

CONFINED INDENTATION AS A VISCOPLASTIC TRIAXIAL TEST: DEVELOPMENT AND VALIDATION OF THE YIELDCOMPRESS® METHOD

A.T. Fonseca^(a), S. Batista^(b), J. Silva^(b), R. Silva^(b), M. Alves^(b) y Custom Technologies, Ltd^(c)

(a) DEMAC, University of Aveiro, 3810-193 Aveiro, Portugal

(b) MCS, Zona Industrial de Oia, Apartado 163, 3840-909 Oia (OBR), Portugal

(c) Custom Technologies, Lda, Beco da Agra n.º 12, Verdemilho, 3810-539 Aveiro, Portugal

ABSTRACT

Conventional rheological methods used to characterize ceramic plastic bodies, particularly oscillatory and extensional rheometry, do not adequately reproduce the triaxial stress states generated during industrial shaping operations. To overcome this limitation, the YIELDcompress® method was developed.

The proposed method enables the direct determination of viscoplastic parameters under conditions representative of industrial shaping processes, ensuring that the measured properties are directly applicable to ceramic bodies used in RAM pressing, roller shaping, extrusion and robocasting. Confined indentation can be interpreted as a viscoplastic triaxial test capable of providing intrinsic rheological parameters relevant to industrial shaping operations.

In the YIELDcompress® device, the ceramic body is confined within a rigid metal ring and subjected to controlled indentation, thereby reproducing stress states representative of those generated during industrial shaping processes.

The interpretation of the experimental results is based on a viscoplastic constitutive framework combining the Herschel–Bulkley power-law model with the Drucker–Prager yield criterion, allowing the determination of intrinsic material parameters such as the confined *yield stress* ($\tau_{yconf.}$), *rheological consistency* (K), *flow behaviour index* (n) and a *characteristic length* (L_c).

Both the porcelain body formulated for robocasting and the stoneware body used for RAM pressing exhibited three distinct deformation regimes: an initial elastic regime, a transient regime associated with the onset of viscoplastic flow when the apparent stress reaches the confined yield stress, and a steady-state regime characterised by a stabilised mechanical response.

Both bodies exhibit, under the test conditions, an almost rate-independent response, that is, $n \approx 0$. This means that the behaviour is governed mainly by confined yielding and by the structural resistance of the particulate network, rather than by a viscous contribution dependent on indentation rate.

The proposed method constitutes a simple and industrially relevant tool for the formulation, optimisation and quality control of ceramic bodies intended for extrusion, RAM pressing, roller shaping and ceramic robocasting.

1. INTRODUCTION

In the plastic shaping of ceramic bodies – including RAM pressing, roller compaction, extrusion and robocasting [1,2] – the rheological behaviour can, as a first approximation, be described using viscoplastic models such as Bingham (an idealised viscoplastic body model with constant plastic viscosity) or Herschel–Bulkley [3], in which the yield stress τ_y defines the threshold required for the onset of plastic flow, followed by a viscous contribution dependent on the deformation rate.

In this context, it is essential to ensure a sufficiently high yield stress to guarantee dimensional stability after shaping and to prevent deformation under the material's own weight. However, an increase in τ_y necessarily leads to a higher extrusion stress required to initiate flow, thereby making the shaping process more difficult.

Additionally, once the yield stress has been exceeded, flow is governed by the viscous contribution of the material, typically described by the Herschel–Bulkley [3] model through a power-law relationship of the form $\tau = \tau_y + K\dot{\gamma}^n$, where K and n strongly influence flow resistance. Moisture reduction, while effective in increasing τ_y , simultaneously leads to an increase in K , further enhancing resistance to viscous flow.

This issue is, fundamentally, the classical trade-off in viscoplastic systems used in the shaping of plastic bodies: a body must be “strong” enough to avoid collapse after shaping, but “soft” enough to flow during shaping (pressing, extrusion or robocasting). The key point is that adjusting only the moisture content does not affect a single parameter in isolation. Instead, it attempts to decouple two rheological responses that are normally coupled, which creates processing difficulties and can lead to failure.

This coupling between yield stress and viscous behaviour highlights the limitations of empirical approaches based exclusively on moisture control and justifies the use of a formal viscoplastic rheological description for the optimisation of plastic body processing, particularly in manufacturing by robocasting [4]. It is therefore necessary to identify which processing parameters are the dominant factors governing, or uniquely determining, each rheological parameter, namely τ_y , the post-yield viscous contribution $(\tau - \tau_y)/\dot{\gamma} = K\dot{\gamma}^{n-1}$ and L_c .

However, in all plastic shaping processes, ceramic bodies are not subjected only to pure shear stresses, as the previous expressions may suggest. In these processes, bodies experience

complex triaxial stress states, due to the constraint preventing deformation in one or more directions. As a result, it is no longer meaningful to refer to a pure shear yield stress τ_y , but rather to a confined yield stress τ_{yconf} . [5-7].

Conventional rheological methods, including rotational and oscillatory rheometry, provide parameters determined under predominantly simple shear conditions. However, these measurements do not directly reproduce the confined triaxial stress states characteristic of industrial ceramic shaping operations. This limitation, both in terms of representativeness and operational robustness, motivated the development of the YIELDcompress® method.

2. THEORETICAL FRAMEWORK

2.1. Confined Indentation as a Viscoplastic Triaxial Test

Industrial shaping processes of plastic ceramic bodies take place under complex stress states in which compression, shear and confinement coexist. Under such conditions, rheological characterisation based exclusively on simple shear tests becomes insufficient to describe the mechanical response of the material during processing.

In the YIELDcompress® apparatus, the ceramic body is confined within a rigid metal ring and subjected to indentation at a constant rate using a flat-ended cylindrical punch. This configuration generates beneath the punch a predominantly triaxial stress state, accompanied by viscous flow localised in the peripheral region adjacent to the punch.

Consequently, the confined indentation test may be interpreted as an implicit viscoplastic triaxial test, capable of reproducing mechanical conditions close to those encountered in industrial shaping processes of plastic ceramic bodies [8-10].

The experimental quantity directly measured is the force F_t transmitted to the load cell installed beneath the base of the system. Defining the punch cross-sectional area by A_p , the mean apparent stress σ_{ap} is:

$$\sigma_{ap}(h) = \frac{F_t(h)}{A_p} \quad (1)$$

where h represents the indentation depth.

2.2. Mechanical Equilibrium and Stress State

During the test, the indentation rate is constant, making inertial effects negligible. Under these conditions, the system evolves under quasi-static conditions.

The force applied to the punch is distributed between the force transmitted to the base and the friction forces developed along the lateral wall of the ring. The global static equilibrium may be represented by:

$$F_p = F_t + F_w^a \quad (2)$$

where F_p is the force applied to the punch and F_w^a is the resultant friction force exerted by the ring wall on the body.

Beneath the flat punch, an approximately axisymmetric stress field develops, characterised by a mean normal stress p [Pa] [6,7,8] :

$$p = -\frac{1}{3}(\sigma_r + \sigma_\theta + \sigma_z) \quad (3)$$

or, equivalently,

$$p = -\frac{1}{3}I_1 \quad (4)$$

Where:

- I_1 is the first invariant of the stress tensor [Pa];
- σ_r , σ_θ , and σ_z are the radial, circumferential and axial normal stress components, respectively [Pa].

The magnitude of this pressure increases with indentation depth, progressively reinforcing particle contacts and modifying the yielding condition of the material.

2.3. Confinement-Dependent Yielding

Plastic ceramic bodies are saturated particulate systems whose mechanical resistance results simultaneously from the structural cohesion of the solid network and from friction developed between compressed particles.

Under these conditions, the stress required to initiate flow depends not only on the intrinsic properties of the body but also on the confinement state.

To incorporate this effect, the Drucker–Prager [13] criterion is adopted, as it is appropriate for cohesive–frictional materials subjected to triaxial stress states [9,14].

The confined yield stress is defined by:

$$\tau_{yconf}(I_1) = \tau_y + 3\alpha p \quad (5)$$

where:

- τ_{yconf} represents the confined yield stress [Pa];
- τ_y represents the intrinsic yield stress [Pa];
- p is the mean hydrostatic pressure [Pa];
- α expresses the sensitivity of yielding to confinement [dimensionless].

This formulation establishes a fundamental distinction between the yield stress measured under simple shear conditions and the yield stress effectively mobilised during industrial shaping processes.

2.4. Post-Yield Regime

Once the yield stress has been exceeded, the body is assumed to follow a Herschel–Bulkley type viscoplastic law:

$$\tau_{eq} = \tau_{y,conf}(p) + K\dot{\gamma}^n \quad (6)$$

where:

- τ_{eq} is the equivalent deviatoric stress;
- $\tau_{y,conf}(p)$ is the press-dependent confined yield stress;
- K is the consistency index [$Pa \cdot s^n$];
- n is the flow behaviour index [dimensionless];
- $\dot{\gamma}$ is the equivalent shear rate [s^{-1}].

In the context of confined indentation, the characteristic deformation rate is estimated as:

$$\dot{\gamma}_{eq} \approx \frac{v}{L_c} \quad (7)$$

where:

- v is the indentation rate [mm/s];
- L_c is a characteristic length associated with the extent of the active deformation zone [mm].

This parameter plays a central role in the physical interpretation of the test.

2.5. Geometrical Activation of the Mobilised Volume

Experimental observations show that the mechanical influence of the indenter does not propagate instantaneously throughout the entire volume of the body. As the indentation depth increases, an increasing volume of material becomes engaged in stress transmission and deformation. To describe this phenomenon, the following geometrical activation function is introduced:

$$\phi(h) = 1 - e^{-h/L_c} \quad (8)$$

This function simultaneously satisfies the following conditions: $\phi(0) = 0$, $\phi(h \approx 0) = h/L_c$ for very small values of h (Maclaurin series expansion around $h=0$), $\phi(L_c) \approx 0.632$ when $h = L_c$ and $\phi(\infty) = 1$. It represents the fraction of the disturbed volume affected by the punch that has already been mechanically mobilised by the indenter.

The parameter L_c corresponds to the indentation depth at which approximately 63% of the final disturbed volume has already been mobilised.

Physically, L_c may be interpreted as a characteristic length governing the propagation of the indenter's mechanical influence within the body. It represents the characteristic dimension of the active viscoplastic zone beneath the indenter.

2.6. Operational Constitutive Equation

A phenomenological activation approach is adopted to describe the progressive mobilisation of the material beneath the indenter. By combining the confinement-dependent yield stress, the Herschel–Bulkley [3] viscoplastic law, and the geometrical activation function, the following operational expression is obtained:

$$\sigma_{ap}(h, v) = \left[\tau_{yconf.} + K \left(\frac{v}{L_c} \right)^n \right] (1 - e^{-h/L_c}) \quad (9)$$

This equation directly relates the experimentally measured quantities—indentation depth and transmitted force—to the constitutive parameters of the body.

The formulation assumes that the apparent stress results from the progressive activation of an increasing volume of material as indentation proceeds. The activation function is therefore introduced as a phenomenological representation of the gradual development of the viscoplastic deformation zone beneath the indenter.

The experimental response is interpreted as the combined effect of two physically distinct contributions:

- A constitutive contribution associated with the cohesive–frictional strength and viscous resistance of the material;
- A geometrical contribution associated with the progressive mobilisation of the active deformation volume.

The explicit separation of these two effects constitutes the conceptual foundation of the proposed method and enables the identification, from confined indentation tests, of viscoplastic parameters relevant to industrial shaping processes.

3. EXPERIMENTAL PROCEDURE

3.1. Test Description

A clay ceramic body in a plastic state is confined within a rigid metal ring with an internal diameter of 80 mm and a height of 30 mm. A polished soft-steel cylindrical punch with a flat end, having a diameter ranging from 5 to 10 mm and a length of 15 mm, penetrates the body at a constant rate, v (mm/s). This rate may vary between tests, taking values between 0.50 and 2.50 mm/s. Figure 1 schematically illustrates the main components of the device and the external forces involved during the test. The top-right corner of the figure shows the relationship between Cartesian and cylindrical coordinates.

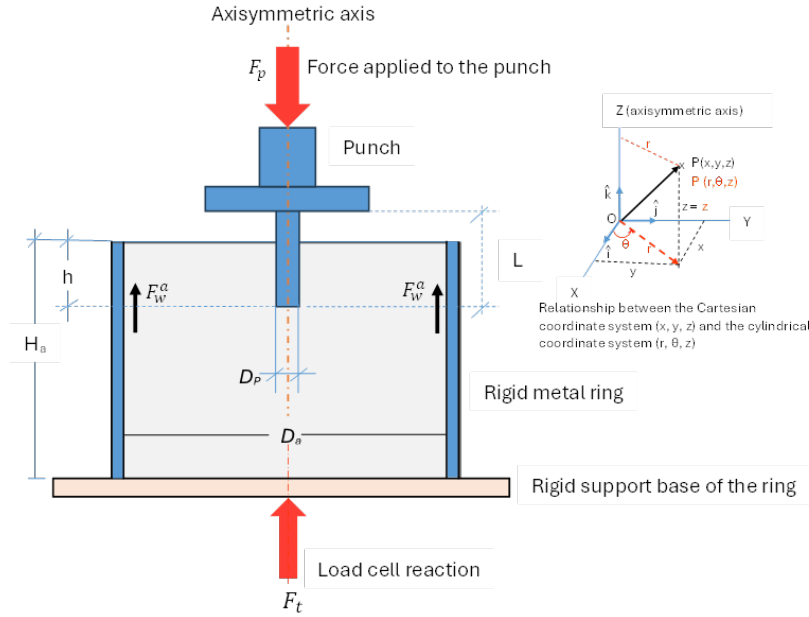


Figure 1. Schematic diagram of the confined indentation apparatus showing the geometry of the test configuration and the vertical components of the externally applied and frictional forces acting on the confined ceramic body. Symbols: H_a – ring height; h – indentation depth; D_a – inner ring diameter; D_p – punch diameter; L_p – punch length; F_p – applied punch force; F_t – force transmitted to the load cell; F_w^a – resultant body–wall friction force.

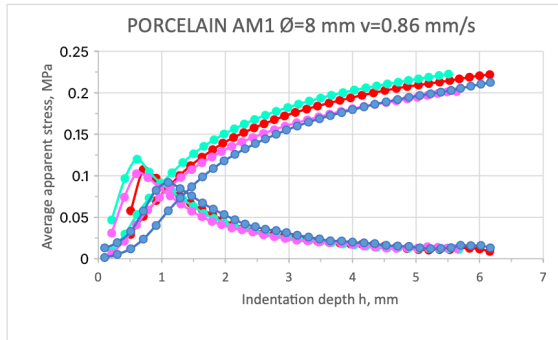
The test samples are obtained directly from rolls of extruded body under vacuum. A disc is cut from the roll with faces perpendicular to the roll axis and a thickness slightly greater than the height of the ring. One face of the disc is placed on a rigid base, and the metal ring is positioned on the opposite face, aligning the centres of the ring and the disc. Uniform pressure is applied around the ring perimeter until it reaches the supporting base of the disc. The excess material (upper face) is removed with a wire cutter, yielding a flat surface without compaction stress.

Before testing, four indentation points are marked on the surface of the specimens at the ends of two perpendicular diameters of a concentric circle with a radius of 20 mm. Point 1 corresponds to the mark left by the conveyor at the extruder outlet. The remaining points are identified sequentially in a clockwise direction. Each specimen is tested at a specific indentation rate, and the corresponding rheological properties are determined from the mean values measured for that specimen.

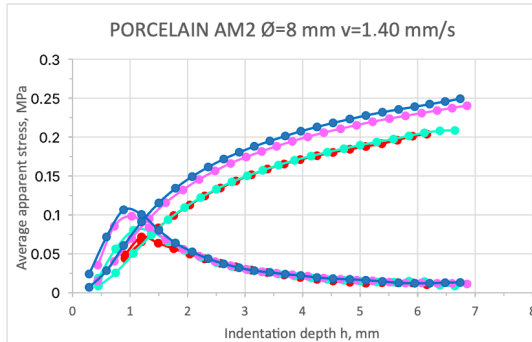
For each test, the computer system records the indentation depth and the transmitted load as functions of time, the mean apparent stress ($\sigma_{ap} = F_t/A_p$) as a function of indentation depth h , and the first derivative of σ_{ap} with respect to h . The maximum value of this derivative indicates the end of the elastic regime and the onset of plastic flow.

4. RESULTS

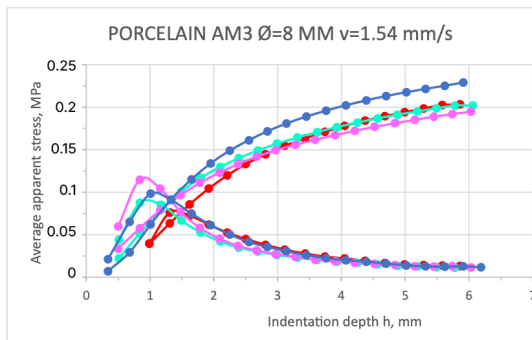
The results of the confined indentation tests on the porcelain and stoneware bodies are presented in the following figures and tables.



Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_c mm	v mm/s
T1	0.71	0.05108	0.22204	0.17096	0.13989	1.96	0.10770	1.25	0.86
T2	0.61	0.05332	0.22436	0.17104	0.14135	1.98	0.10776	1.37	0.85
T3	0.60	0.04086	0.20161	0.16075	0.12701	1.80	0.10127	1.20	0.85
T4	1.10	0.05767	0.21245	0.15478	0.13384	1.81	0.09751	0.71	0.87
Mean	0.66	0.05220	0.21725	0.16586	0.13686	1.89	0.10449	1.23	0.86
SD (s)	0.24	0.00713	0.01037	0.00802	0.00654	0.10	0.00505	0.29	0.01
Mean-3s	-0.05	0.03082	0.18612	0.14179	0.11726	1.60	0.08933	0.35	0.83
Mean+3s	1.37	0.07358	0.24837	0.18992	0.15647	2.17	0.11965	2.10	0.88

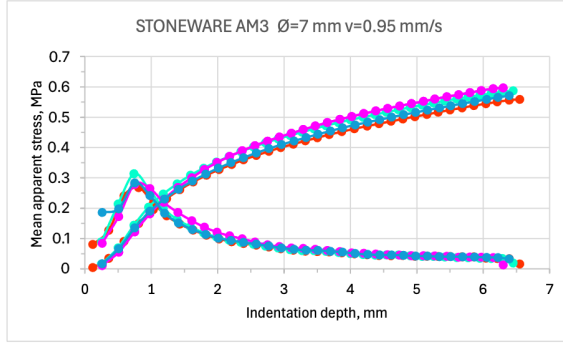


Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_c mm	v mm/s
T1	1.2	0.06551	0.2039	0.13839	0.12846	2.40	0.08719	1.20	1.38
T2	1.1	0.05049	0.20862	0.15813	0.13143	2.37	0.09962	1.27	1.41
T3	1.0	0.06987	0.24038	0.17051	0.15144	2.35	0.10742	1.35	1.41
T4	0.9	0.06064	0.24938	0.18874	0.15711	2.24	0.11891	1.34	1.41
Mean	1.1	0.06308	0.22450	0.16432	0.14144	2.36	0.10352	1.31	1.41
SD (s)	0.13	0.00833	0.02268	0.02117	0.01429	0.07	0.01334	0.07	0.02
Mean-3s	0.66	0.03809	0.15646	0.10080	0.09857	2.15	0.06351	1.10	1.37
Mean+3s	1.44	0.08806	0.29254	0.22784	0.18430	2.57	0.14354	1.52	1.46

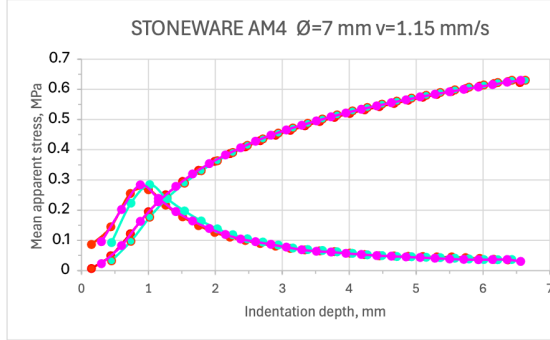


Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_c mm	v mm/s
T1	1.31	0.06364	0.20351	0.13987	0.12821	2.43	0.08812	1.12	1.52
T2	0.84	0.05196	0.20201	0.15005	0.12727	2.00	0.09453	1.16	1.54
T3	0.8	0.06844	0.23595	0.16751	0.14865	1.93	0.10553	1.09	1.54
T4	1.0	0.0622	0.22953	0.16733	0.14460	2.1	0.10542	1.09	1.54
Mean	0.9	0.06292	0.21652	0.15869	0.13641	2.05	0.09997	1.13	1.54
SD (s)	0.22	0.00693	0.01752	0.01362	0.01104	0.22	0.00858	0.03	0.01
Mean-3s	0.26	0.04212	0.16397	0.11784	0.10330	1.39	0.07424	1.03	1.51
Mean+3s	1.59	0.08372	0.26907	0.19954	0.16951	2.71	0.12571	1.22	1.57

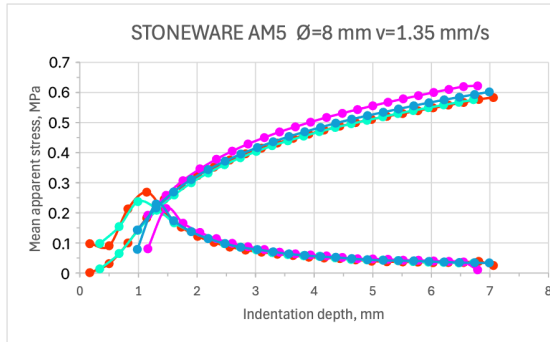
Figure 2. Response of the porcelain body subjected to the confined indentation test: upper curves σ_{ap} ; lower curves $d\sigma_{ap}/dh$. Colour code: test 1 (red), test 2 (light blue), test 3 (light purple) and test 4 (dark blue). Table columns: h_e and s_e are the indentation depth and average apparent stress, respectively, at the end of the elastic period; $A(v)$ is the asymptotic stress and $A(v)_{correct} = A(v) - s_e$; h_c the characteristic length before correction and L_c is the characteristic length.



Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_C mm	v mm/s
T1	0.81	0.14969	0.55905	0.40936	0.35220	2.29	0.25790	1.48	0.95
T2	0.74	0.14416	0.58748	0.44332	0.37011	2.17	0.27929	1.43	0.94
T3	0.75	0.12217	0.59645	0.47428	0.37576	2.18	0.29880	1.43	0.94
T4	0.75	0.13515	0.57092	0.43577	0.35968	2.29	0.27454	1.54	0.96
Mean	0.75	0.13966	0.57920	0.43955	0.36490	2.24	0.27691	1.49	0.95
SD (s)	0.03	0.01202	0.01672	0.02671	0.01053	0.07	0.01683	0.05	0.01
Mean-3s	0.65	0.10361	0.52904	0.35940	0.33330	2.04	0.22642	1.33	0.92
Mean+3s	0.85	0.17570	0.62936	0.51969	0.39650	2.43	0.32740	1.64	0.97



Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_C mm	v mm/s
T1	1.00	0.19458	0.62608	0.43150	0.39443	2.37	0.27185	1.37	1.14
T2	1.02	0.17654	0.63022	0.45368	0.39704	2.29	0.28582	1.27	1.14
T3	0.88	0.16312	0.62986	0.46674	0.39681	2.37	0.29405	1.49	1.16
T4	-	-	-	-	-	-	-	-	-
Mean	1.00000	0.17654	0.62986	0.45368	0.39681	2.37	0.28582	1.37	1.14
SD (s)	0.07572	0.01579	0.00229	0.01782	0.00144	0.05	0.01122	0.11	0.01
Mean-3s	0.77284	0.12918	0.62298	0.40023	0.39248	2.23	0.25215	1.04	1.11
Mean+3s	1.22716	0.22390	0.63674	0.50713	0.40115	2.51	0.31949	1.70	1.17



Test	h_e mm	σ_e MPa	$A(v)$ MPa	$A(v)$ correct. MPa	$0.63A(v)$ MPa	h_c mm	$0.63 \cdot A(v)$ correct. MPa	L_C mm	v mm/s
T1	1.14	0.18343	0.58352	0.40009	0.36762	2.43	0.25206	1.29	1.37
T2	0.99	0.14192	0.57614	0.43422	0.36297	2.50	0.27356	1.51	1.39
T3	1.16	0.19227	0.62219	0.42992	0.39198	2.57	0.27085	1.41	1.34
T4	1.30	0.21623	0.60215	0.38592	0.37935	2.52	0.24313	1.22	1.37
Mean	1.15000	0.18785	0.59284	0.41501	0.37349	2.51000	0.26145	1.35000	1.37000
SD (s)	0.12685	0.03097	0.02061	0.02335	0.01298	0.05802	0.01471	0.12842	0.02062
Mean-3s	0.76944	0.09495	0.53101	0.34495	0.33454	2.33593	0.21732	0.96474	1.30815
Mean+3s	1.53056	0.28075	0.65466	0.48506	0.41243	2.68407	0.30559	1.73526	1.43185

Figuer 3. Response of the stoneware body subjected at the confined indentation test: upper curves σ_{ap} ; lower curves $d\sigma_{ap}/dh$. Point numbering and orientation are the same as those adopted for the porcelain specimens shown in Figure 2.

Using the mean values from the tables in Figures 2 and 3, where h_e , σ_e , $A(v)_{correct}$, L_C and v are given for the porcelain and stoneware bodies, and assuming the confined yield stress τ_{yconf} as the mean apparent stress at the end of the elastic regime/onset of plastic flow, then:

$$\tau_{yconf} \approx \sigma_e \quad (10)$$

For the post-yield contribution, the following expression was used:

$$A(v)_{correct} = K \left(\frac{v}{L_C} \right)^n \quad (11)$$

or considering the definition (7):

$$A(v)_{\text{correct}} = K(\dot{\gamma}_{eq})^n \quad (12)$$

From graphics and the tables of the Figure 1, the Tables 1 and 2 condense the rheological data from porcelain and the stoneware bodies:

Sample	v mm/s	L_c mm	$\dot{\gamma}_{eq}$ s ⁻¹	t MPa	$A(v)_{\text{correct.}}$ MPa
AM1	0.86	1.23	0.699	0.052	0.166
AM2	1.41	1.31	1.076	0.063	0.164
AM3	1.54	1.13	1.363	0.063	0.159

Table 1. Rheological data of robocasting's porcelain body

and the overall values are calculated:

$$\tau_{y,\text{conf.}} = 0.059 \pm 0.006 \text{ MPa}$$

$$L_c = 1.22 \pm 0.09 \text{ mm}$$

By fitting $A(v)_{\text{correct}} = K(v/L_c)^n$, the following values are obtained:

$$K = 0.163 \text{ MPa}^n$$

$$n = -0.061$$

$$n \approx 0$$

$$K \approx 0.163 \text{ MPa}$$

The fitted values of n were close to zero and within the experimental uncertainty. Therefore, both bodies may be considered rate-independent over the investigated indentation-rate range ($n \approx 0$).

Thus, the porcelain body exhibits an almost rate-independent response within the range of indentation rates tested.

Sample	v mm/s	L_c mm	$\dot{\gamma}_{eq}$ s ⁻¹	t MPa	$A(v)_{\text{correct.}}$ MPa
AM1	0.95	1.23	0.699	0.052	0.166
AM2	1.14	1.31	1.076	0.063	0.164
AM3	1.37	1.13	1.363	0.063	0.159

Table 2. Rheological data for RAM pressing's stoneware body

and the overall values:

$$\begin{aligned}\tau_{y,\text{conf.}} &= 0.168 \pm 0.025 \text{ MPa} \\ L_c &= 1.40 \pm 0.08 \text{ mm}\end{aligned}$$

By fitting $A(v)_{\text{correct}} = K(v/L_c)^n$, the following values were obtained:

$$\begin{aligned}K &= 0.426 [\text{MPa}\cdot\text{s}^n] \\ n &= -0.110\end{aligned}$$

Within the tested range, the stoneware body exhibits a response that is predominantly governed by confined yielding and is only weakly sensitive to indentation rate. The conclusions drawn for the porcelain body regarding n are equally applicable to the stoneware body.

Thus, the recommended physical interpretation is:

$$\begin{aligned}n &\approx 0 \\ K &\approx 0.436 \text{ MPa}\end{aligned}$$

Thus, the recommended final rheological parameters for the bodies studied are those from following Table 3:

Parameter	Units	Porcelain robocasting	Stoneware RAM pressing
$t_{y \text{ conf.}}$	$\text{MPa}\cdot\text{s}^{-n}$	0.059 ± 0.006	0.168 ± 0.025
K	MPa	≈ 0.163	≈ 0.436
n	adimensi.	≈ 0	≈ 0
L_c	mm	1.22 ± 0.09	1.40 ± 0.08

Table 3. Rheological comparison of porcelain and stoneware bodies

The stoneware body exhibits a confined yield stress approximately 2.8 times higher than that of the porcelain body. It also exhibits a post-yield consistency approximately 2.7 times higher.

Direct fitting yielded slightly negative values of n . However, because the variation of the post-yield contribution with indentation rate is comparable to the experimental scatter, these values have no clear physical significance. Both bodies were therefore considered rate-independent within the studied range ($n \approx 0$).

5. DISCUSSION OF THE RESULTS

The results clearly distinguish the two ceramic bodies. The porcelain body, formulated for robocasting, exhibits low values of confined yield stress and consistency, which is consistent with the need for flow through deposition nozzles under relatively moderate stresses. Such behaviour is generally consistent with the requirements reported for extrusion-based additive manufacturing systems [14]. At the same time, the presence of a measurable yield stress indicates that the body retains some ability to hold its shape after deposition, which is essential for layer-by-layer construction.

The stoneware body exhibits a much higher confined resistance. Its $\tau_{y,conf.}$ is almost three times higher than that of the porcelain body, and the same applies to the post-yield contribution K . This behaviour is consistent with a body intended for RAM pressing, where greater resistance to deformation, higher dimensional stability and a greater ability to withstand compressive and confined stress states during mould filling and compaction are required.

The parameter L_c also differentiates the two bodies. The porcelain body exhibits a mean value of approximately 1.22 mm whereas the stoneware body exhibits a value of about 1.40 mm. This difference suggests that, in the stoneware body, the active deformation zone mobilised by the punch is slightly more extensive, which may be associated with a stronger particulate network and more efficient stress transmission. In the porcelain body, the lower mechanical resistance and greater flowability lead to a more localised mobilisation.

The analysis of the flow behaviour index n requires caution. The direct mathematical fitting gives slightly negative values for both bodies, but these should not be presented as intrinsic rheological properties. The range of indentation rates is narrow, and the values of $A(v)_{correct.}$ vary only slightly, with experimental scatter being comparable to the variation with indentation rate. Therefore, the most scientifically robust conclusion is that both bodies exhibit, under the tested conditions, an almost rate-independent response, i.e.:

$$n \approx 0$$

This means that the behaviour is governed mainly by confined yielding and by the structural resistance of the particulate network, rather than by a viscous contribution dependent on indentation rate.

From a technological point of view, this is an important conclusion: the YIELDcompress® method makes it possible to separate the initial yield resistance, the post-yield resistance and the spatial extent of the deformed zone. This separation is particularly relevant because the processing requirements are different. The porcelain body must flow easily during robocasting, whereas the stoneware body must resist deformation during RAM pressing. The ability to identify independently τ_y , K and L_c from a single confined indentation test supports the proposed interpretation of the test as an implicit viscoplastic triaxial characterisation method.

6. CONCLUSIONS

The porcelain body exhibits a low confined yield stress, low consistency and a characteristic length slightly lower than that of the stoneware body. These results are consistent with its greater suitability for processes requiring controlled flow, such as robocasting.

The stoneware body exhibits significantly higher values of $\tau_{y,conf.}$ and K , reflecting a stronger particulate structure and a greater ability to withstand deformation under confinement. This behaviour is suitable for RAM pressing, where dimensional stability and mechanical resistance during shaping are priorities.

In both bodies, the flow behaviour index should be considered approximately zero within the range of indentation rates tested. Thus, the stress dependence on indentation rate is weak, and the response is dominated by confined yielding and by the internal structure of the body.

The comparison between the two formulations confirms that the confined indentation test can discriminate between ceramic bodies intended for different shaping processes, providing parameters directly related to their industrial processability: $\tau_{yconf.}$, K , n and L_C .

The results support the interpretation of confined indentation as an implicit viscoplastic triaxial test. The YIELDcompress® methodology therefore provides a practical means of characterising plastic ceramic bodies under confined stress states representative of industrial shaping operations, while simultaneously identifying parameters associated with confined yielding, post-yield resistance and deformation-zone mobilisation.

7. REFERENCES

- [1] J.A. Lewis, Colloidal processing of ceramics, *J. Am. Ceram. Soc.* 83 (2000) 2341–2359.
- [2] J.S. Reed, *Principles of ceramic processing*, Journal of the European Ceramic Society, 17 (1997) 541–548.
- [3] W.H. Herschel, R. Bulkley, Consistency of rubber–benzene solutions, *Kolloid-Zeitschrift* 39 (1926) 291–300.
- [4] J.A. Lewis, Direct ink writing of 3D functional materials, *Advanced Functional Materials* 16 (2006) 2193–2204.
- [5] H.A. Barnes, The yield stress – a review or ‘ $\pi\alpha\nu\tau\alpha$ $\rho\epsilon\iota$ ’ – everything flows?, *Journal of Non-Newtonian Fluid Mechanics* 81 (1999) 133–178.
- [6] P. Coussot, Yield stress fluid flows: A review of experimental data, *Journal of Non-Newtonian Fluid Mechanics* 211 (2014) 31–49.
- [7] A. M'Barki, L. Bocquet, A. Stevenson, Linking rheology and microstructure in confined and concentrated suspensions, *Soft Matter* 13 (2017) 2454–2465.
- [8] R. Buscall, L.R. White, The consolidation of concentrated suspensions, *J. Chem. Soc., Faraday Trans.* 83 (1987) 873–891.
- [9] A.N. Schofield, C.P. Wroth, *Critical State Soil Mechanics*, McGraw-Hill, London, 1968.
- [10] Needleman, A., Tvergaard, V., Van der Giessen, E. Indentation of elastically soft and plastically compressible solids. *Journal of the Mechanics and Physics of Solids*, 2015.
- [11] R. Hill, *The Mathematical Theory of Plasticity*, Oxford University Press, Oxford, 1950.
- [12] S.P. Timoshenko S.P., Goodier J.N., *Theory of Elasticity*, McGraw-Hill, New York, 1970.

- [13] D.C. Drucker, W. Prager, Soil mechanics and plastic analysis or limit design, *Q. Appl. Math.* 10 (1952) 157–165.
- [14] D.M. Wood, *Soil Behaviour and Critical State Soil Mechanics*, Cambridge University Press, Cambridge, 1990.