Characterization of impact-induced fracture in copper ore specimens using compact instrumentation as an alternative to the Hopkinson bar method for application in discrete element breakage models

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Abstract. Comminution accounts for 36% of a mining operation's energy consumption and is indispensable for extracting copper from its ore. Optimizing this stage requires measuring specific primary breakage energy under representative dynamic loading conditions. However, reference single-particle testing devices based on Hopkinson bars are often expensive and difficult to replicate, which limits the generation of comparable data. In this work, a compact drop-weight test rig is built and instrumented with a piezoelectric force sensor and a load cell. In addition, a reference long rod with strain gauges (based on Hopkinson bars) is built, and the measurements are benchmarked against it. Cylindrical copper ore and cement-based specimens with diameters between 7 and 13 mm are prepared with an aspect ratio of 1:1. Impacts are carried out at impact speeds between 1.0 and 1.5 m/s, while maintaining identical conditions, including material type, specimen geometry, impact energy, and striker shape. A total of 336 tests are conducted on copper ore and 252 on cement-based samples. The primary breakage energy is successfully measured using the three measurement systems, and it is shown that the most portable systems allow the measurement of primary breakage energy without a significant loss of accuracy.

1. Introduction

Copper is an indispensable material for technologies associated with electrification, power transmission, and electromobility, which is driving a sustained increase in global demand [1-3]. To produce copper from its ore, comminution is required, and it constitutes a critical stage due to its high energy consumption, accounting for 35–50% of the total energy used in a mining operation, equivalent to about 1.3% of global electricity consumption [4,5]. Therefore, improving comminution efficiency requires a more accurate understanding and quantification of the fracture mechanisms occurring at the single-particle scale.

The size reduction of particulate materials originates from microscopic events of crack initiation and in particular, primary breakage—understood as the first macroscopic rupture event that produces appreciable fragmentation of a particle under dynamic loading [6]—is relevant because it defines a physical threshold at which the applied energy begins to be converted into the creation of new surfaces [7]. Accordingly, the energy absorbed up to the instant of primary fracture is a key quantity to characterize the mineral response and to inform or validate breakage models in numerical simulations [6,10].

Reliable measurement of dynamic loads and energy in high-rate impacts has traditionally been addressed using instrumented configurations such as Hopkinson bars and high-frequency load cells (Ultra Fast Load Cell, UFLC), which provide high temporal fidelity and have been widely used for dynamic characterization [10,11]. However, their implementation requires large-scale infrastructure (on the order of 3–5 m long) and strict alignment and calibration procedures, which prevents their use as portable or in-situ characterization tools and concentrates testing capabilities in a handful of dedicated facilities. In response to these limitations, compact instrumentation alternatives have emerged, including piezoelectric sensors and reduced-size load cells, which promise portability and ease of implementation without sacrificing access to high-frequency signals [11-14].

Despite these advances, a gap remains, there is a lack of consistent experimental evidence comparing specific primary breakage energy under dynamic conditions obtained with compact instrumentation against reference configurations [11], while keeping identical conditions such as material type, geometry, impact energy, striker shape, size, and sampling rate. In this context, this work proposes an experimental methodology to quantify the response associated with primary breakage in individual copper ore specimens using compact instrumentation consisting of a piezoelectric force sensor (PFS) and load cells (LC), assessing its performance as a practical alternative to standard systems [7], namely based on strain-gauge with a long rod (LRSG), and its potential

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application in the calibration/validation of breakage models within the discrete element method.

2. Method

2.1. Materials

Two materials will be used: copper ore and cement-based samples. Homogeneous material such as cement-based will be used first to compare the different test benches (LC vs PFS vs LRSG) changing with four impact velocity while keeping the impact energy constant using four steel spheres with different masses M_s as reported in Table 1. The diameter of the ball is d_s, the drop height is h, and the impact velocity is v.

Table 1. Configurations to achieve a constant impact energy.

d_s [cm]	M_s [kg]	h [cm]	v [m/s]
7.32	1.588	11.1	1.48
7.96	1.955	9.0	1.33
8.59	2.395	7.4	1.20
9.23	3.050	5.8	1.07

In cement-based tests, a single specimen diameter of 13 mm will be selected. Twenty-one tests with cement-based will be performed at each impact velocity and each measurement system giving a total of 252 tests. The samples of cement-based are cast in 3D-printed molds to obtain a cylindrical shape, as presented in Figure 1.

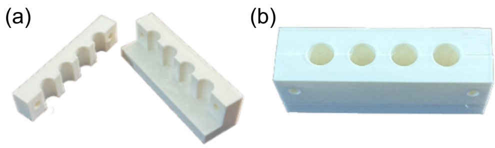


Figure 1. 3D printed mold for the manufacture of cement-based samples: (a) Parts of mold, (b) 3D mold.

Figure 2 shows the manufacturing methodology for copper ore samples. The first step is to cut it into 25 mm-thick slabs to ensure stability while scoring with a hole saw to obtain cylindrical geometry. For copper ore and cement-based materials, the samples must be trimmed with an angle grinder to achieve an aspect ratio of 1:1; then, each specimen will be weighed.

For the copper ore are selected four diameters for the samples, and four impact velocities of the striker with the same considerations maintaining of the impact energy constant, the summary of configuration shows in

Table *2*.

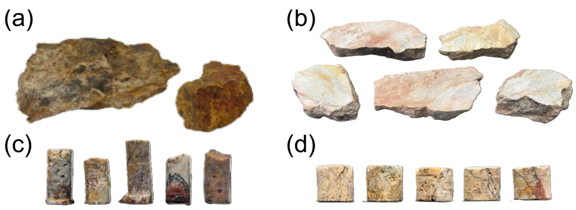


Figure 2. Steps for manufacturing the samples of copper ore: (a) Run-of-mine copper ore, (b) ore cutting in slabs, (c) cylindrical samples, (d) samples with aspect ratio 1:1.

Table 2. Configurations for the test of samples copper ore.

	Diameter [mm]			
v [m/s]	**7**	**9**	**11**	**13**
1.48	21	21	21	21
1.33	21	21	21	21
1.20	21	21	21	21
1.07	21	21	21	21
			Total	336

2.2. Tests bench

The reference test bench is a long bar instrumented with strain gauges, as shown in Figure 1. The design is based on other test bench available in the literature [3]. The bar is made of ASTM 4340 steel, measures 3.05 m in length and has a diameter of 25.4 mm. The measurement is performed with semiconductor strain gauges, model KSPH-4-2K-E4 from Kyowa and with a Picoscope 5442D oscilloscope measuring at 8 MHz.

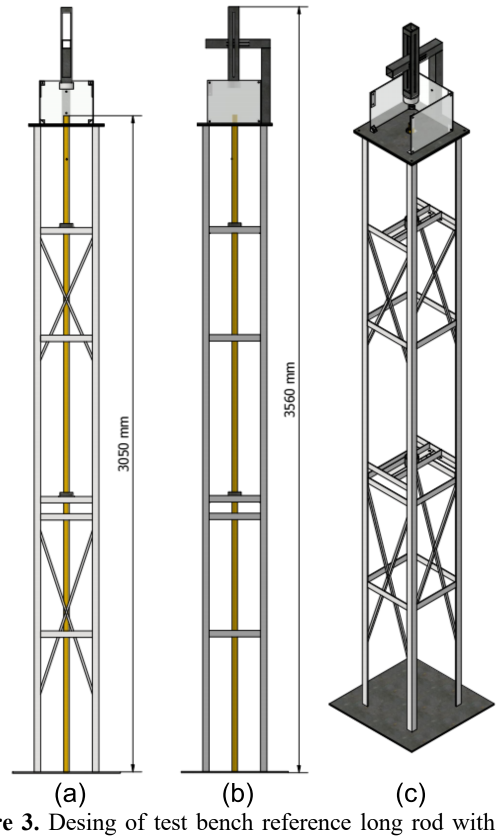
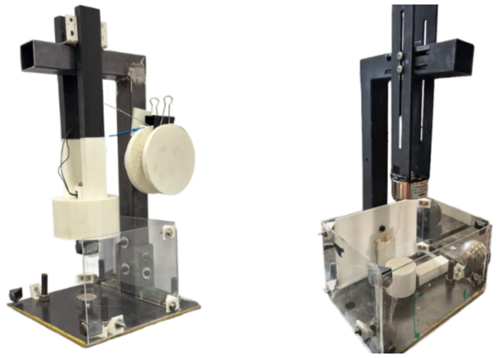


Figure 3. Desing of test bench reference long rod with strain gauges (LRSG). (a) Front view. (b) Side view. (c) Isometric view.

The compact versions of the test benches are based on measurement with commercial load cells, and can use either, the DYMH-102 load cell of 2000 kg or PCB 208C05 piezoelectric force sensor of 5000 lb, as shown in Figure 4. The release system of the steel ball is the same of the LRSG.



(a) (b)

Figure 4. Proposed compact test bench to measure primary breakage energy. (a) Piezoelectric PCB 208C05. (b) Load cell DYMH-102.

2.3. Primary breakage energy

In both the reference system and the proposed compact system, the primary breakage energy cannot be directly measured. 5 Figure 5 shows a diagram of the tests to be performed. In (a) the initial moment is shown where the steel ball is at a height h_i, and in (b) the moment of impact is shown, where the ball is in contact with the sample and the primary fracture is generated. To calculate the primary breakage energy, an energy balance is performed on the system, as presented in the following equation:

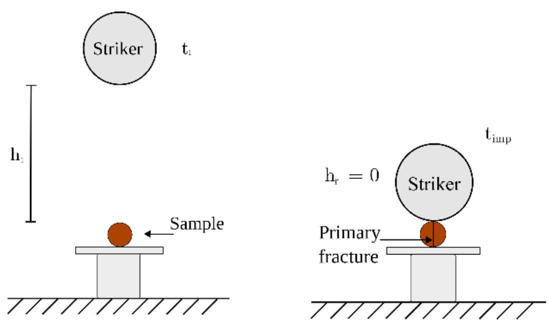
$$E_{i,p} = E_{i,r} + E_c + E_m \tag{1}$$

where $E_{i,p}$ is the potential energy of the steel ball before the impact, $E_{i,r}$ is the potential energy of the steel ball after the impact; i.e. the energy that the ball retains after the impact, E_C is the energy absorbed by the load cell (or force sensor) obtained from the measurements, and E_m is the energy absorbed by the sample up to the moment of the fracture, namely, primary breakage energy.

For the case when the LRSG is used, the energy balance equation can be calculated as [9]:

$$E_m = v_0 \int_0^{t_c} F(\tau)d\tau + g \int_0^{t_c} F(\tau)\tau d\tau - \frac{1}{2m_b}\left(\int_0^{t_c} F(\tau)d\tau\right)^2 - \frac{1}{\rho_r A_r C_r}\int_0^{t_c} F^2(\tau)d\tau \tag{2}$$

In the case of LC and PFS, the calculation is performed using the impulse absorbed by the sensor.



(a) (b)

Figure 5. Impact load cell. (a) Start of the test. (b) Time at which the primary fracture occurs.

3. Preliminary results

Figure 6 shows impact test results using PFS and copper ore. Force versus time graphs are shown, identifying the start of the impact and the instant of the primary breakage.

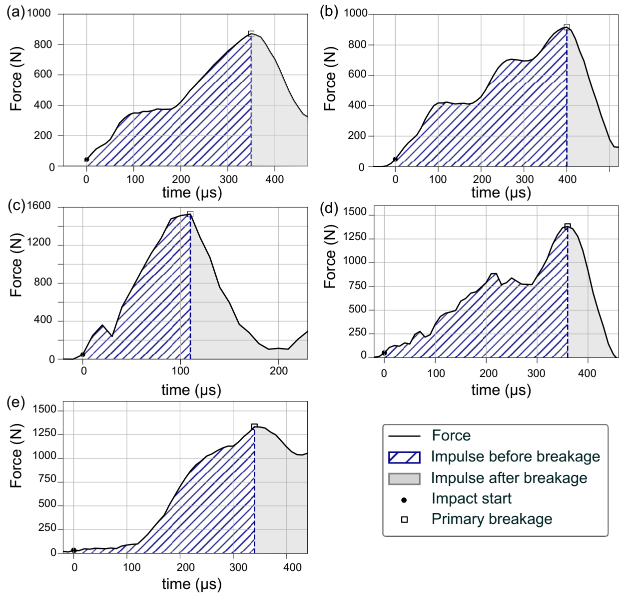


Figure 6. Impact load cell using PFS for different copper ore samples tested at 1.4 m/s using (a-b-c), and 1.08 m/s (d-e) with a diameter of 13 mm. (a) Test 45. (b) Test 49. (c) Test 53. (d) Test 80. (e) Test 85.

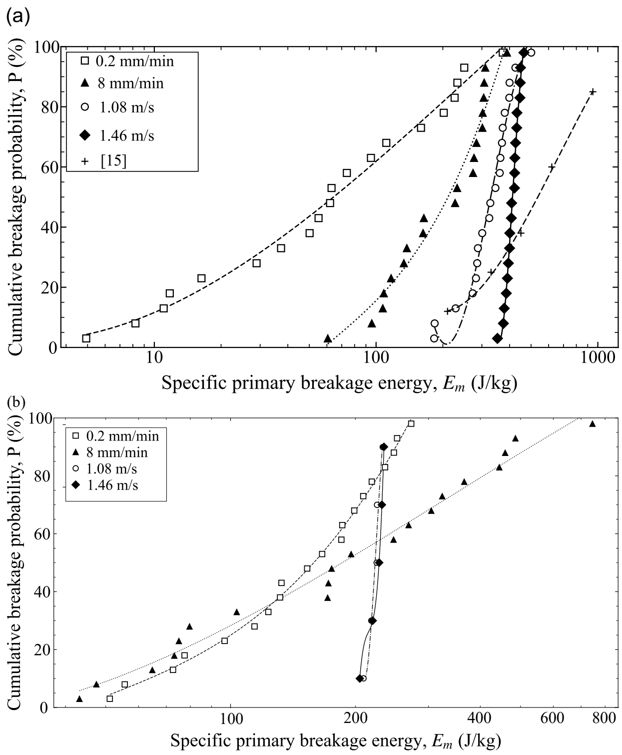


Figure 7. Specific primary breakage energy of copper ore versus its primary fracture probability tested at different impact and compression velocities. (a) 13 mm diameter samples compared with literature [15]. (b) 7 mm diameter.

Tests were conducted at different speeds as shown in Figure 7 for both diameters to demonstrate the influence of impact velocity on specific primary breakage energy.

4. Conclusions

A compact drop-weight test rig instrumented with a piezoelectric force sensor (PFS) and a load cell (LC) was designed, manufactured, and benchmarked against a long rod strain-gauge system (LRSG) based on Hopkinson-bar principles. The compact system reliably captures the force-time signature to primary fracture in a single copper-ore specimens and is approximately three times cheaper to build than outsourcing equivalent testing services, making it suitable for laboratories with limited structures.

Preliminary measurements on 130 copper-ore specimens (80 at d = 13 mm and 50 at 7 mm) confirm a clear dependence of specific primary fractured energy on impact velocity in the 1.07-1.48 m/s range. The median breakage energy E_{50} obtained with the PFS increased from 327 J/kg at 1.08 m/s to 408 J/kg at 1.46 m/s for 13 mm samples and reached values up to 8 times higher than those obtained under quasi-static compression at 0.2 mm/min (62 J/kg) using a Zwick Roell Z005. At the lower-velocity end, the measured E_{50} for 13 mm samples agrees within 2% with the value of 333 J/kg predicted by the breakage model of Tavares et al. [16].

The proposed methodology provides a portable and reproducible route to generate the size and rate dependent in breakage energy distributions required to calibrate and validate single-particle breakage models within the discrete element method. The remaining test on copper ore and cement-based, together with the full LC vs PFS vs LRSG cross-validation under identical conditions, are currently in progress and will allow quantifying the relative accuracy of each compact system against the strain-gauge reference, which is the central hypothesis of this study.

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References

[1] Valero, A., Valero, A., Calvo, G., Ortego, A. (2018) Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev., 93, 178–200.

[2] Soares, A.F., Spers, R.G., de Oliveira Santos Jhunior, R. (2025) Projection of global copper demand in the context of energy transition. Resour. Policy, 103, 105567.

[3] Schipper, B.W., Lin, H.C., Meloni, M.A., Wansleeben, K., Heijungs, R., van der Voet, E. (2018) Estimating global copper demand until 2100 with regression and stock dynamics. Resour. Conserv. Recycl., 132, 28–36.

[4] Ballantyne, G.R., Powell, M.S. (2014) Benchmarking comminution energy consumption for the processing of copper and gold ores. Miner. Eng., 65, 109–114.

[5] Jeswiet, J., Szekeres, A. (2016) Energy consumption in mining comminution. Procedia CIRP, 48, 140–145.

[6] King, R.P., Bourgeois, F. (1993) Measurement of fracture energy during single-particle fracture. Miner. Eng., 6, 353–367.

[7] Tavares, L.M., King, R.P. (1998) Single-particle fracture under impact loading. Int. J. Miner. Process., 54, 1–28.

[8] Wang, J., Zhou, L., Liu, S., Deng, Z., Cao, Z., Li, P. (2025) An advanced calibration technique for contact parameters in ball milling DEM simulations. Powder Technol., 454, 120716.

[9] Tavares, L.M., King, R.P. (2004) Measurement of the load–deformation response from impact-breakage of particles. Int. J. Miner. Process., 74, S267–S277.

[10] Yang, Y., et al. (2023) Review of SHPB dynamic load impact test characteristics and energy analysis methods. Processes, 11, 3029.

[11] Li, P., Liu, S., Wang, Y., Deng, Z., Wang, J., Cao, Z. (2024) A new device and calibration method for the fracture energy testing of single-particle impact. Powder Technol., 445, 120142.

[12] Barbosa, K., Esterle, J., Bonfils, B., Chen, Z. (2019) The use of short impact load cell to derive geomechanical properties of sub-bituminous coal and mudstone. J. Nat. Gas Sci. Eng., 72, 103018.

[13] Bourgeois, F.S., Banini, G.A. (2002) A portable load cell for in-situ ore impact breakage testing. Int. J. Miner. Process., 65, 31–54.

[14] Lois-Morales, P., Evans, C., Weatherley, D. (2021) Characterising tensile strength and elastic moduli of altered igneous rocks at comminution scale using the Short Impact Load Cell. Powder Technol., 388, 343–356.

[15] Tavares, L.M., André, F.P., Potapov, A., Maliska, C. (2020) Adapting a breakage model to discrete elements using polyhedral particles. Powder Technol., 362, 208–220.