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Hydraulic Substitute Base for Demolition Hammers

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Abstract.

Demolition hammers are currently tested on mineral materials or on mechanical substitute base systems such as the steel ball energy absorber Dynaload. These bases are either destroyed during testing or not designed to replicate different materials. This work investigates a hydraulic substitute base as an equivalently effective, repeatable, adjustable, and low-wear alternative. Various arrangement concepts are evaluated. The selected concept combines a tool of a demolition hammer and a cylinder piston into a single impact body. The design approach uses a co-simulation that couples an FEM model of the impact mechanism with a hydraulic base model. Parameter studies show that by tuning hydraulic capacitance, resistance, and inductance, the tool displacement curves and dissipated energy can be targeted to approximate real materials. Therefore, this paper shows how a hydraulic substitute base could be adjusted. For concrete-like behavior (penetration depth $\approx$ 0.4 mm, energy absorption $\approx$ 83%), the simulation yields a required volume of 0.3 ml with mineral oil and an orifice cross-section of about 1.1 mm^2. With the identified adjustment ranges for capacitance and resistance, a hydraulic substitute base for a handheld rotary hammer with 4.2 J impact energy can be designed. The methodology can be transferred to other impact demolition hammers, such as hydraulic breakers, enabling reproducible testing.

Keywords. hydraulic substitute base, co-Simulation, rotary hammer testing.

1. INTRODUCTION

Demolition hammers are used to break up mineral materials or building materials. Their core is an impact mechanism that acts on the chisel at a frequency in the single-digit or double-digit Hz range. The resulting impact force crushes the material beneath the chisel tip. Prototype testing remains indispensable for developing such machines because model assumptions and simplifications in simulations leave residual uncertainties. However, tests on mineral materials are problematic. These materials are destroyed during the test, limiting long-duration testing. In addition, mineral materials are structurally inhomogeneous, which reduces the repeatability of test results. Especially for the tests required by EU directives to assess vibration emissions, high repeatability is essential [1]. Consequently, "artificial" test bases - also called substitute bases - are used [2]. They should replicate mineral materials in an equivalently effective way with low scatter. Existing solutions, such as the Dynaload system [3] specified in DIN EN ISO 28927-10 [2] for hand-held demolition hammers without rotary motion, are predominantly mechanical and only partially meet testing needs. For example, the mechanical substitute base Dynaload used for vibration tests is not designed to represent different materials via adjustable parameters [3].

This paper addresses the research gap stemming from the lack of an adjustable substitute base. It investigates alternatives to purely mechanical systems, with a focus on an adjustable hydraulic substitute base. Due to the low compressibility of hydraulic fluids, high impact forces can be damped while chisel displacements remain small. Hydraulic components also allow targeted adjustment of stiffness and damping [6]. The paper shows, using a rotary hammer as an example, how such a substitute base should be designed in order to combine equivalent effectiveness, repeatability, adjustability, and wear resistance.

2. STATE OF THE ART IN TECHNOLOGY AND RESEARCH

2.1. *Substitute Bases*

For experimental evaluation of demolition, substitute bases are used to reproduce the behavior of mineral materials and provide a reproducible test environment. In practice, predominantly mechanical substitute base systems are employed [2], [3].

A well-established representative is the Dynaload system, developed by the PNEUROP Tools Committee [3]. Dynaload is a standardized test device for evaluating vibration, noise, and performance of hand-held percussive tools according to DIN EN ISO 28927-10 [2]. The system consists of a metallic cylinder filled with steel balls, as shown in Figure 1. The tool transfers the impact wave to this column of balls via a metallic piston plate. Part of the impact energy is dissipated upon impact through elastic deformations and relative motions of the balls. About 15% to 20% of the impact energy is reflected back to the tool, creating a loading situation similar to working on a hard mineral material. The system is available in several sizes (cylinder diameters 20 mm, 40 mm, 60 mm) and can be fitted with various tool - piston combinations. These variants extend test-stand capabilities (e.g., rotary hammers can also be tested in hammer-drilling mode where the tool additionally rotates). PNEUROP test series showed that Dynaload provides high repeatability and is insensitive to small manufacturing tolerances or wear; repeatability remained stable throughout the test day and from one day to another. [3]

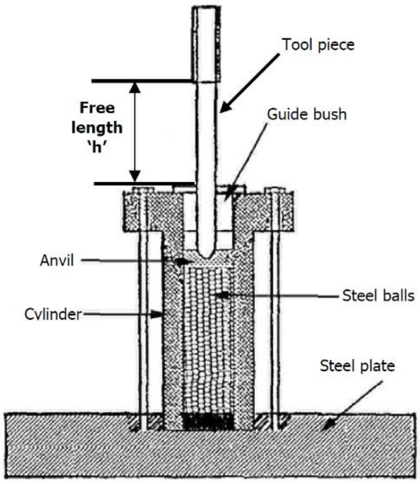

Figure 1: Mechanical steel ball energy absorber Dynaload [3]

For hydraulic breakers, the literature presents a test bench for determining impact energy as described in [5]. A key element is a shock- and vibration-absorbing base realized as a multilayer combination of sand, crushed stone, wood, and rubber, as shown in Figure 1. This design serves to decouple environmental influences and ensure repeatable measurements. [4]

The base is not intended to be adjustable. Moreover, it is reasonable to expect that the layered materials - especially crushed-stone layers - densify over time, changing their mechanical properties and affecting repeatability.

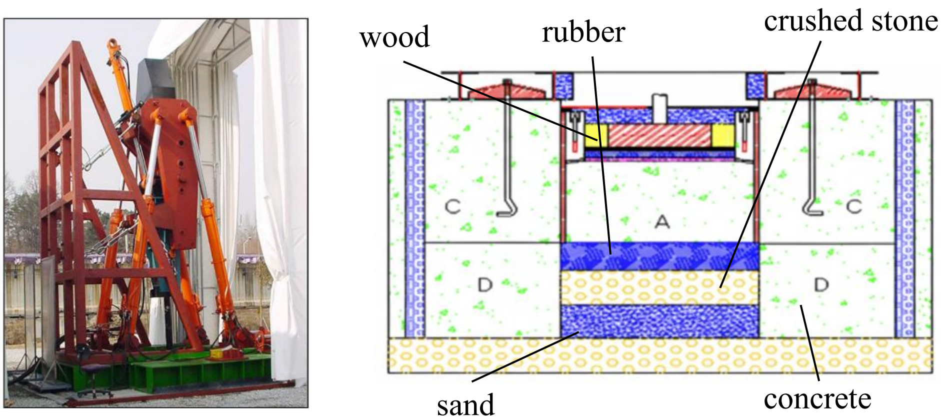

Figure 2: (left) test bench for hydraulic breakers; (right) impact absorbing base [4]. Text boxes were added by the authors.

In summary, mechanical substitute bases like Dynaload are suitable for standardized comparative measurements, but they cannot be tuned to different material properties and therefore cannot provide equivalently effective replication of different mineral materials. An advanced concept - such as the hydraulic substitute base presented by Klotz et al. offers the possibility to adjust both stiffness and damping by varying oil volume and orifice cross-section, thereby reproducing the behavior of different materials in a repeatable manner [6].

2.2. *Simulation of Hydraulic Impact Damping*

Hasenöhrl et al. investigate the shock-induced propagation of strain waves in a rotary hammer, taking into account the geometry of the impact body, using FEM simulation [7].

Klotz et al. describe a simulation environment enabling the determination of system parameters required to develop a hydraulic substitute base. The described co-simulation couples a structural FEM model of the impact mechanism with a hydraulic model of the substitute base, thus realistically representing the dynamic interaction between tool and base. In the FEM model, relevant impact events in the rotary hammer and at the hammer - tool interface are represented, modeling flying piston, firing pin, and tool as deformable bodies. The FEM model outputs the time-dependent displacement of the hydraulically pressurized piston area, which is passed to the hydraulic model via a co-simulation engine. The hydraulic model describes the substitute base as a hydraulic system comprising capacitance, and resistance. From piston displacement, the model computes the cylinder pressure history and the resulting reaction force, which is fed back to the FEM model. This bidirectional coupling captures energy flows between the impact mechanism and the substitute base comprehensively. By varying hydraulic parameters - especially the enclosed oil volume and the orifice cross-section - the influence on stiffness, damping, and energy absorption can be systematically investigated. Low hydraulic capacitance leads to a stiffer base with smaller penetration depth and higher peak pressures, whereas a larger orifice increases damping and thus energy absorption. In simulation, hydraulic damping could be varied between nearly 0% and 84% of the initial impact energy of the modeled rotary hammer. In this way, the interaction of hydraulic components can be tuned so that the substitute base reproduces the behavior of different mineral materials in an equivalently effective manner [6].

This simulation-driven approach allows different design variants to be evaluated before building hardware. The co-simulation thus serves as a tool for designing and parameterizing the hydraulic substitute base by revealing the relationships between geometric, hydraulic, and dynamic quantities and enabling virtual tuning to different base types.

3. CONCEPT SELECTION

3.1. *Requirements for a Substitute Base for Demolition Hammers*

For developing and testing demolition hammers, a test base is required that reproduces the behavior of mineral materials in an equivalently effective way. Because natural rock or concrete - due to inhomogeneity, anisotropy, and irreversible destruction under impact loading do not allow repeatable results, a substitute base is needed that can emulate the governing physical characteristics of the real material. From the authors’ perspective, such a base must satisfy four key requirements: equivalent effectiveness, repeatability, adjustability, and wear resistance.

Equivalent effectiveness means that the dynamic response of the substitute base - i.e., the time histories of penetration depth, contact force, and dissipated energy - matches those of a real mineral material as closely as possible. Only if the energy uptake and rebound of the base reflect typical building materials or rock tool loads can be represented realistically.

Repeatability describes the ability to reproduce identical impact events multiple times with minimal deviation, enabling comparisons of demolition hammers tested at different times and places.

Adjustability is required to emulate different base types such as concrete, granite, or limestone with varying stiffness and damping. An adjustable base allows systematic variation of material parameters and investigation of substrate influence on impact-mechanism behavior.

Finally, the substitute base must have high wear resistance to provide stable characteristics over many tests even at high impact frequencies and energies, enabling cost-effective testing.

3.2. *Evaluation of possible System Concepts for Substitute Bases*

Various technical concepts can in principle meet the requirements of equivalent effectiveness, repeatability, adjustability, and wear resistance. The following assesses mechanical, pneumatic, mechatronic, and hydraulic approaches for their suitability from the authors' perspective.

Mechanical systems combine springs, dampers, and mass elements. Very stiff bases can be realized, but their characteristics are only limitedly variable. Adjusting stiffness or damping typically requires part changes, increasing test effort. If damping relies on relative motion of components, wear and long-term stability can be problematic.

Pneumatic systems provide a soft, strongly damping characteristic due to the high compressibility of air. System parameters can be readily adjusted via pressure, volume, or orifice size. However, they are only of limited suitability for hard bases such as concrete or granite because the achievable stiffness is far below that of real mineral materials.

Electronic/mechatronic linear actuators or other controlled actuators could in principle emulate the interaction between tool and base. In practice, the high impact forces and very short strokes characteristic of demolition hammers impose stringent demands on structural stiffness and dynamics. Electric linear motors lack the required structural stiffness to absorb or dissipate these forces equivalently. Mechatronic concepts are therefore presently of limited suitability for reproducing the physical boundary conditions of a real mineral material.

Hydraulic systems combine high power density with low compressibility of the working fluid. As a result, they can represent both high impact forces and small deformations as observed in hard mineral materials. By adjusting enclosed oil volume and flow resistance, stiffness and damping can be tuned. At the same time, dissipative energy conversion in the fluid provides high repeatability with low wear. The simple adjustability of hydraulic components enables flexible adaptation to different material characteristics, making the system particularly suitable to meet the requirements of equivalent effectiveness, repeatability, adjustability, and wear resistance.

In summary, pneumatic and electric systems can reproduce the stiffness of mineral materials only to a limited extent. Mechanical systems have been developed but are impractical for adjusting damping characteristics and are prone to wear. Hydraulic systems therefore represent the most promising approach to achieve an equivalently effective, adjustable, reproducible, and low-wear substitute base. The following describes hydraulic concepts.

3.3. *Evaluation of possible Arrangement Concepts for Hydraulic Substitute Bases*

Two arrangement concepts were considered and are illustrated using a rotary hammer as an example. The first concept, as shown in Figure 3, is straightforward: the real mineral material is replaced by a hydraulic system consisting of a cylinder and other components. A commercial chisel is clamped in the rotary hammer as the tool. The hammer impacts a hydraulic cylinder via the chisel; the chisel and the cylinder piston are two separate bodies. Advantages include use of tools with original geometry, thus accounting for geometry effects on stress-wave propagation. Tools can be easily exchanged, allowing chisels of different length, diameter, and tip geometry. Another advantage is that the classical coefficient of restitution k can be used as a comparison metric, calculated from the velocities of the colliding bodies:

$$k = \frac{c_2 - c_1}{v_1 - v_2} \text{ [8]} \qquad (3.1)$$

where $v_1 - v_2$ is the relative velocity of chisel and base (i.e., cylinder piston) before impact, and $c_2 - c_1$ is the velocity difference after impact. A disadvantage is the wear at the chisel tip and on the hydraulic piston caused by the high-frequency impacts.

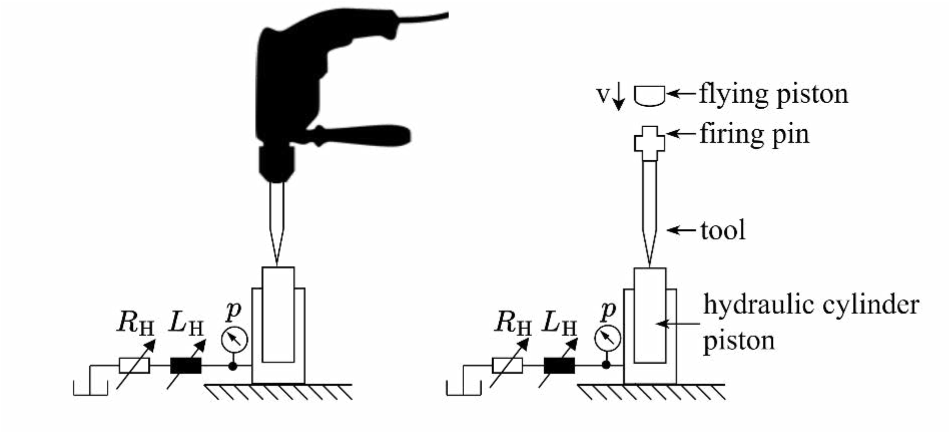

Figure 3: Arrangement concept 1: (left) The rotary hammer strikes a hydraulic cylinder piston with a standard tool; (right) Schematic representation of the relevant impact bodies.

Figure 4 shows the second arrangement concept. It differs from Concept 1 in a way that the tool acts as the cylinder piston. Therefore, no additional contact partner like the hydraulic cylinder piston in Concept 1 is needed. This arrangement has one fewer impact body than Concept 1. A drawback is that a coefficient of restitution according to Eq. (3.1) between tool and base cannot be computed, since the base in this concept is the pressure fluid and its "velocity" is hard to define. However, dissipated energy can be used as a comparison metric alongside penetration depth - specifically the ratio to the initial kinetic energy $\frac{E_{\mathrm{diss}}}{0{,}5 \cdot m_{\mathrm{fp}} \cdot \left(v_{\mathrm{fp}}(t_0)\right)^2}$. Concept 2 requires a custom-built cylinder that allows low-friction movement of the piston in the vertical direction and has a DSH-plus mount at the top. Cylindrical grinding can be used to produce a precisely fitting gap seal that is both low-friction and low-leakage. This eliminates the need for a friction-prone and flexible elastomer seal. The tool can be supported radially at the top and bottom to absorb radial forces transmitted by the rotary hammer.

Concept 2 is selected because of the advantage that the energy of the chisel is directly transferred to the hydraulic system, and a defined part of this energy is reflected back to the chisel. There is no additional contact partner. Due to the larger number of bodies between the flying piston and the hydraulics in Concept 1, more reflections of the incoming stress wave occur before they reach the hydraulics. With Concept 2, the impact characteristics can be influenced more directly by varying hydraulic parameters.

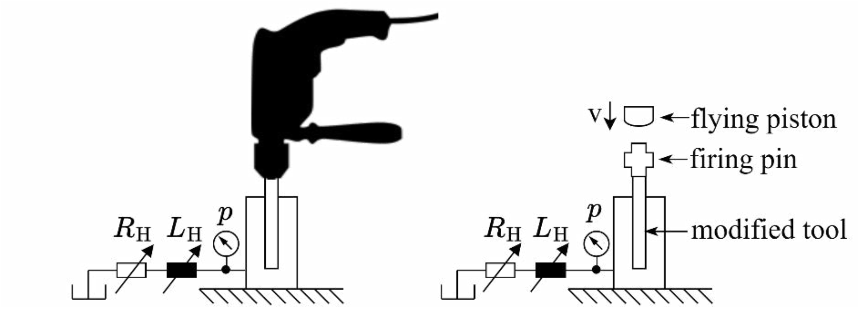

Figure 4: Arrangement concept 2: (left) The rotary hammer tool also functions as a cylinder piston; (right) Schematic representation of the relevant impact bodies of the rotary hammer.

4. HYDRAULIC SUBSTITUTE BASE

4.1. *Components of a Hydraulic Substitute Base*

A hydraulic substitute base for demolition hammers reproduces the mechanical interaction between tool and mineral material via a hydraulic system. The goal is to replicate the forces, displacements, and energy flows occurring during the impact process in an equivalently effective manner. The hydraulic substitute base can be described as a combination of hydraulic capacitance, hydraulic resistance, and hydraulic inductance. These elements determine the system's stiffness, damping, and inertia characteristics. [6] Their interplay allows the complex behavior of mineral materials to be replicated in an equivalently effective way; by varying these parameters, both stiffness and dissipated energy can be precisely adjusted. A hydraulic substitute base thus provides an adjustable, reproducible, and low-wear foundation for studying and developing percussive tools.

4.1.1. Hydraulic Capacitance

The hydraulic capacitance with elastically expanding vessel walls C'_H measures the compliance of a pressure chamber considering both fluid compressibility and wall elasticity: $C'_\mathrm{H} = -\frac{\mathrm{d}V}{\mathrm{d}p}$ [9]. Where $\mathrm{d}V$ is the volume change resulting from a pressure change $\mathrm{d}p$. It holds that $C'_\mathrm{H} = \frac{V}{K'}$ [9]. Where V is the chamber volume and K' the effective bulk modulus including both fluid compressibility K and wall elasticity [9]. Because the impact acts on a fluid in a hydraulic substitute base, at least one hydraulic capacitance is present. Low hydraulic capacitance leads to high stiffness and thus small tool displacements at high impact forces - behavior typical of hard rock. Larger capacitance produces a softer characteristic with greater penetration and lower peak pressures.

Figure 5 shows the penetration characteristic of a flat chisel clamped in a rotary hammer impacting concrete. The median penetration is 0.4 mm, with the maximum depth reached after 0.17 ms. Scatter during the intrusion phase is low. Using the co-simulation described in [6], a required hydraulic capacitance of $C'_\mathrm{H} = 4.4 \cdot 10^{-16}\ \frac{\mathrm{m^4 \cdot s^2}}{\mathrm{kg}}$ was determined to achieve the same penetration depth without damping. In the simulation, the elasticity of the walls and possible gas components in the liquid were neglected: $K' = K$.

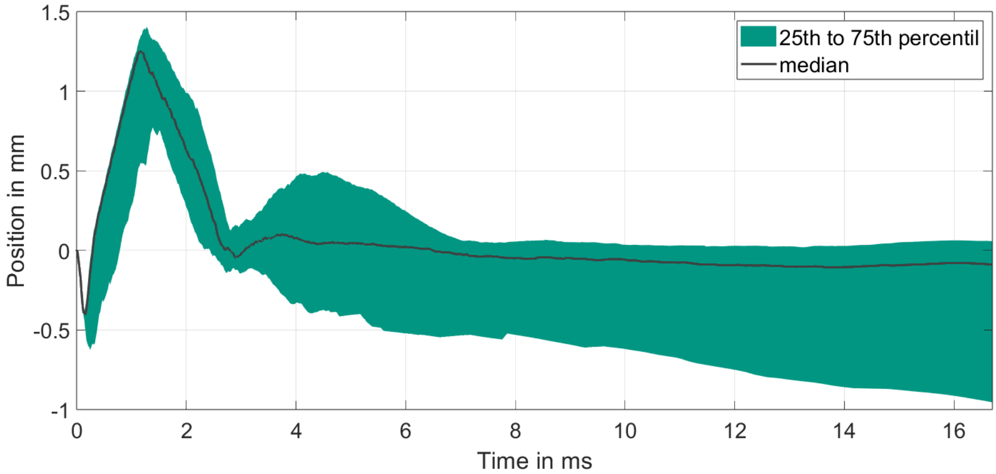

Figure 5: Displacement profile of 172 impacts of a rotary hammer with 4.2 J impact energy (Bosch GBH 4-32) on concrete C50/60 with 150 N feed force, recorded with a vibrometer.

The hydraulic capacitance can be practically varied via the adjustable oil volume to emulate different material stiffnesses. For mineral oils ($K \approx 1.6$ GPa), the volume required to achieve the penetration depth obtained in Figure 5 without damping is 0.7 ml. Softer materials require a larger volume. Harder materials require a smaller volume, which can be challenging to realize from a design standpoint.

If such small volumes are not feasible, a pressure fluid with a higher bulk modulus can be used to achieve the same capacitance at a larger fluid volume. Table 1 lists alternatives to mineral oil with significantly higher bulk modulus and thus higher system stiffness. At the same time, viscosity must be considered due to the precharge system and flow resistances. Very stiff media such as glycerol are highly viscous at room temperature, but blending with water allows adjustment to mineral-oil-like viscosity levels [15]. Replacing mineral oil with an ester fluid (HEES/HFDU, $K \approx 1.9$ GPa), allows the fluid volume to be increased by ~20% for the same capacitance without changing viscosity grade. For maximum stiffness, glycerol–water mixtures are an option. With about 10 wt% water, viscosity can be reduced to mineral-oil-like values ($\nu_{40°C} = 49\,{}^{mm^2}/_{s}$), while largely retaining the high bulk modulus ($K_{40°C} = \rho_{40°C} \cdot (u_{sound,40°C})^2 = 1{,}222.1\,{}^{kg}/_{m^3} \cdot (1{,}862.9\,{}^{m}/_{s})^2 = 4.24$ GPa) [15], [16]. Ionic liquids offer high stiffness and good tribological properties at viscosities similar to mineral oil and are suitable as hydraulic fluids [10]. The bulk moduli in Table 1 refer to the properties of pure liquid. If the liquid contains free or dissolved air, the compression module of the fluid decreases and the hydraulic capacity increases. Figure 6 shows the influence of air on the compression modulus of a mineral oil. At low pressures, the influence of air is greater than at higher pressures. To avoid free air, the system must be carefully vented. It is important to ensure during the design phase that no air pockets can form.

Table 1: Alternatives to mineral oil with higher stiffness

Fluid family	**Bulk modulus**	**Viscosity**
Mineral oil (HLP 46)	$K_{0\text{bar}} = 1.64$ GPa [10] $K_{200\text{bar}} = 1.86$ GPa [10]	$\nu_{40°\text{C}} = 47.07\ \text{mm}^2/\text{s}$ [10] $\nu_{100°\text{C}} = 7.36\ \text{mm}^2/\text{s}$ [10]
HEES (BIO-FR 46, ester fluid)	$K_{210\text{bar}} = 1.87$ GPa [11]	$\nu_{40°\text{C}} = 49.7\ \text{mm}^2/\text{s}$ [11] $\nu_{100°\text{C}} = 9.7\ \text{mm}^2/\text{s}$ [11]
HFDU (between VG 46 and VG 68)	$K_{210\text{bar}} = 1.87$ GPa [12]	$\nu_{40°\text{C}} = 55\ \text{mm}^2/\text{s}$ [12] $\nu_{100°\text{C}} = 12\ \text{mm}^2/\text{s}$ [12]
HFC (VG 46)	$K_{140\text{bar}} = 1.55$ GPa [13] $K_{200\text{bar}} = 1.9$ GPa [13]	$\nu_{40°\text{C}} = 46\ \text{mm}^2/\text{s}$ [14]
Glycerin (≥ 99 %)	$K_{20°\text{C}} = \rho_{20°\text{C}} \cdot (u_{\text{sound},20°\text{C}})^2 = 1{,}261.3\ \text{kg}/\text{m}^3 \cdot (1{,}923\ \text{m}/\text{s})^2 = 4.66$ GPa [15]	$\nu_{40°\text{C}} = 227.39\ \text{mm}^2/\text{s}$ [15] $\nu_{100°\text{C}} = 12.07\ \text{mm}^2/\text{s}$ [15]
Ionic liquids (EMIM-EtSO4)	$K_{0\text{bar}} = 3.1$ GPa [10] $K_{200\text{bar}} = 3.32$ GPa [10]	$\nu_{40°\text{C}} = 39.44\ \text{mm}^2/\text{s}$ [10] $\nu_{100°\text{C}} = 7.66\ \text{mm}^2/\text{s}$ [10]

Another way to reduce penetration depth is to increase the precharge pressure. Simulations have shown that with a precharge of 350 bar, a penetration depth of 0.4 mm can be realized with a volume of 1.5 ml. A positive side effect of increasing the preload pressure is the reduced effect of dissolved air, as shown in Figure 6.

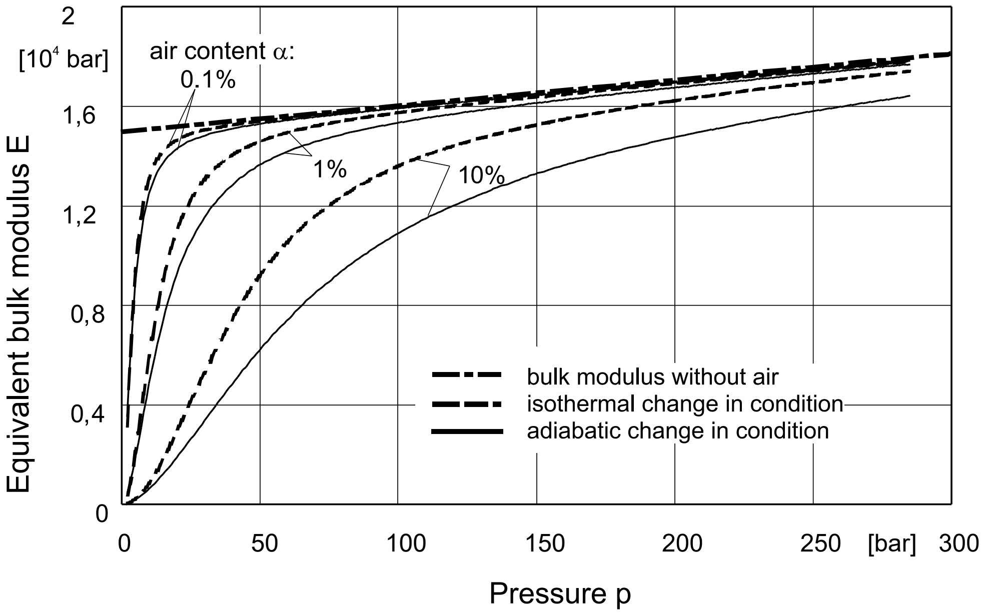

Figure 6: Equivalent bulk modulus of mineral oil-air mixture [17]

Figure 7 shows the measured penetration characteristic in concrete and the simulated penetration characteristic in the hydraulic substitute base for different parameter combinations. In the simulation, the elasticity of the walls and possible gas components in the liquid were neglected: $K' = K$.

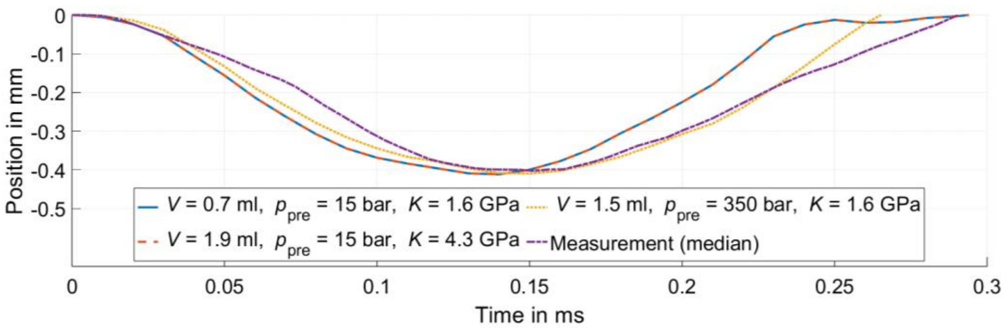

Figure 7: Measured and simulated profiles with identical penetration depth into the base. The cross-section of the orifice in the simulation is set to zero. The hydraulic resistance is therefore infinite. There is also no hydraulic inductance.

4.1.2. Hydraulic Resistance

Hydraulic resistance represents dissipative losses in the system and determines damping of the pressure history. It can be realized via orifices or throttles whose cross-section influences the outflow and thus pressure history. Compared with throttles, orifices show viscosity-

/temperature-independent flow behavior assumed turbulent flow occurs. As the orifice cross-section increases, energy absorption increases. Targeted adjustment of hydraulic resistance therefore allows tuning of the damping characteristic to different rock types. According to the guideline on the Dynaload steel ball energy absorber cited in DIN EN ISO 28927-10, about 15%– 20% of the impact energy in real materials is reflected back to the tool (rotary hammer) [3]; the remainder is dissipated in the base. Simulations have shown that, for 17% of the impact energy to be reflected back to the tool at a penetration depth of 0.4 mm, an orifice cross-section of 1.1 mm^2 and an oil volume of 0.3 ml are required.

4.1.3. Hydraulic Inductance

Hydraulic inductance describes the inertia of the fluid flow and is directly related to the moving fluid mass. It is determined by the geometry and length of the line as well as the fluid density. High hydraulic inductance affects pressure build-up in the system and causes a phase shift between force and displacement. This allows influencing the impact dynamics, particularly the temporal evolution of energy transfer between tool and substitute base. Due to the required low hydraulic capacitance, it is possible only to a limited extent to integrate inductances intentionally between capacitance and resistance. The additional line volume would simultaneously increase capacitance. A long pipeline with a small cross-section would also exhibit significant temperature dependence due to viscosity.

5. SUMMARY, DISCUSSION AND OUTLOOK

The paper demonstrates the advantages of a hydraulic substitute base for demolition hammers as an adjustable, low-wear, and highly reproducible alternative to conventional mechanical test bases. A coupled FEM–hydraulic co-simulation is used to identify the hydraulic capacitance and resistance required to replicate the penetration depth and energy absorption of concrete C50/60. This approach enables a material-realistic and transferable testing methodology for the development and assessment of demolition hammers.

Based on the requirements and mechanisms derived in this work, a prototype hydraulic substitute base will be designed, built, and instrumented. The challenge here is to achieve high stiffness. When using conventional pressure fluids in the design, the oil volume must be limited to 1.5 ml. If this is not possible for design reasons, a combination of alternative pressure fluids and a pressure preload can be used to increase the permissible volume. At the same time, care must be taken to ensure that the wall elements are constructed stiffly. One way to ensure high stiffness would be to manufacture the cylinder bore, as well as the bores for the pressure sensor and aperture, from a solid steel block. This eliminates the need for voluminous and elastic pipes or hoses. Consequently, the volume can be kept to a minimum. Keeping the pressure fluid chamber free of air is also challenging. The goal is to experimentally confirm the displacement and energy curves determined in co-simulation and to verify the identified adjustment ranges. If validation succeeds, the setup can serve as an adjustable, repeatable, and low-wear alternative to the Dynaload steel ball energy absorber and extend its scope of use, especially for material-specific studies. In addition, development of a larger hydraulic test rig is planned to enable testing of hydraulic breakers.

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