

Under pressure: poroelastic regulation of flow in espresso brewing

Radost Waszkiewicz^{1,2}, Franciszek Myck³, Łukasz Biały³, Maria Puciata-Mroczynska^{1,3}, Michał Dzikowski³, Piotr Szymczak^{1,3} and Maciej Lisicki^{1,3,*}

¹*Institute of Physics and Astronomy, University of Potsdam,
Karl-Liebknecht-Strasse 24/25, 14476 Potsdam-Golm, Germany*

²*Laboratory of Biological Physics, Institute of Physics,
Polish Academy of Sciences, 02-668 Warsaw, Poland*

³*Faculty of Physics, University of Warsaw, L. Pasteura 5, 02-093 Warsaw, Poland*

(Dated: December 29, 2025)

The sensory richness of coffee is widely recognised and arises from the complex chemistry and immersion in cultural practices of coffee preparation. In contrast, the physical complexity of espresso has received less attention. The multiphase reactive flow through a dissolving, elastic porous medium remains challenging to describe. Using a controlled experimental setup based on a café-grade espresso machine, we demonstrate that the interplay between elasticity and porosity governs the long-time flow rate during espresso extraction and, consequently, the concentration of solubles in the final beverage. We introduce a minimal model that captures the resulting non-linear pressure–flow relationship and propose a methodology capable of reproducing the time-dependent behaviour of the espresso brewing process. Finally, we show that dissolution dynamics play a central role in determining the temporal evolution of flow during extraction.

I. INTRODUCTION

Espresso is a relatively recent addition to the long and diverse history of coffee preparation. Its emergence is traced back to the early 20th century [1], in response to the growing demand for quick and concentrated coffee beverages [2, 3]. While earlier methods, such as the cezve (or ibrik) used in the Ottoman Empire or filter-based devices popularised in European cafés, relied on extended steeping times or gentle percolation, espresso introduced a new paradigm based on pressure-driven extraction. Since its invention, espresso has evolved not only into a distinct brewing technique but also into a cultural phenomenon, particularly within the Italian caffè culture, where its preparation has acquired an almost ritualistic significance. The technical differences between all these methods lead not only to different sensory profiles, but also a different extraction efficiency and chemical composition of the final beverage [4].

Among the many methods of coffee preparation, espresso remains particularly complex and often mystifying. Despite the apparent standardization of equipment and ingredients, espresso shots – even brewed from the same coffee batch – can vary significantly in taste and quality [5]. This variability is not merely anecdotal; it reflects the sensitivity of the espresso brewing process to a range of physical parameters, including the grind size [6, 7], water pressure [8], water quality and alkalinity [9], temperature [10, 11], and flow rate. The extent to which this variability influences the final beverage helps explain why the underlying physics of the brewing process remains an open and active area of research.

To brew an espresso, one typically uses finely ground coffee [6, 12, 13], through which hot water is forced at

high pressure, commonly around 9 bar. This pressure standard is often traced back to the force achievable in the first lever-operated espresso machines, most notably the Gaggia and Faema machines of the late 1940s and early 1950s [2, 5]. Over time, a wide array of devices and tools have been developed to aid espresso preparation, promising improved consistency, efficiency, or flavour. However, determining the true performance of such devices remains difficult, complicated by the subjective nature of sensory perception and the level of technical expertise and tools needed to assess brew quality.

Efforts to address these challenges have led to initiatives aimed at developing more objective and reproducible descriptors of coffee flavour and aroma. Notable among these are the World Coffee Research Sensory Lexicon [14], the Specialty Coffee Association’s standards for espresso brewing [15], and protocols for evaluating various aspects of coffee quality, as well as the widespread Coffee Taster’s Flavour Wheel [16]. These initiatives strive to bring rigour and reproducibility to a domain often clouded by marketing language and anecdotal expertise, while also promoting greater equity in the coffee value chain by enabling producers, particularly in origin countries, to better demonstrate the quality of their coffee and access premium markets through standardised, transparent assessment criteria.

To explore the multi-scale and multi-physics dynamics of dissolving coffee bed, continuum models have been proposed for the transport of solubles and fine coffee particles [6, 12, 17–20], often combined with numerical simulations (smoothed dissipative particle dynamics, finite element method, or lattice Boltzmann models) to incorporate the effects of swelling [21], chemical erosion [19, 22], or their interplay [18, 23]. Uneven erosion can lead to the formation of channels [19] and uneven extraction [24], an undesirable process in the coffee industry.

A separate category of studies focusses on visualis-

* mklis@fuw.edu.pl

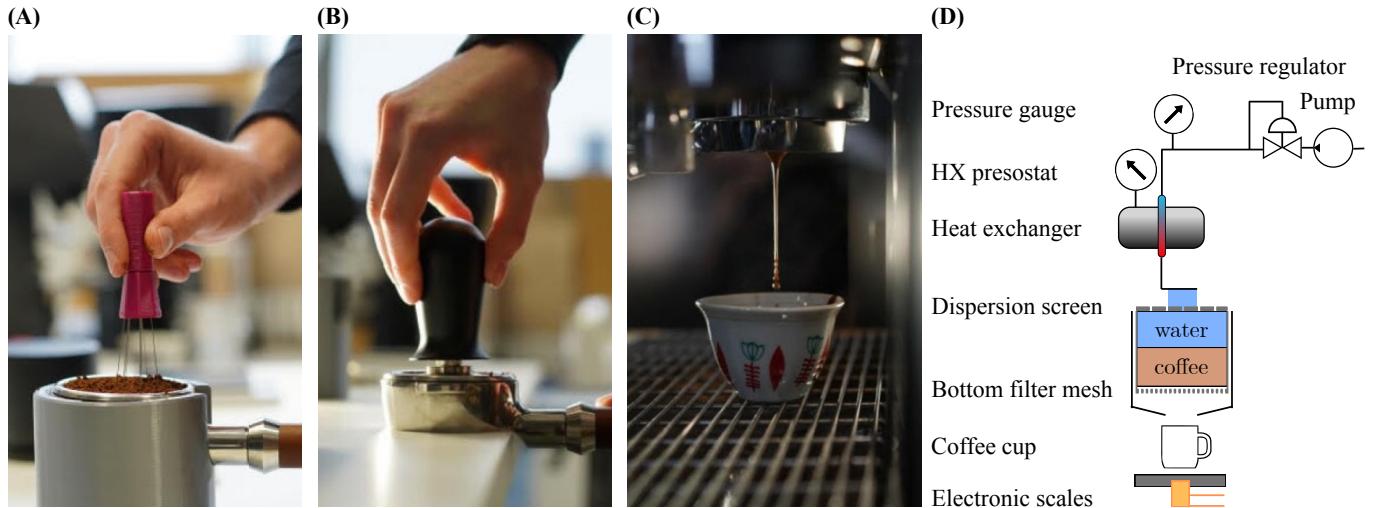


Figure 1. The espresso brewing process. First the weighed grounds are placed in the brewing chamber (called portafilter), then clumps are removed with a needle tool (panel (A), necessary for good reproducibility). Then the grounds are tamped level with a tamper (panel (B), manual tamper pictured for demonstration only) to ensure consistent preparation pressure, the espresso can then be brewed (panel (C)). (D) Simplified diagram of the heat exchange espresso machine (typical for commercial caf  s). Water flows from the pump via pressure regulator and flow meter, then through a heat exchanger (large amount of water in a boiler is kept at high temperature (typically 200 °C) ensuring repeatable conditions) and into the brewing group. Inside the brewing group the water passes through a shower screen then the coffee grounds and filter basket sieve. Finally coffee ends up in the cup resting on digital scales. Data from digital pressure gauge, flow meter and scales were collected simultaneously.

ing and examining the structural changes accompanying the brewing, where X-ray computer tomography (CT) proves useful. By comparing the microCT images of pre- and post-extraction coffee matrices, Mo et al. [21] found that a decreasing porosity profile (from the bottom filter to the top of the puck) always develops after extraction, which can be explained their earlier model of pressure-dependent erosion [22]. Recently, Foster et al. [25] used time-resolved CT to track the infiltration front of the water into the dry coffee bed, and proposed a one-dimensional unsaturated porous medium flow model to explain the dynamics of initial wetting.

Since the preparation of an espresso in a pressurised container requires a consolidated bed of finely ground coffee, an intuitive modelling choice to quantify the flow would be a Darcy-like approach with assumed constant bed permeability, used in multiple studies of coffee brewing. In earlier studies, Darcy's law coupled with a migration mechanism for fine coffee grounds has been found to explain some of the espresso flow characteristics [17], but with limited experimental validation. Corrochano et al. [26] reported Darcy-like behaviour of coffee (with phenomenological permeability) for low pressures (< 5 bar). In filter brew coffee, the flow is driven by hydrostatic pressure, and Darcy's law has been successfully used to predict the dynamics [12], and has been employed to model a related problem of moka pot brewing [27–29]. In brewing espresso, Darcy's constitutive law was also proposed to estimate the strength of the coffee shot and extraction time [6], and develop multi-physics models [20].

However, due to the complex nature of the brewing process, it is difficult to identify the sole effect of pressure on the resulting flow response of a coffee bed. We address this question by a combination of theoretical modelling and experimental validation. We propose a theoretical model for the long-time poroelastic deformation of the coffee puck and later expand it to describe the effect of temporal evolution of the porosity upon dissolution. We perform experiments on espresso brewed in a conventional, caf  -grade espresso machine, in a range of parameters following the industry standards and preparation protocols. We demonstrate the predictive power of our simple model of coffee bed deformation by examining a range of brewing pressures, where Darcy-like, linear response is seen at low brewing pressures (< 5 bar), while the flow saturates as a function of pressure in the standard brewing regime. By performing time-resolved TDS measurements on a typical espresso, we can relate the long-time brewing characteristics to the early stages of brewing, thus elucidating the details of mass transport of solubles into the cup.

The paper is structured as follows. In Sec. II, we describe the experimental details, including the characterisation of coffee samples, puck preparation procedure, details of our brewer and its calibration, measurements of coffee characteristics, and visualisation techniques. In Sec. III, we describe the poroelastic theoretical model. First, we focus on equilibrium, long-time pressure-flow relationship. Then, we extend our theory to include time-dependent effects of coffee bed dissolution seen at earlier times. We describe our results and compare theoretical

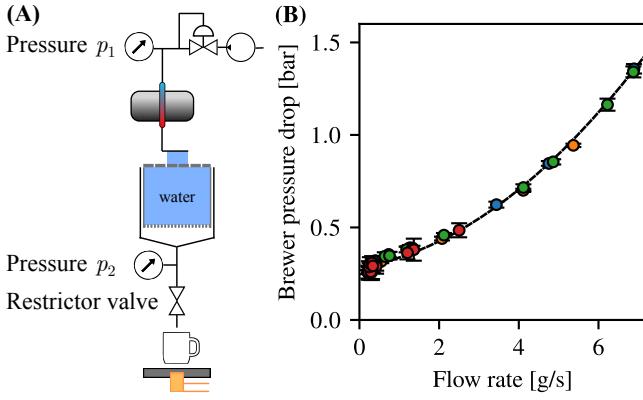


Figure 2. **Brewing assembly pressure drop calibration.** (A) Espresso machine with empty basket with second pressure sensor and control valve added below the portafilter. (B) Combined measurements from multiple series and fitted quadratic approximation. Two with a control valve sweep and two with pressure regulator sweep. Brewer pressure drop depends only on the flow rate through it. Brewer pressure drop, $p_1 - p_2$, as a function of the flow rate can be then used to obtain basket pressure from driving pressure.

predictions to the experimental measurements in Sec. IV, followed by a more detailed discussion in Sec. V. We conclude the paper in Sec. VI.

II. EXPERIMENTS

A. Coffee Samples

The coffee used in all measurements was a single origin specialty grade coffee from the Igarape region of Brazil, roasted by Coffeelab Warsaw. It was a light to medium-light espresso roast, scoring 85.5 as analysed using Le-Brew RoastSee C1 colour analyser.

The espresso preparation method followed the approach devised by Lance Hedrick with the help of Samo Smrke and Jonathan Gagné in [30, 31]. For each brewing process recording, a fixed dose of $m_0 = 18.50 \pm 0.05$ g was ground using Fiorenzato F64 EVO grinder at a setting of 1.9. The grind setting was chosen based on the Specialty Coffee Association recommended brewing speed at 9 bar – 2:1 ratio, that is the desired 37 grams of liquid in a cup to be obtained at 32 seconds, although there is a natural variability of this characteristic. The grounds were transferred into the portafilter after shaking in a Weber Workshops blind shaker for 10 seconds to ensure proper distribution, upon which a 3d-printed WDT-tool (see Fig. 1(A)) equipped with acupuncture needles was used to homogenise the powder distribution in the upper layer of the coffee bed. Next, the puck was tamped with a Perfex CPP-145 58mm Automatic Tamper set to a tamping force of 20 kg, ensuring repeatable tamping force. After such preparation, the coffee was brewed. This puck preparation approach was chosen to conform

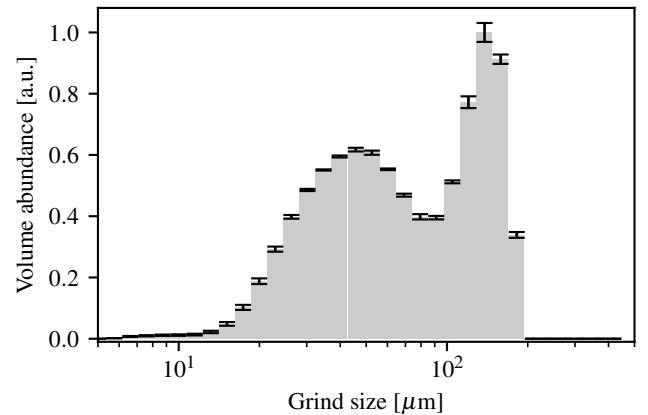


Figure 3. **Particle abundance as a function of size.** The coffee grounds show a characteristic bimodal distribution with smaller component called ‘fines’ of typical size of $50 \mu\text{m}$ and larger grounds of typical size below $200 \mu\text{m}$.

with the current standard within espresso brewing [31].

Ground coffee size distribution is a parameter which is crucial to flow rate and extraction [6, 26]. To facilitate reproducibility of this study we analysed the size distribution of ground coffee, with a laser diffraction method. Data was obtained using Mastersizer 2000 by Malvern for three different samples of the coffee yielding the distribution visible in Fig. 3. The shape follows the typical bi-modal distribution, with a maximum for ‘boulders’ of sizes between 100 – $200 \mu\text{m}$ and a considerable fraction of ‘fines’ of sizes of the order of $50 \mu\text{m}$.

B. Espresso Brewer

For brewing, we used a two-group Sanremo Zoe Competition espresso machine, augmented with a scale under the cup (Hx711 tensometry driver), and a pressure sensor (DFRobot SEN0257), connected to a computer with a custom-built Arduino controller. A schematic illustration of the setup is drawn in Fig. 1(D). This allowed for accurate measurement of the mass of coffee in the cup and water pressure at the pump outlet with a frequency of 10 Hz. The parallel measurement allowed us to determine the precise moment when brewing started, which precedes the first drops falling into the cup by a couple of seconds.

In all experiments presented, coffee was brewed for longer than normally recommended for an espresso shot. We continued brewing each coffee for a prolonged time (typically about 120s) to collect more precise hydrodynamic data. However, this does not affect the first 30–40 seconds of the brewing process required for an espresso. At longer times, we reached the steady state flow profile by pumping water through the espresso puck for 60+ seconds, whilst continuously measuring the mass of liquid that had flowed out of the machine and the driving pressure.

C. Brewer Calibration

To obtain measurements relative to the pressure just above the coffee puck rather than the pressure driving the brewing group assembly, we performed additional calibration measurements with a second pressure sensor placed below the empty brewing basket, followed by a control valve giving variable resistance, as illustrated in Fig. 2(A). We performed several measurement series, varying the control valve setting, as well as the driving pressure regulator. In this way, we found the pressure drop on the brewing group assembly as a function of the flow rate. As shown in Fig. 2(B), the pressure drop follows a quadratic dependence on the flow rate. The non-linear hydrodynamic response of the brewer is associated with the presence of valves. The calibration curve from these measurements was used to compute the basket pressure from the raw (pump) pressure driving the brewing group, and the established relationship was subsequently used in all analyses.

D. Solutes Concentration

To characterise the dissolution process, we measured the TDS (Total Dissolved Solids) [32] using an optical refractometer (VST-LAB coffee refractometer). To obtain time-resolved measurement, we separated an espresso shot into different containers every 5 seconds of the brewing process. The experiment was repeated three times and the results were averaged. In the case of most concentrated brew portions at early brewing times, samples were diluted with distilled water to measurable values of TDS.

E. X-ray Microtomography

To visualise the structure of coffee pucks before and after brewing, we employ X-Ray μ -CT imaging. Radiograms were collected with RX-Solutions EasyTom X-Ray tomograph, at $20\ \mu\text{m}$ resolution. Image acquisition was done with the lamp set to 150kV. Scans were done just before and a couple of minutes after brewing, without removing the coffee cake from the basket.

III. THEORETICAL MODELLING

A. Quasistatic theory

The flow of espresso is a highly nonlinear phenomenon. However, in the long-time regime, when the dissolution process is almost complete, the flow rate through the porous bed of brewed coffee stabilises. Here we establish a relationship between the equilibrium flow rate and the applied pressure in this stable regime using a combination

of the Darcy equation and a poroelastic description of the medium.

Flow through porous media has been classically modelled with the Darcy equation that postulates a linear relationship between apparent flow Q of fluid of viscosity μ through a porous medium layer of cross-section A and thickness L under a pressure difference ΔP , with the proportionality constant k being the permeability. Thus

$$Q = k \frac{A \Delta P}{\mu L}. \quad (1)$$

This approach can be extended to include dissolution and reactions [33]. Deviations from the linear Darcy relationship can be modelled by allowing k to be a local quantity. Since all of the phenomena under consideration depend on pressure gradients only, thus we report all pressures relative to atmospheric pressure. Further, we assume that k depends only on the local porosity of the medium, ϕ , and that its variations across the flow direction are negligible. Introducing the coordinate z along the flow direction, we shall assume that all quantities are functions of z only. The local formulation of Darcy flow in terms of superficial velocity u is thus given by

$$u(z) = \frac{k(\phi(z))}{\mu} \frac{dp(z)}{dz}. \quad (2)$$

We postulate that at a realistic espresso brewing pressure, the coffee bed deforms, and the resulting reduction of inter-pore spaces poses additional resistance to flow. This effect of compactification of the coffee bed has been noted by coffee industry experts [5, 34], but it has never been systematically explored or quantified.

To construct a model that incorporates the interplay between bed permeability and deformation, we build on the ideas outlined by Hewitt et al. [35], who devised it to describe the flow of water through a saturated pack of small, soft, hydrogel spheres, driven by a pressure head. Here, we ignore the hydrostatic gradients, which are ca. 10^4 times smaller than the driving pressure gradient.

In the quasi-static approximation, we assume that the porosity of the coffee bed at any given time is a function of the matrix pressure σ only, so that $\phi(z) = \phi(\sigma(z))$. Since the porous matrix is in mechanical equilibrium, so that the stress field $\sigma(z)$ (porous matrix pressure) inside the coffee bed is given by the Cauchy equation

$$\frac{\partial}{\partial z} (\sigma(z) + p(z)) = 0. \quad (3)$$

This formulation is also called the Terzaghi's effective stress principle in the context of soil and rock poroelasticity [36, 37]. The mass balance of water is given by $u(z) = \text{const.}$

We combine equations (2) and (3) to arrive at a separable equation

$$u = -\frac{k(\phi(\sigma(z))}{\mu} \frac{\partial \sigma}{\partial z}, \quad (4)$$

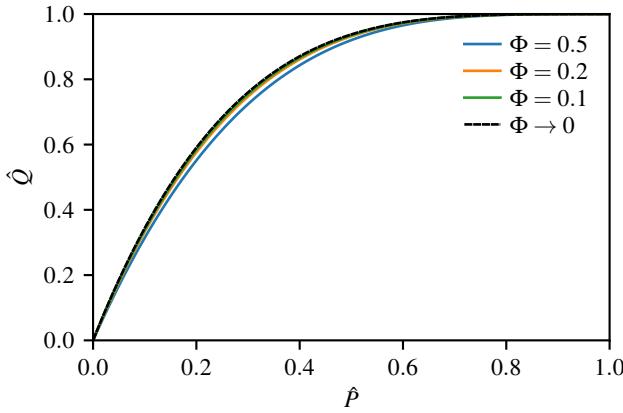


Figure 4. Theoretical equilibrium flow rate as a function of pressure Full theoretical expression (15) for normalised flow rate \hat{Q} as a function of normalised pressure \hat{P} at several values of control parameter Φ together with limit $\Phi \rightarrow 0$. Within the range of possible values of Φ the dependence is negligible.

which we integrate along the coffee bed to get

$$\mu u(h_0 - z) + C = K(\sigma), \quad K(\sigma) = \int_0^\sigma k(\phi(\sigma')) d\sigma' \quad (5)$$

where h_0 is the initial bed height and C is the integration constant. From the free surface condition $\sigma(z = h_0) = 0$ we get $C = 0$. Note that since $k > 0$, K is monotonic and therefore K^{-1} exists and a solution for σ can be written as

$$\sigma = K^{-1}(\mu u(h_0 - z)). \quad (6)$$

Next, imposing $\sigma(z = 0) = P$ at the basket filter mesh, and recalling that $Q = Au$, we find the pressure-flow relationship

$$Q = K(P) \frac{A}{\mu h_0}. \quad (7)$$

Precise computation of k from the porosity ϕ of a medium is a difficult task; We shall assume the phenomenological Carman-Kozeny relationship [38], typically used to approximate the permeability of granular materials, such as sand or glass beads, which yields

$$k(\phi) = \frac{d_p^2}{\kappa} \frac{\phi^3}{(1 - \phi)^2}. \quad (8)$$

where d_p^2 is the effective pore diameter, and $\kappa = 150$ [24, 39].

Finally, we need to relate the matrix pressure with the porosity of the coffee bed. We assume a simplified version

of the constitutive relationship used by Hewitt et al. [35], in which we keep the relationship between the matrix strain e and the porosity ϕ , given by

$$e = \frac{\Phi - \phi}{1 - \phi}, \quad (9)$$

where the stress-free porosity is Φ , and assume a linear, Hookean relationship between the strain and the matrix stress

$$\sigma = Ye, \quad (10)$$

where Y is the Young's modulus. In this description, Φ , Y and d_p are the only material constants.

Using these constitutive laws, we write the permeability $k(\sigma)$ as

$$k(\sigma) = \frac{d_p^2}{\kappa} \frac{(\Phi - \sigma/Y)^3}{(\Phi - 1)^2(1 - \sigma/Y)} \quad (11)$$

which is valid for $\sigma < \Phi Y$. When the pressure exceeds this threshold, the pores close completely.

Introducing dimensionless pressure $P^* = P/Y$, and using Eq. (11), we rewrite the solution of Eq. (7) in the dimensionless form

$$Q \frac{\kappa \mu h_0}{Y Ad_p^2} = (1 - \Phi) \log(1 - P^*) + \frac{P^* (6 + 18(\Phi - 1)\Phi + 3P^*(1 - 3\Phi) + 2(P^*)^2)}{6(1 - \Phi)^2} \quad (12)$$

Superficially, Eq. (12) is a function of three parameters: reference flow rate $Q_{\text{ref}} = Y Ad_p^2 / (\mu h_0)$, Young's modulus Y and the porosity Φ . A closer examination, however reveals that a combination of these parameters has a negligible influence on the pressure-flow relationship. To demonstrate that, we parametrise Eq. (12) by scaling P and Q by their maximal allowed value, so that

$$\hat{P} = \frac{P}{Y\Phi}, \quad \hat{Q} = \frac{Q}{Q_m(\Phi)}. \quad (13)$$

The maximal flow is given by

$$\begin{aligned} Q_m(\Phi) &= \\ &= \frac{Ad_p^2 Y}{\kappa \mu h_0} \frac{\Phi(\Phi(11\Phi - 15) + 6) - 6(\Phi - 1)^3 \log(1 - \Phi)}{6(\Phi - 1)^2} \\ &= Q_{\text{ref}} F(\Phi), \end{aligned} \quad (14)$$

where we defined the characteristic flow rate $Q_{\text{ref}} = Ad_p^2 Y / \kappa \mu h_0$. Then, Eq. (12) takes the form

$$\hat{Q} = \frac{6(\Phi - 1)^3 \log(1 - \hat{P}\Phi) + \hat{P}\Phi \left((9\hat{P} - 2\hat{P}^2 - 18)\Phi^2 + (18 - 3\hat{P})\Phi - 6 \right)}{6(\Phi - 1)^3 \log(1 - \Phi) + \Phi((15 - 11\Phi)\Phi - 6)}. \quad (15)$$

As shown in Fig. 4, the dependence of \hat{Q} on Φ for a given value of \hat{P} is negligible. This result can be further understood by the examination of the series expansions of the logarithmic terms up to the fourth order. We are thus free to take the limit of $\Phi \rightarrow 0$ in Eq. (15), to arrive at a simplified expression

$$\hat{Q} \approx \hat{P}(4 - 6\hat{P} + 4\hat{P}^2 - \hat{P}^3) \quad (16)$$

without a noticeable loss of precision. Therefore, Eq. (16) represents the universal shape of the long-time flow-pressure curve, independent of the value of initial bed porosity. We can use this form to determine the calibration pressure $P_c = P_m(\Phi_m)$ and calibration flow $Q_c = Q_m(\Phi_m)$, corresponding to the stress-free equilibrium value of porosity of the dissolved bed. The calibration values can be used to compare model results with experiments even without explicit knowledge of the value of Φ_m .

B. Time-dependent model for early stages of brewing

To describe the time-dependent flow rate during the early stages of dissolution (brewing), we introduce a simplified model, wherein only the stress-free matrix porosity is a function of time, $\Phi(t)$. The flow rate in Eq. (13) can be written as

$$Q = Q_m(\Phi(t)) \hat{Q}(\hat{P}) = Q_{\text{ref}} F(\Phi(t)) \hat{Q} \left(\frac{P}{Y\Phi(t)} \right). \quad (17)$$

The constants Q_{ref} and Y can be eliminated using the calibration flow and pressure to yield the final expression

$$Q = Q_c \frac{F(\Phi(t))}{F(\Phi_m)} \hat{Q} \left(\frac{P\Phi_m}{P_c\Phi(t)} \right). \quad (18)$$

We now assume $\Phi(t)$ to be the ratio of dissolved solids m_d to the initial dose of ground coffee m_0 : $\Phi(t) = m_d(t)/m_0$. The dissolved mass $m_d(t)$ can be estimated from experiments measuring the concentration of solutes as a function of time, combined with flow rate experiment performed at the same experimental conditions.

IV. RESULTS

Using our experimental setup (cf. Fig. 1) we conducted measurements of espresso coffees brewed at different water pressures ranging from ca. 1 bar and up to 12 bar (in terms of basket pressure, calculated from the measured pump pressure as described in Sec. II). The

evolution of mass in the cup and mass flow rate is presented in Fig. 5, where pressures are coded by colours in panel (A). In panel 5(B), we shifted the brewing time so that the point corresponding to the mass of 5g in the cup is taken as $t = 0$. We see non-monotonic dynamics, where the brews at lowest pressures exhibit very slow flow, but upon increasing the pressure above a certain threshold, the flow rate decreases again. From the mass flow rate evolution curves in panel 5(C), we can delineate three regimes of brewing an espresso. Firstly, the water front has to penetrate the coffee bed and expel the air entrapped within the pores. At the same time, the wetting front is accompanied by gradual swelling of the coffee bed. This process takes about 5 – 10 s, during which percolation is achieved and the first drops of coffee fall into the cup. Next, we see an almost linear increase in the flow rate, which extracts material from the now wetted coffee bed [25]. At times which are past the typical brewing time of an espresso shot, we see that the flow rate saturates, or even slightly decreases towards a stable (equilibrium) value.

We first focus on this stable flow. The non-linear dependence of the long-time flow rate on the applied basket pressure can be explained using the quasi-static theoretical model introduced in Sec. III.A. Assuming that the fully dissolved coffee bed remains elastic, we can compare the theoretical flow-pressure relationship, Eq. (13) with experimental data. To this end, we brewed a total of 60 coffees at 11 different values of the basket pressure. Each coffee was brewed for at least 120s, with the puck preparation protocol described in Sec. II. The equilibrium flow rate was taken to be the average value from the last 10s of each experimental run. The results are presented in Fig. 6, together with a fitted theoretical curve. The fitting parameters are the calibration flow $Q_c = 1.90 \pm 0.15$ g/s and the calibration pressure $P_c = 12 \pm 3$ bar. At low basket pressures, the model reproduces Darcy-like flow reported in literature before [40] for comparable pressures. However, for higher pressures the flow stalls, which is consistent with earlier empirical reports of coffee professionals. We note that a similar behaviour was also observed in the percolation models of Fasano et al. [17], where they introduce a non-linear flow-dependent threshold for dissolution.

We now turn to the time-dependent effects in the flow of espresso. The early stages of brewing result from an interplay between the wetting and subsequent swelling of coffee, which results in a delayed flow response to applied pressure, and the dissolution kinetics. To visualise this competition, we brewed an espresso and divided the brew into 5 s intervals, illustrated in Fig. 7(A). The first tube (0 – 5s) was empty, and the flow rate increased systematically, beyond the capacity of a single tube in a 5s

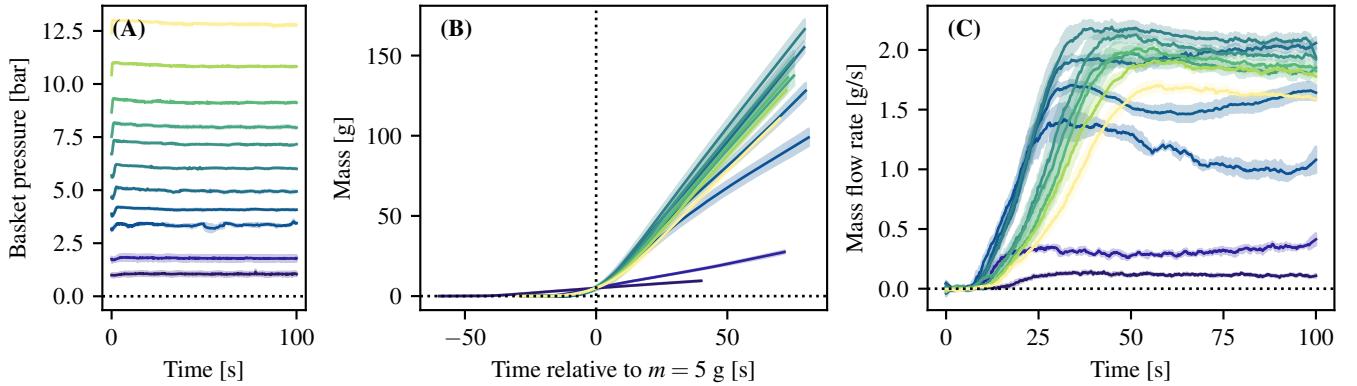


Figure 5. Experimental data on espresso flow at controlled pressures. (A) Basket pressure as function of time. (B) Simultaneously measured mass in cup. (C) Derived mass flow rate as a function of time. At low pressures (dark blue) increase in pressure results in an increase in flow rate, this is contrasted with opposite trend for large pressures (light yellow). Each line is an average result of multiple experiments with shaded regions denoting standard deviation of the mean.

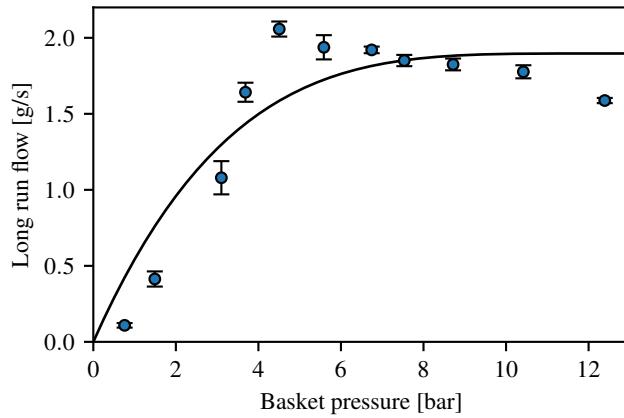


Figure 6. Experimental long-time flow rate as a function of pressure. Symbols indicate flow rate values 110 – 120s after brewer activation, averaged over multiple experimental runs (error bars show the standard error of the mean), together with the fitted theoretical model of Eq. (16) that assumes pressure-induced compactification of the coffee bed and predicts flow rate saturation at higher pressures, while reproducing the linear, Darcy behaviour for low pressure gradients.

window. At the same time, the brightening colour of the brew at longer times indicates a decrease in the amount of dissolved material. To quantify the dissolution kinetics, we measured the TDS of subsequent samples, as shown in Fig. 7(B). The first and most concentrated drops of espresso have a high TDS of ca. 25% which, after a stable phase of ca. 20s, rapidly decreases, reaching values close to zero at about 60s. Given this sigmoidal shape, we propose an empirical relation to describe the data,

$$\text{TDS}(t) = \frac{k_t}{2} \left[1 - \tanh \left(\frac{t - \ell_t}{m_t} \right) \right], \quad (19)$$

sketched as a dashed line in Fig. 7(B), with fitting parameter $k_t = 25.6 \pm 1.3\%$, a time offset $\ell_t = 20.9 \pm 0.9$ s and a decay time of $m_t = 8.8 \pm 1.5$ s. Knowing the time-

dependent flow rate $Q(t)$ from an experimental run, we can thus obtain the flow rate of solutes into the cup by multiplying $\text{TDS}(t) \times Q(t)$, as presented in Fig. 5(C). While the flow rate picks up and increases monotonically during the typical brewing time, the solute flux has a maximum around ca. 30s. The solute flow is thus initially limited by the low flow rate, while at longer times it is limited by the availability of soluble material inside the coffee puck. We calculate the total mass of solids removed from the coffee puck, $m_d(t)$ from the solute flux in Fig. 7(D). Again, the sigmoidal shape of this curve can be accurately represented by an empirical relationship

$$m_d(t) = \frac{k_m}{2} \left[1 + \tanh \left(\frac{t - \ell_m}{m_m} \right) \right], \quad (20)$$

where k_m is the total soluble mass, and ℓ_m and m_m represent the time offset and the characteristic time scale of dissolution, respectively. These three parameters are estimated by fitting the relationship (20) to the experimental data, and read in this case $k_m = 2.257 \pm 0.001$ g, $\ell_m = 19.83 \pm 0.01$ s, and $m_m = 9.34 \pm 0.02$ s. We note that, since the underlying temporal dynamics are governed by the dissolution kinetics, the time scales and offset are nearly identical, so one can effectively assume $\ell_m \approx \ell_t$ and $m_m \approx m_t$. Motivated by these observations, we propose a model to quantify the dissolution process, described in Sec. III.B. In essence, the dissolution-induced removal of mass can be related to an increase in effective porosity of the medium, which in turn affects its permeability. Assuming the instantaneous porosity $\Phi(t)$ to be proportional to the relative dissolved mass of coffee, Eq. (18) provides us with a predictive tool to estimate the time-dependent flow during brewing, where the only parameters are estimated from the long-time equilibrium calibration pressure and flow, P_c and Q_c , and the long-time porosity $\Phi_m = \lim_{t \rightarrow \infty} m(t)/m_0 = k_m/m_0$. For convenience, we repeat the values here: $P_c = 12 \pm 3$ bar, $Q_c = 1.90 \pm 0.15$ g/s; The estimated equilibrium porosity is $\Phi_m \approx 0.122$. The results of such calculations are

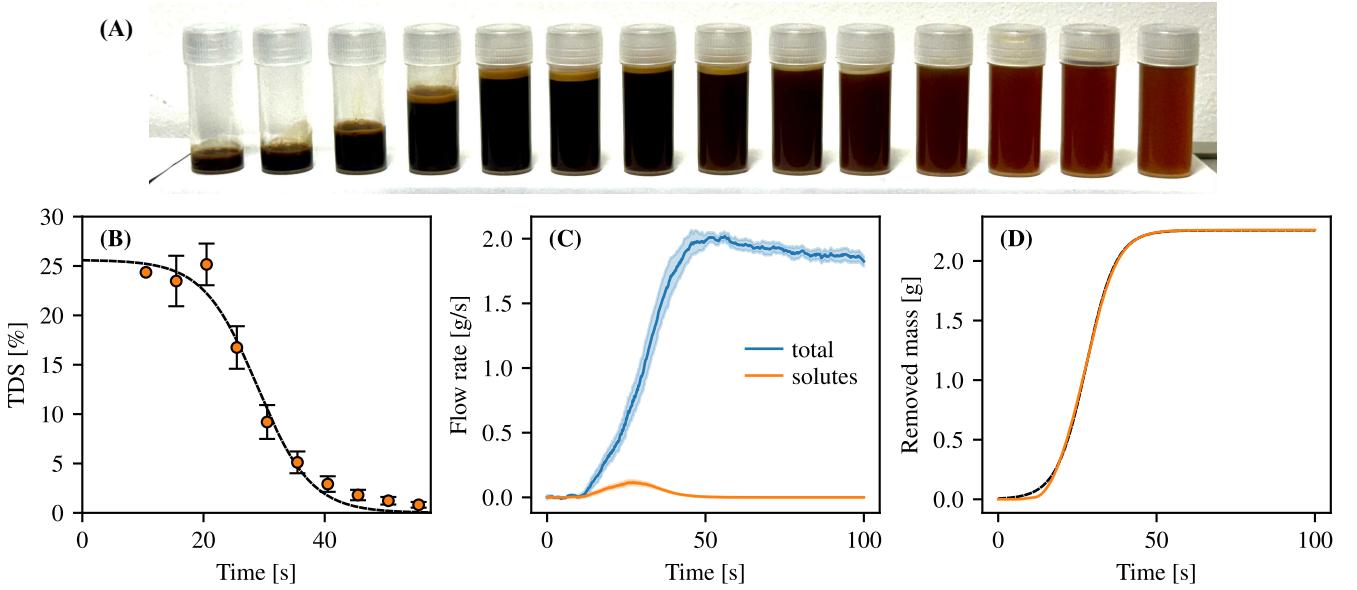


Figure 7. Determination of dissolution kinetics (A) A single espresso split into 14 fractions of 5 seconds each. Flow rate during first 20 seconds is much smaller than in later intervals. (B) Total dissolved solids (TDS) derived from refractometric measurements together with fitted approximation of Eq. (19). (C) Total flow rate (blue) and solutes flow rate (orange) obtained by multiplying total flow rate by the smooth TDS approximation. Solutes flow is concentrated in the time of rapidly increasing total flow rate. (D) Total removed solids $m(t)$ as a function of time - computed from the solutes flux (orange) together with a fitted smooth approximation (gray)

presented in Fig. 8(A) for a representative example of a typical brewing pressure of 9 bar. Although the minimal model deviates from the flow rate measurement at short times, where swelling and air removal complicate the dynamics, it seems to approximately grasp the flow curve. A similar comparison for other values of brewing pressure (with colour coding as in Fig. 5) in Fig. 8(B) shows that the model fails to grasp the quantitative dynamics for the lowest brewing pressures, when the puck satisfies Darcy's law, but becomes increasingly accurate at higher pressures, providing quantitative predictions of the flow rate dynamics.

Although the time scales of the brewing process and the structure of a typical espresso machine preclude direct visualisation of flow *in situ*, we performed X-ray μ -CT scans of a coffee puck after sample preparation and shortly after brewing. An overlay of typical images is presented in Fig. 9. The pre-brew puck in panel (A) reveals a tightly packed structure with evident small-scale heterogeneity. A comparison of the sample thickness with the same puck imaged after brewing in panel (B) shows a considerable swelling but also a reconfiguration of the sample. In the post-brew tomographic slice, multiple horizontal delaminations and cracks are seen. In the bottom part, close to the filter mesh, the coffee puck has peeled off the basket and a void space was created in between the filter mesh and the puck. However, we associate this with the operation of the overpressure valve which may reverse the direction of flow for an instant after the brewer flow is turned off to relieve the built up pressure. This short

backflow might lead to a reconfiguration of the sample after brewing has finished.

To explore the effect of the delaminations on the brewing process, we additionally performed an experiment where the coffee puck was first exposed to a long brewing process when pressure of 8 bar was applied for ca. 75s, followed by repeated cycles of turning the brewer on and off. The pressure signal, together with the resulting flow rate is plotted in Fig. 10. Upon repeated brewing, we witness a significant increase of the flow rate without additional dissolution, which suggests that a reconfiguration of the sample takes place each time the pressure is applied. The driving pressure, indicated at the pump, switches between the working pressure of ca. 8 bar and no flow (closed valves) at ca. 3 bar. Upon switching off the pump, there is a slight backflow due to the presence of a three-way valve in the hydraulic circuit above the coffee puck. We argue that the delaminations that occur when the brewing process stops contribute to an increasing channelling in the sample, a process long known in the coffee community to negatively affect the quality of the brew. In a channelled coffee, the flow through a puck is focused in one or several channels instead of uniformly penetrating the sample. As a result, even at relatively high flow rates, the extraction yield of coffee remains low. The evidence in Fig. 10, although presented with no visualisation of internal reconfiguration, suggests that any brewing process that involves a temporary pause or repeated application of pressure might be prone to channelling and therefore should be avoided.

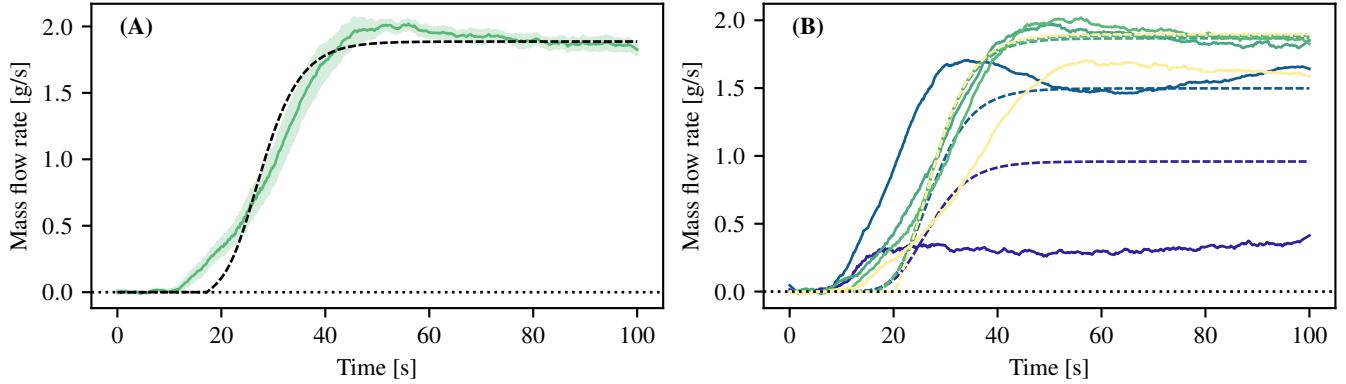


Figure 8. **Dissolution induced changes in porosity.** (A) Comparison of time dependent flow profile derived from the exponential dissolution model for the most typical (9 bar) brewing pressure. (B) Comparison of several time dependent trajectories at different pressures.

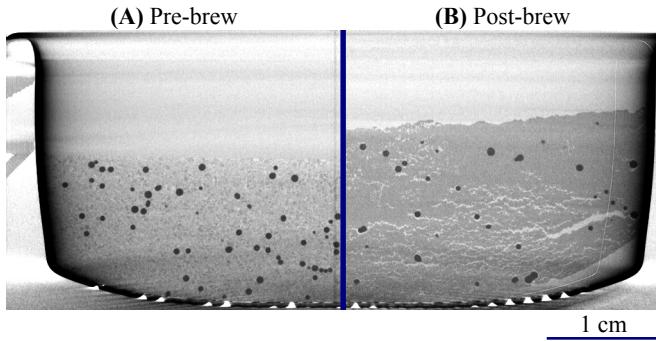


Figure 9. **X-ray tomographic slice through an espresso puck.** (A) Tamped puck before brewing. Glass microbeads (dark) are added for visualisation. (B) Coffee puck after brewing. Considerable swelling is seen as compared to the pre-brewing puck, as well as numerous horizontal delaminations. The coffee puck as a whole was also lifted from the bottom filter mesh, leaving a layer of air in between.

V. DISCUSSION

A. Ground coffee as a poroelastic medium

When coffee is treated as a porous medium, a crude estimation of the flow rate directly from the Darcy' law, Eq. (1), with the Carman-Kozeny closure, Eq. (8), taking $d_p = 200 \mu\text{m}$ (the typical grind size for coffee) yields a flow rate of the order of 2000 g/s at $\Phi = 0.5$, thus overestimating the typical espresso flow rate by a factor of 10^3 . This is consistent with our control experiments, where we packed the coffee basket with an equivalent volume of $200 \mu\text{m}$ diameter glass beads, which at typical brewing pressures give virtually no resistance to flow compared to coffee grounds of similar size. Moreover, the flow rate through the glass is weakly dependent on the water temperature. On the other hand, we note that the Carman-Kozeny relationship is of little predictive value in typical applications, and we expect it to break down completely

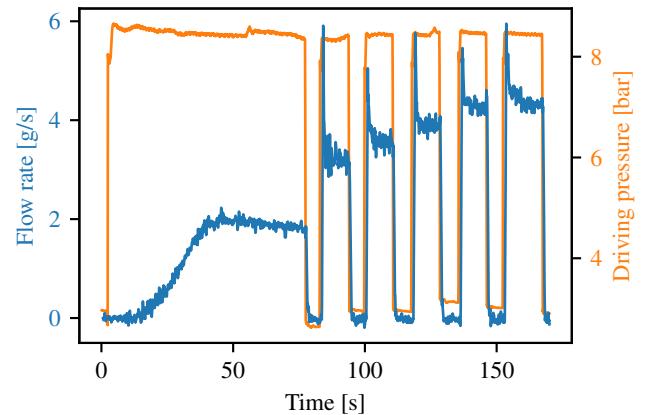


Figure 10. **Flow rate changes upon repeated brewing.** Restarting the brew cycle several times increases the flow rate without causing additional dissolution. This effect arises from the rapid reorganization of the coffee puck induced by partial backflow through the three-way valve found in all modern espresso machines, which evacuates water from the puck's surface after brewing. The rapid flow changes produce the delaminations seen in tomographic images in Fig. 9.

when the medium is close to clogging and $\Phi \rightarrow 0$, which is a limitation of the presented simple model [41]. The universal character of the behaviour of permeability at low porosities could be the result of the chosen constitutive law. A possible improvement would be to consider different models for the behaviour of permeability near the percolation threshold.

During brewing, coffee undergoes significant changes; Spent coffee pucks resemble sugar cubes or dry cookies that can be carefully handled but crumble under moderate stress. This behaviour contrasts strongly with that of dry coffee grounds. The source of this difference is the significant swelling that occurs when coffee is in contact with hot water (cf. Fig. 9), which in conjunction with mechanical confinement leads to a large decrease of the effective pore diameter. A 1000-fold decrease in perme-

ability can be explained by a 30-fold decrease in effective pore diameter, which leads to estimated pore sizes of the order $6 \mu\text{m}$. Such crude estimates correspond well to microporosity observations performed using electron tomography [42].

At the same time, we argue in this contribution that elasticity of the coffee puck is an important factor that determines the flow response. While the proposed theoretical model circumvents the need for the determination of Young's modulus for coffee, instead fitting the long-time calibration pressure and flow, an independent measurement of Y would be useful for independent validation. However, to the best of our knowledge, no such mechanical measurements have been conducted on wetted ground coffee. As a reference point, measurements of elastic properties of roasted coffee beans of Severin et al. [43] report forces of around 50 N at a displacement of 0.15 mm. Taking the size of a coffee bean to be 1cm and an effective cross section 80 mm^2 yields Young's modulus of $40 \text{ MPa} = 400 \text{ bar}$ for whole roasted beans.

B. Solubility kinetics of ground coffee

The model proposed in this work, coupled with experimental results, shows that the time-dependent kinetics of the coffee dissolution are coupled to the flow dynamics through this reactive medium, rendering a complex response in terms of the mass flux of solutes. The results of our TDS measurements in Fig. 5 support the claim that during a typical espresso brewing the majority of readily extractable compounds are dissolved almost instantaneously [44, 45], and are subsequently removed by the increasing flow. We introduced the time-dependent porosity, $\Phi(t)$, into the flow model to obtain predictions for the time dependence of the flow rate Q at different driving pressures (cf. Fig. 5), which are in qualitative agreement for both the high and low pressures, reproducing the initial delay between wetting and onset of the flow for higher pressures. Our simplistic model predicts a complete shut-off of the flow at $P_{\text{ext}}/Y > \Phi$. This might be relevant for the initial stage of brewing, where the value of Φ is low, and would provide a qualitative explanation of the delayed onset of flow, but we note that this phase is complicated by the multi-phase character of flow and swelling. Beyond a qualitative model which describes the initial slow percolation, the detailed modelling of this phase is beyond the scope of this manuscript and requires higher time resolution of flow, TDS and pressure data.

The dissolution process crucially relies on the structure of the porous medium. In the case of coffee, the bimodal distribution of grain sizes (cf. Fig. 3) is universal across different grind settings and devices [32]. Recently, an approach with sieving grounds to achieve a unimodal (single-peak) distribution has been proposed [42]. What is interesting, Smrk et al. [13] find that, for a given coffee, the extraction time of an espresso can be predicted

by knowing the share of fines and the size of the large particles (boulders). The effect of increased surface area due to smaller particle size for coffee with a high fraction of fines on the extraction efficiency seems to be marginal.

Finally, we note that in Refs. [34, ch. 7.5.7] and [5, 17] the authors state that the flow during espresso brewing does not linearly depend on pressure for pressures around 9 bar, and that an increase in pressure actually causes a decrease in the average flow, despite Darcy's law suggesting otherwise – we corroborate these findings and propose an explanation of the mechanism underlying this behaviour. However, other mechanisms have been proposed to explain the complex behaviour of coffee, including the migration of coffee fines within the basket, jamming, or the formation of preferential flow paths that change the effective pore sizes in the medium. Future experiments, in particular time-resolved measurements of structural changes in the coffee puck might bring new evidence to examine these hypotheses.

VI. CONCLUSIONS

The flow of hot water under pressure through a tightly packed bed of ground coffee is a phenomenon of paramount importance to many amateurs of the beverage worldwide. To a scientist, coffee is a beverage of many faces, from the cultural perspective, through the chemical complexity and biological effect, to the solid and fluid mechanics of the preparation process. From the physics point of view, it is a fascinating multi-physics and multi-scale system, which can be approached using a variety of theoretical and experimental tools.

Motivated by the non-linear flow response of coffee to the driving pressure and scarce evidence, in this study we perform systematic experiments to explore this dependence using a café-grade espresso machine, augmented with pressure and mass sensors. The examination of flow rate at long brewing times allows us to observe the saturated, equilibrium behaviour of flow rate after the dissolution process of coffee solubles is complete. Our measurements reveal a clear deviation from the classical Darcy behaviour, particularly at higher pressures, where the flow rate does not scale linearly with pressure. To rationalise these observations, we propose a minimal theoretical model that assumes poroelasticity of the coffee bed, and captures the essential features of the pressure-dependent flow rate. Further, by measuring time-resolved solute concentrations, we show that the temporal evolution of the flow is governed primarily by the dissolution dynamics rather than a structural rearrangement of the porous matrix. These insights establish that espresso brewing is a self-regulating process where solute dissolution and matrix elasticity interact to shape the overall extraction dynamics, and suggest that future optimisation efforts should consider the coupled physico-chemical nature of the coffee bed, and that the assumption of constant bed permeability should be relaxed to

formulate realistic predictions.

VII. ACKNOWLEDGMENTS

ML and RW acknowledge funding from the University of Warsaw IDUB programme. The work of FM was partially supported by a DAAD scholarship for master's studies in Germany. We thank Dorota Nowicka and Kamil Kolasa for their contributions to the early versions of the experiments. The project benefitted from guidance, support, and equipment from coffee industry specialists, including in particular (in alphabetical order): Krzysztof Blinkiewicz, Łukasz Jura, Bartosz Krzymowski, Rafael Młodzianowski, Kacper Ornat, Justyna Sarnowska, Wojtek Szymański, Maciej Zielenkiewicz.

We are indebted to Coffeelab Warsaw (coffeelab.pl) for providing high quality coffee beans, barista and sensory training, as well as technical support. Coffee Machines Sale (cmsale.com) is gratefully acknowledged for access to barista-grade equipment essential for reproducible espresso brewing, measurements, and invaluable know-how.

DATA AVAILABILITY

All data and analysis codes used in this study are publicly available. The source code and datasets are hosted

on GitHub [46], with an archived, citable version available on Zenodo [47].

AUTHOR CONTRIBUTIONS

Conceptualization: RW, ML (lead), FM, MD, PS (supporting). **Data curation:** RW, LB, MPM, ML (supporting). **Formal analysis:** RW (lead), FM, LB, MPM, PS, ML (equal). **Funding acquisition:** RW, ML (lead). **Investigation:** RW, ML (equal), FM, LB, MPM, MD (supporting). **Methodology:** RW, ML (lead), MD, PS (supporting). **Project administration:** ML (lead), RW (supporting). **Resources:** ML (lead), FM (supporting). **Software:** LB (lead), RW (equal). **Supervision:** RW, ML (lead). **Validation:** ML (supporting). **Visualization:** RW (lead), FM, LB, MPM (supporting). **Writing – original draft:** RW, ML (lead), FM (supporting). **Writing – review & editing:** RW, ML (lead), FM, LB, MPM, MD, PS (supporting).

-
- [1] A. Farah, Coffee constituents, in *Coffee* (John Wiley & Sons, Ltd, 2012) Chap. 2, pp. 21–58.
 - [2] J. Morris, Making Italian Espresso, Making Espresso Italian, *Food and History* **8**, 155–183 (2010).
 - [3] J. Morris, Why espresso? explaining changes in european coffee preferences from a production of culture perspective, *European Review of History: Revue européenne d'histoire* **20**, 881–901 (2013).
 - [4] A. N. Gloess, B. Schönbächler, B. Klopprogge, L. D'Ambrosio, K. Chatelain, A. Bongartz, A. Strittmatter, M. Rast, and C. Yeretzian, Comparison of nine common coffee extraction methods: instrumental and sensory analysis, *European Food Research and Technology* **236**, 607–627 (2013).
 - [5] J. Hoffmann, *The World Atlas of Coffee* (Octopus Publishing Group, 2018).
 - [6] M. I. Cameron, D. Morisco, D. Hofstetter, E. Uman, J. Wilkinson, Z. C. Kennedy, S. A. Fontenot, W. T. Lee, C. H. Hendon, and J. M. Foster, Systematically improving espresso: Insights from mathematical modeling and experiment, *Matter* **2**, 631 (2020).
 - [7] W. T. Lee, A. Smith, and A. Arshad, Uneven extraction in coffee brewing, *Physics of Fluids* **35**, 10.1063/5.0138998 (2023).
 - [8] S. Andueza, L. Maeztu, B. Dean, M. P. de Peña, J. Bello, and C. Cid, Influence of water pressure on the final quality of arabica espresso coffee. application of multivariate analysis, *Journal of Agricultural and Food Chemistry* **50**, 7426–7431 (2002).
 - [9] L. Navarini and D. Rivetti, Water quality for espresso coffee, *Food Chemistry* **122**, 424–428 (2010).
 - [10] S. Andueza, L. Maeztu, L. Pascual, C. Ibáñez, M. P. de Peña, and C. Cid, Influence of extraction temperature on the final quality of espresso coffee, *Journal of the Science of Food and Agriculture* **83**, 240–248 (2003).
 - [11] C. A. Salamanca, N. Fiol, C. González, M. Saez, and I. Villaescusa, Extraction of espresso coffee by using gradient of temperature. effect on physicochemical and sensorial characteristics of espresso, *Food Chemistry* **214**, 622–630 (2017).
 - [12] K. Moroney, W. Lee, F. Suijver, J. Marra, *et al.*, Modelling of coffee extraction during brewing using multiscale methods: An experimentally validated model, *Chemical Engineering Science* **137**, 216 (2015).
 - [13] S. Smrke, A. Eiermann, and C. Yeretzian, The role of fines in espresso extraction dynamics, *Scientific Reports* **14**, 10.1038/s41598-024-55831-x (2024).
 - [14] World Coffee Research, Sensory lexicon, <https://worldcoffeeresearch.org/resources/sensory-lexicon> (2017).
 - [15] D. Fasman, Defining the ever-changing espresso, 25 Magazine **3** (2018).
 - [16] M. Spencer, E. Sage, M. Velez, and J. Guinard, Using single free sorting and multivariate exploratory methods to design a new coffee taster's flavor wheel, *Journal of Food Science* **81**, 10.1111/1750-3841.13555 (2016).

- [17] A. Fasano, F. Talamucci, and M. Petracco, The espresso coffee problem, in *Complex flows in industrial processes*, edited by A. Fasano (Springer, 2000) pp. 241–280.
- [18] A. F. V. Matias, D. F. Valente-Matias, N. R. Neng, J. M. F. Nogueira, J. S. Andrade, R. C. V. Coelho, and N. A. M. Araújo, Continuum model for extraction and retention in porous media, *Physics of Fluids* **35**, 10.1063/5.0176273 (2023).
- [19] A. Mahadevan, A. V. Orpe, A. Kudrolli, and L. Mahadevan, Flow-induced channelization in a porous medium, *EPL (Europhysics Letters)* **98**, 58003 (2012).
- [20] J. Giacomini, G. Khamitova, P. Maponi, S. Vittori, and L. Fioretti, Water flow and transport in porous media for in-silico espresso coffee, *International Journal of Multiphase Flow* **126**, 103252 (2020).
- [21] C. Mo, R. Johnston, L. Navarini, F. S. Liverani, and M. Ellero, Exploring the link between coffee matrix microstructure and flow properties using combined x-ray microtomography and smoothed particle hydrodynamics simulations, *Scientific Reports* **13**, 16374 (2023).
- [22] C. Mo, R. Johnston, L. Navarini, and M. Ellero, Modeling the effect of flow-induced mechanical erosion during coffee filtration, *Physics of Fluids* **33**, 10.1063/5.0059707 (2021).
- [23] A. F. Matias, R. C. Coelho, J. S. Andrade, and N. A. Araújo, Flow through time-evolving porous media: Swelling and erosion, *Journal of Computational Science* **53**, 101360 (2021).
- [24] K. M. Moroney, K. O'Connell, P. Meikle-Janney, S. B. O'Brien, G. M. Walker, and W. T. Lee, Analysing extraction uniformity from porous coffee beds using mathematical modelling and computational fluid dynamics approaches, *PLoS One* **14**, e0219906 (2019).
- [25] J. Foster, W. Lee, K. Moroney, D. Prjamkov, M. Salamon, A. Smith, J. Petrassem-de Sousa, and M. Vynnycky, Dynamics of liquid infiltration into an espresso bed using time-resolved micro-computed tomography: Insights from experiment and modeling, *Physics of Fluids* **37**, 10.1063/5.0245167 (2025).
- [26] B. R. Corrochano, J. Melrose, A. Bentley, P. Fryer, and S. Bakalis, A new methodology to estimate the steady-state permeability of roast and ground coffee in packed beds, *J. Food Eng.* **150**, 106 (2015).
- [27] C. Gianino, Experimental analysis of the italian coffee pot “moka”, *American Journal of Physics* **75**, 43 (2007).
- [28] W. D. King, The physics of a stove-top espresso machine, *American Journal of Physics* **76**, 558–565 (2008).
- [29] L. Navarini, E. Nobile, F. Pinto, A. Scheri, and F. Suggi-Liverani, Experimental investigation of steam pressure coffee extraction in a stove-top coffee maker, *Applied Thermal Engineering* **29**, 998–1004 (2009).
- [30] L. Hedrick, This changes everything... (Wdt, Autocomb, Moonraker, NCD, etc), <https://www.youtube.com/watch?v=0yUaCuoqYWc&t=8s> (2024).
- [31] L. Hedrick, How I Brew Tasty Coffee: My Espresso Obsession Observed, <https://youtu.be/eUc31vF8mHM?si=cPBzma9w1T2XEnJi> (2024).
- [32] J. Gagné, *The physics of espresso* (Scott Rao, 2025).
- [33] A. J. Ladd and P. Szymczak, Reactive flows in porous media: Challenges in theoretical and numerical methods, *Annual review of chemical and biomolecular engineering* **12**, 543 (2021).
- [34] A. Illy, *Espresso coffee: the science of quality* (Elsevier, 2004).
- [35] D. R. Hewitt, J. S. Nijjer, M. G. Worster, and J. A. Neufeld, Flow-induced compaction of a deformable porous medium, *Phys. Rev. E* **93**, 023116 (2016).
- [36] V. Guerriero and S. Mazzoli, Theory of effective stress in soil and rock and implications for fracturing processes: a review, *Geosciences* **11**, 119 (2021).
- [37] L. S. Bennethum, M. Murad, and J. Cushman, Modified darcy's law, terzaghi's effective stress principle and fick's law for swelling clay soils, *Computers and Geotechnics* **20**, 245 (1997).
- [38] P. C. Carman, Fluid flow through granular beds, *Trans. Inst. Chem. Eng. London* **15**, 150 (1937).
- [39] W. L. McCabe, J. C. Smith, and P. Harriott, *Unit operations of chemical engineering*, Vol. 5 (McGraw-hill New York, 1967).
- [40] C. Mo, L. Navarini, F. S. Liverani, and M. Ellero, Modeling swelling effects during coffee extraction with smoothed particle hydrodynamics, *Physics of Fluids* **34**, 10.1063/5.0086897 (2022).
- [41] C. Tien and B. V. Ramarao, Can filter cake porosity be estimated based on the kozeny–carman equation?, *Powder Technology* **237**, 233–240 (2013).
- [42] Z. R. Lindsey, J. R. Williams, J. S. Burgess, N. T. Moore, and P. M. Splichal, Caffeine content in filter coffee brews as a function of degree of roast and extraction yield, *Scientific Reports* **14**, 10.1038/s41598-024-80385-3 (2024).
- [43] H. G. Severin and B. Lindemann, Elasticity of coffee beans: A novel approach to understanding the roasting process, *J. Food Eng.* **383**, 112212 (2024).
- [44] B. Zanoni, E. Pagliarini, and C. Peri, Modelling the aqueous extraction of soluble substances from ground roasted coffee, *Journal of the Science of Food and Agriculture* **58**, 275–279 (1992).
- [45] M. Spiro, Modelling the aqueous extraction of soluble substances from ground roast coffee, *Journal of the Science of Food and Agriculture* **61**, 371–372 (1993).
- [46] R. Waszkiewicz, F. Myck, Ł. Białas, M. Puciata-Mroczyńska, M. Dzikowski, P. Szymczak, and M. Lisicki, *Under pressure: Poroelectric regulation of flow in espresso brewing*, GitHub repository (2025).
- [47] R. Waszkiewicz, F. Myck, Ł. Białas, M. Puciata-Mroczyńska, M. Dzikowski, P. Szymczak, and M. Lisicki, *Under pressure: Poroelectric regulation of flow in espresso brewing*, Zenodo (2025).