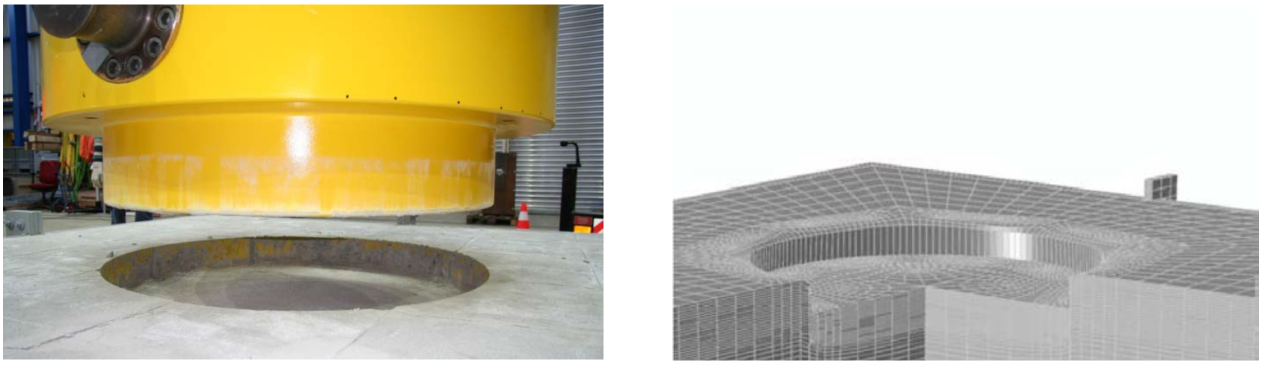

Fig. 16. Imprint of indenter in damping concrete foundation and FE-simulated imprint

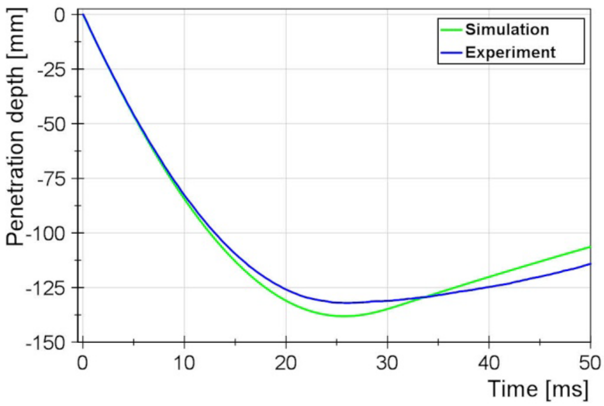

Fig. 17. Comparison of penetration depth of experiment and simulation

CONCLUSIONS

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

Model-size dynamic penetration tests were conducted with damping concrete specimens at the BAM drop test machine for guided drop tests. Therefore, laterally constrained specimens with dimensions of 1,200 x 400 x 500 mm³ were mortared in two different joint pattern configurations. These dynamic drop tests were carried out with different indenters consisting of a base and a penetration element. Combinations of penetration elements with plane and hemispherical front as well as base elements with different diameters were used to examine geometrical and frictional effects. Penetration depth as well as force and deceleration in load direction were measured to characterize the damping concrete during tests with a total drop weight of 1,100 kg and a drop height of 6 m. Indenters with hemispherical front yielded a larger penetration depth as well as a slower increase of force during the impact than the ones with plane front. The influence of friction was more significant in the tests with hemispherical shaped indenters. Penetration depths as well as the rebounds were larger for the indenter configurations with reduced lateral friction..

To verify the developed material model under realistic drop conditions, a penetration test with a cask-like 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 2,400 x 2,400 x 500 mm³. Deceleration data of accelerometers as well as high-speed recordings were used to determine the penetration depth. Both measurement methods provide reliable results, which can be used to verify the numerical calculations of the penetration test [2]. The comparison of the experimental measured results and the numerical calculated ones regarding penetration depth and deceleration show a good agreement.

To get a more complete understanding of the complex failure process of damping concrete and to develop more accurate numerical 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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