

The workability index of three tap-hole clays

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Abstract – In clay-gun operation, when closing a furnace tap-hole, plasticity is the clay characteristic of importance. As a measure of plasticity, the workability index of tap-hole clay (often shortened to workability) is typically reported on datasheets, often without quoting the method applied. Even when results and standard methods applied are known, the correlation between the workability index and clay-gun performance is not clear. In the study presented here, the workability indexes of three different tap-hole clays were determined, by applying ISO 1927-3 (2012) as a standard, and using three different sand-rammers, two manual and one automated.

Keywords: tap-hole clay, workability index, sand-rammer

INTRODUCTION

Tap-hole clay is used to close the tap-hole after tapping slag and/or alloy from a smelter and, in some instances, to repair the tap-hole (Nelson & Hundermark, 2016). Clay-guns are typically used to force clay into tap-holes (Dienenthal, 2014), and the clay characteristic of importance is plasticity. As a measure of plasticity, the workability index of tap-hole clay (often shortened to workability) is typically reported on product datasheets. Although standard methods are available to determine the workability index (ASTM-C180, 2011; ISO 1927-3, 2012), the method applied is seldom reported. In a survey of 14 product datasheets for tap-hole clays available commercially, 10 reported workability index results (with values ranging between 22 and 70 per cent). Only one reported the internationally recognised standard method applied (EN 1402-3 which was superseded by ISO 1927-3). Even when results and standard methods applied are known, the correlation between the workability index and clay-gun performance is not clear. The work presented here reports on the first step taken towards developing an understanding of the correlation between the workability index of tap-hole clay and performance of the clay-gun.

BACKGROUND

Plasticity of a material is defined as the ‘quality of being easily shaped or moulded’ (Oxford Dictionary, 2017).

According to the laws of physics (Sears *et al.*, 1987), when a compressive force (F , N) is applied perpendicularly to the surface (A , m²) of a material, as in Figure 1(a), the material is in compressive stress (σ , Nm⁻²), according to Equation [1].

$$\sigma = \frac{F}{A} \quad [1]$$

The change in the length of the body due to the application of F is referred to as the compressive strain (ϵ , dimensionless) as defined in Equation [2].

$$\epsilon = \frac{\Delta H}{H} \quad [2]$$

According to Hooke's law, the compressive stress is proportional to compressive strain when a relatively small force is applied to a material, and the ratio of stress and strain remains constant. This constant ratio is called Young's modulus and describes elastic behaviour of a material. When plotting a stress – strain curve for any material (Figure 1(a)), Hooke's law will apply when stress is directly proportional to strain. Under these conditions, the material shows elastic behaviour and returns to its original shape when the force is removed. When the stress-strain curve deviates from linearity, plastic deformation occurs and the material does not return to its original shape when the force is removed.

Plasticity therefore enables a solid to undergo plastic deformation, without rupture, when subjected to an external force.

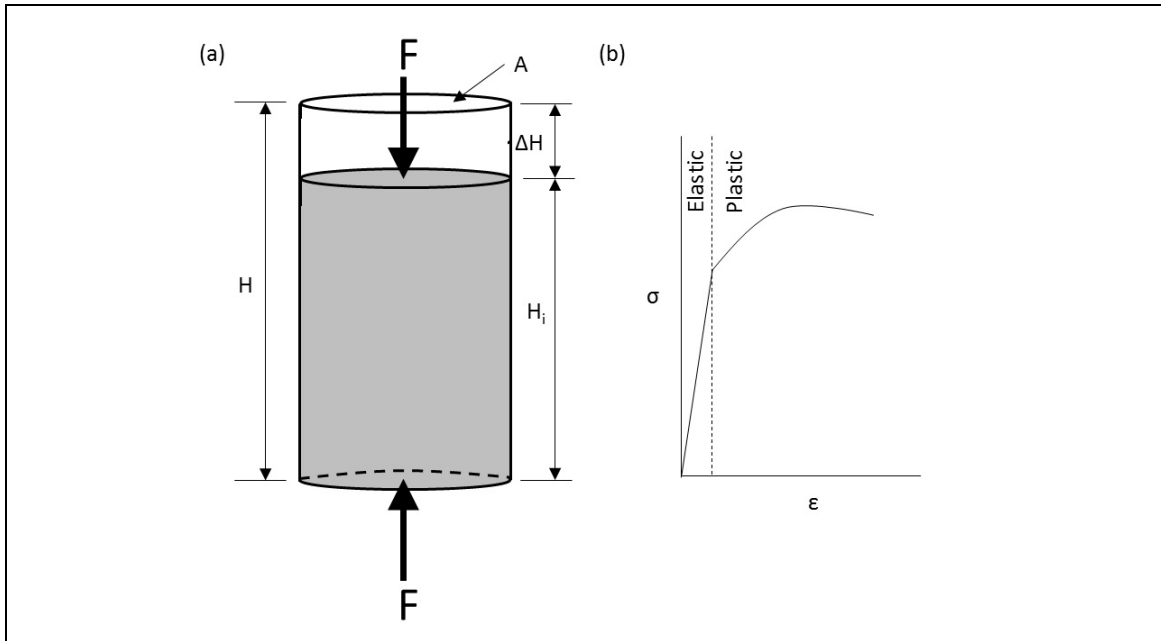


Figure 1: (a) A cylinder in compression and (b) a conceptual stress-strain curve that illustrates the difference between elastic and plastic behaviour

A clay-gun works like a syringe, where a hydraulic cylinder pushes a piston in the cylindrical clay barrel, and the force applied extrudes the clay into the tap-hole (Anonymous, 2016) – see Figure 2. With the application of a large enough force, and use of tap-hole clay with the ideal plasticity, an effective seal is formed in the tap-hole that contains liquid alloy and/or slag in the furnace until the next tap is due.

Plasticity of clays is quantified using standard laboratory tests. Andrade *et al.* (2011) reviewed a number of laboratory-scale tests that are available to quantify the plasticity of water-based clays. They identified that the measuring principles applied depended on moulding, impact deformation, penetration, pressure, or torque. The measuring principle applied in the ISO 1927-3 standard is impact deformation. ASTM C180 describes a similar method and states that the tests:

1. Produce a workability index that serves as a measure of the facility with which refractory plastic materials can be rammed, gunned, or vibrated into place, and is used as a quality control measure during manufacturing and by clients.
2. Give an indication that the material is 'short' or lacking in plasticity, when a sample splits under impact. Should the sample split under impact, a workability index cannot be reported.

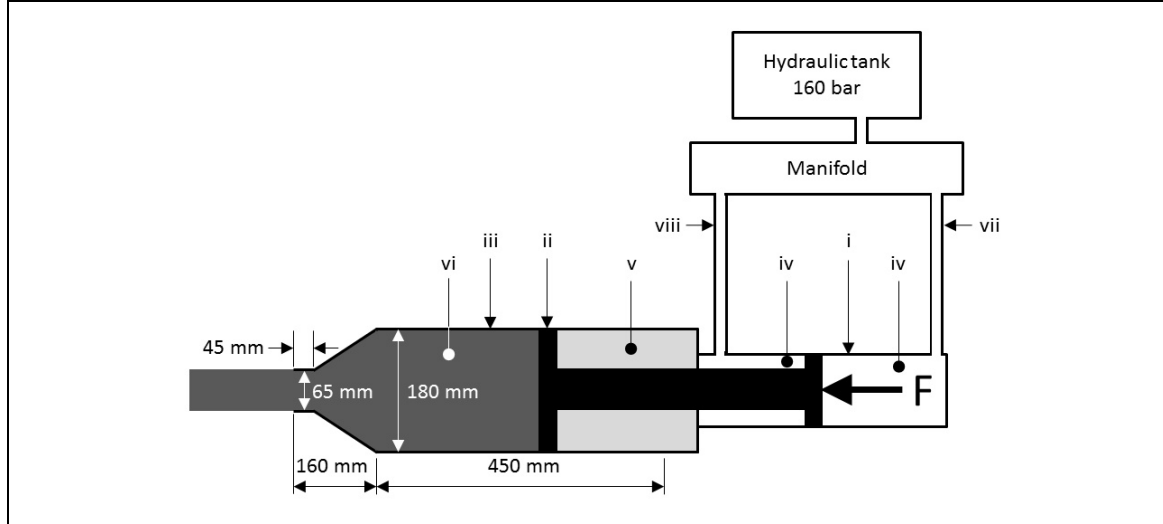


Figure 2: Schematic layout of the pilot-scale clay-gun, which consists of (i) a hydraulic cylinder, (ii) a piston, and (iii) a clay barrel. The hydraulic cylinder is filled with (iv) oil; the clay barrel to the back of the piston with (v) air; and to the front with (vi) tap-hole clay. When pushing the clay towards the tap-hole, pressurised oil is applied through pipe (vii), and non-pressurised oil released through pipe (viii). When the piston is pulled back, pressurised oil is applied through pipe (viii), and non-pressurised oil released through pipe (vii). F indicates the force applied to the clay by the hydraulic system.

In principle, the method (ISO 1927-3, 2012) works as follows: a sample of tap-hole clay, of predetermined mass, is placed in a cylindrical steel mould (50 mm inside diameter, 140 mm height) and is rammed three times by a piston to which a weight of $6.67 \text{ kg} \pm 50 \text{ g}$ is attached. With each ram, the piston is dropped from a fixed position, 47 mm above a flange that stops the momentum of the weight. The equipment used is referred to as a “sand-rammer for refractory materials”, and ramming can be done either manually, using a crank, or automatically. To reduce the effect of temperature, material is tested in the range 18°C to 24°C (ASTM-C180, 2011).

The height of the sample (H) is measured before ramming, and again after three rams (H_3) – see Figure 3. The workability index (W_1) is calculated according to Equation [3].

$$W_1 = \frac{100(H - H_3)}{H} \quad [3]$$

The required sample mass is determined by ramming between 200 g and 300 g of tap-hole clay, 10 times on one side and 10 times on the other, targeting a height of $50 \text{ mm} \pm 2 \text{ mm}$. The sample mass is adjusted until the target height is achieved. Results are reported in Table I.

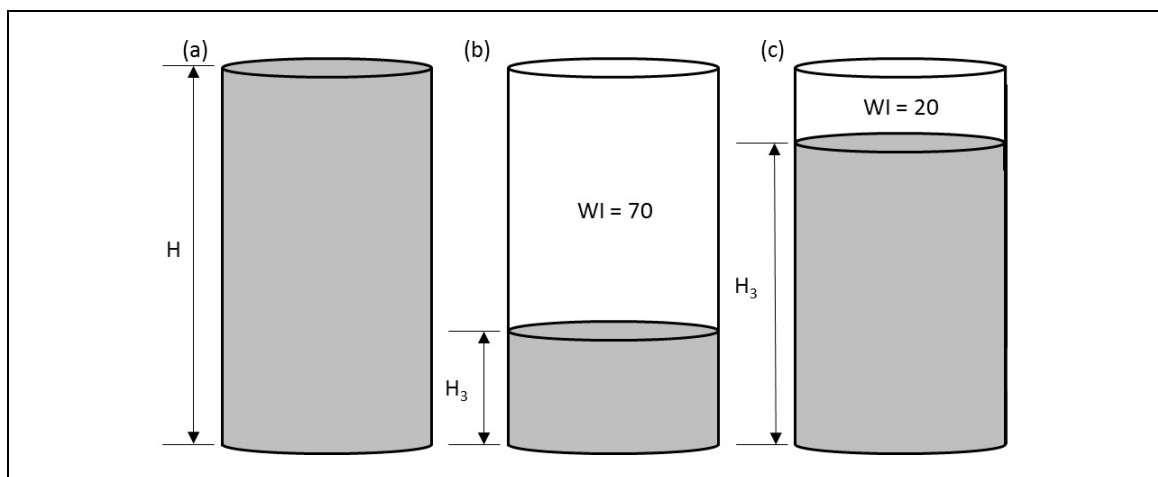


Figure 3: Schematic of tap-hole clay sample (a) prior to and (b, c) after being rammed three times using a sand-rammer. (b) illustrates what the sample height will be after ramming for a workability index of 70 and (c) for 20, for an initial height as in (a).

In the datasheets surveyed, the reported workability indexes ranged between 22 and 70 per cent, with an average value of 49, and standard deviation of 12. In Figure 3, the sample height for workability indexes of 70 and 20 are indicated: a workability index of 70 requires a reduction in sample height to one third of its original height in only three rams. This is highly unlikely for any tap-hole clay, and values such as these are questionable.

METHOD

In the study reported here, the workability indexes were determined for three different tap-hole clays. The clays were supplied by a South African producer of ferrochromium which operates three open and two closed submerged arc furnaces (SAFs). The clays were labelled A, B, and C. All five SAFs operated with carbon-based, conductive lining designs. At the open SAFs, clay B was used for general closing of the tap-hole, and clay C for tap-hole repairs. As tap-hole wear was much more significant in the closed SAFs, only clay C was used. Clay A was an experimental clay, and considered as an alternative to both clay B and C.

As is the case with refractory materials, tap-hole clay typically consists of aggregate and binder phases. According to the product datasheets, clay B was resin and water-bonded with mainly silica as aggregate. Clay C was tar and resin bonded, with mainly alumina as aggregate. In both instances, the maximum particle size of the aggregate was 3 mm. For neither of the two clays was a workability index reported. No datasheet was available for clay A.

ISO 1927-3 was applied using a sand-rammer procured for the purpose of the investigation (manual sand-rammer #1). To validate the results obtained, the workability indexes for samples from the same clays were determined at a laboratory in Norway, using both a manual (sand-rammer #2) and an automated sand-rammer. Manual sand-rammer #1 was supplied by Simpson Technologies, a company based in Switzerland, and the model number was 42100. Manual sand-rammer #2 was more than 50 years old, and neither the supplier details nor the model number was available. The automated sand-rammer was supplied by Research and Development of Carbon in Switzerland, and the model number was RDC194.

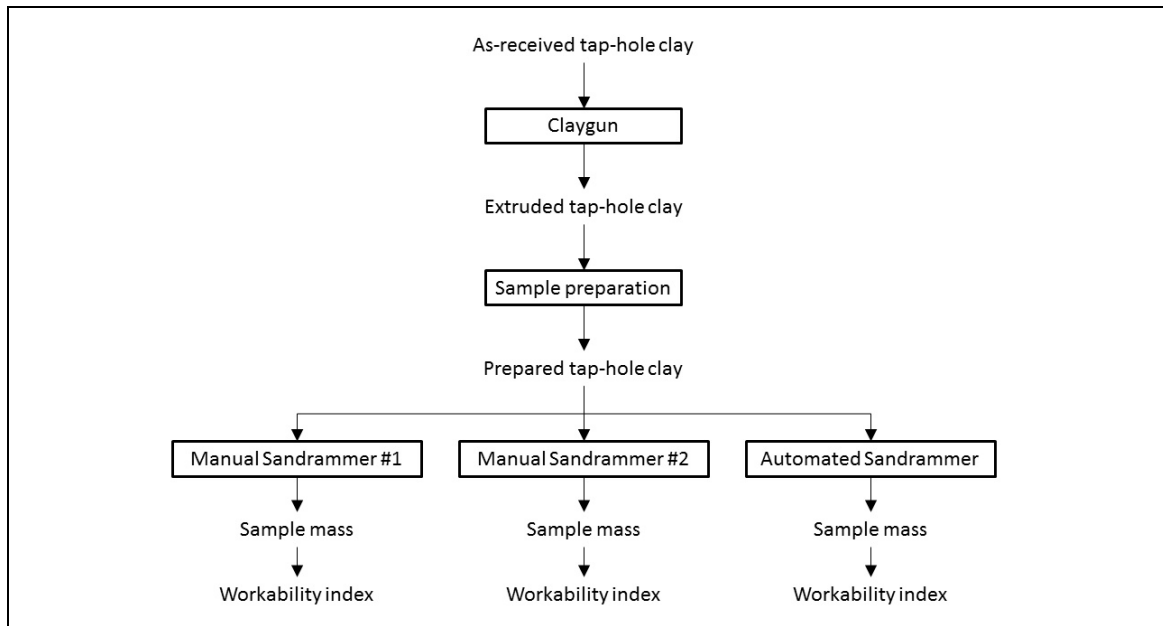


Figure 4: Experimental procedure applied per clay

The procedure applied to prepare the clay is outlined in Figure 4. To prepare the samples, the tap-hole clays were loaded and extruded in a pilot-scale clay-gun available in South Africa – see schematic in Figure 2 for dimensions of the clay-gun. During extrusion, the extruded clay was supported by angle iron attached to the mouth-piece of the clay-gun. The extruded clay was cut into 70 mm lengths. The sample mass per clay was determined (reported in Table I) and then the workability index. When determining the workability index, the height of the sample before and after ramming, the sample temperature, sample weight, and whether the sample crumbled as a result of ramming or not, were recorded. All clays were analysed within the shelf-life limitations stated by the supplier, and care was taken to seal clays from the atmosphere, between sample preparation and ramming.

RESULTS AND DISCUSSION

The sample masses determined per clay, per type of equipment, was reported in Table I. The results for clay A were consistent for the three different pieces of equipment. The values for clay B and C were not, and the reason became clear when studying the results from the automated sand-rammer – see discussion below.

In Figure 5, the average workability index, per type of clay, is reported (5 repeats per clay per method), as determined by the three different pieces of equipment. If the techniques were repeatable, one would expect the results obtained between equipment types to be similar for each clay. That was the case for clay A only, with the largest workability index, and where no statistically significant difference in the average workability index was observed when the automated sand-rammer was used when compared to manual ramming. It was not the case for clay B and clay C.

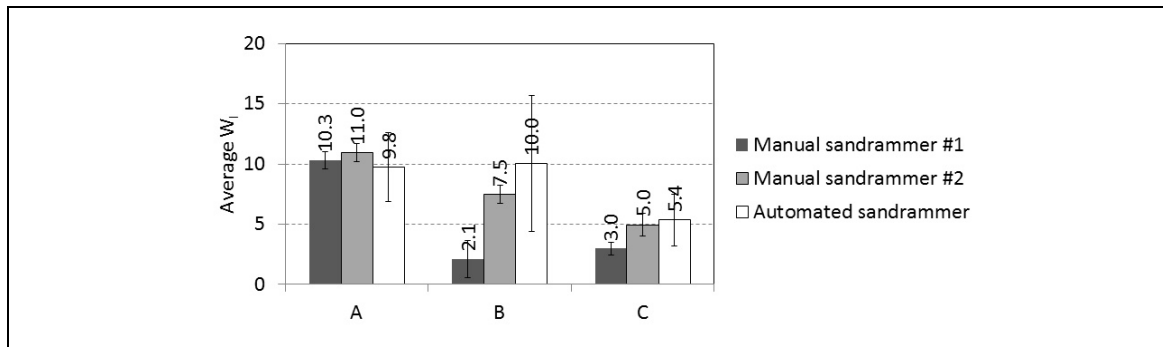


Figure 5: Average workability index per type of clay determined for the three different pieces of equipment. Error bars indicate the 95% confidence interval on the average workability calculated from five data points per test.

Being automated, one would expect the results obtained with the automated sandrammer to be most repeatable. Surprisingly, that was not the case, as the 95% confidence interval on the average was largest for the automated sandrammer – see Figures 5 and 6.

According to the standard, the workability index is determined after 3 rams. For the automated sandrammer, the sample height after 3, 50, and 100 rams could be determined – see Figure 7. Only for clay B was the average sample height after 3 rams the same as after 50 and 100 rams. For clay A, this point was reached only after 13 rams, and for clay C after 36 rams.

For clay B, the error in the initial two measurements was fairly large, but thereafter very small – see Figure 8(b). For clay A, the error in the initial measurements was largest, and stabilised at 6 rams (Figure 8(a)). The initial error for clay C was the same as for clay B, but, unlike clay B, the error in the measurements remained constant throughout (Figure 8(c)).

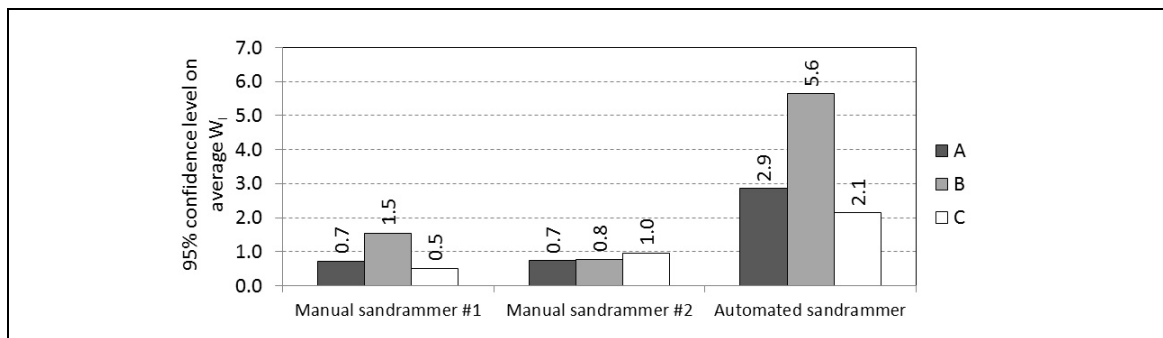


Figure 6: 95% confidence interval on the average workability index per type of equipment for each type of clay from five data points per test

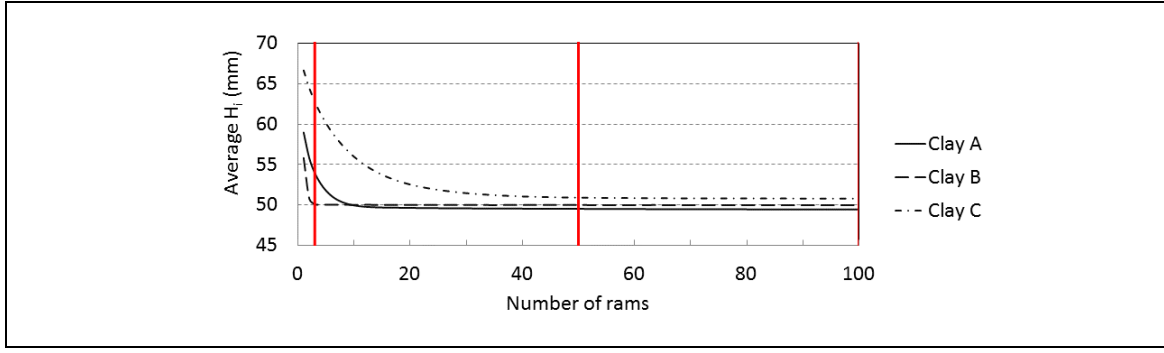


Figure 7: Average sample height as a function of number of rams for the three clays determined by the automated sand-rammer (clay A: 6 data points, clay B: 5 data points, and clay C: 5 data points). Vertical lines indicate 3, 50, and 100 rams.

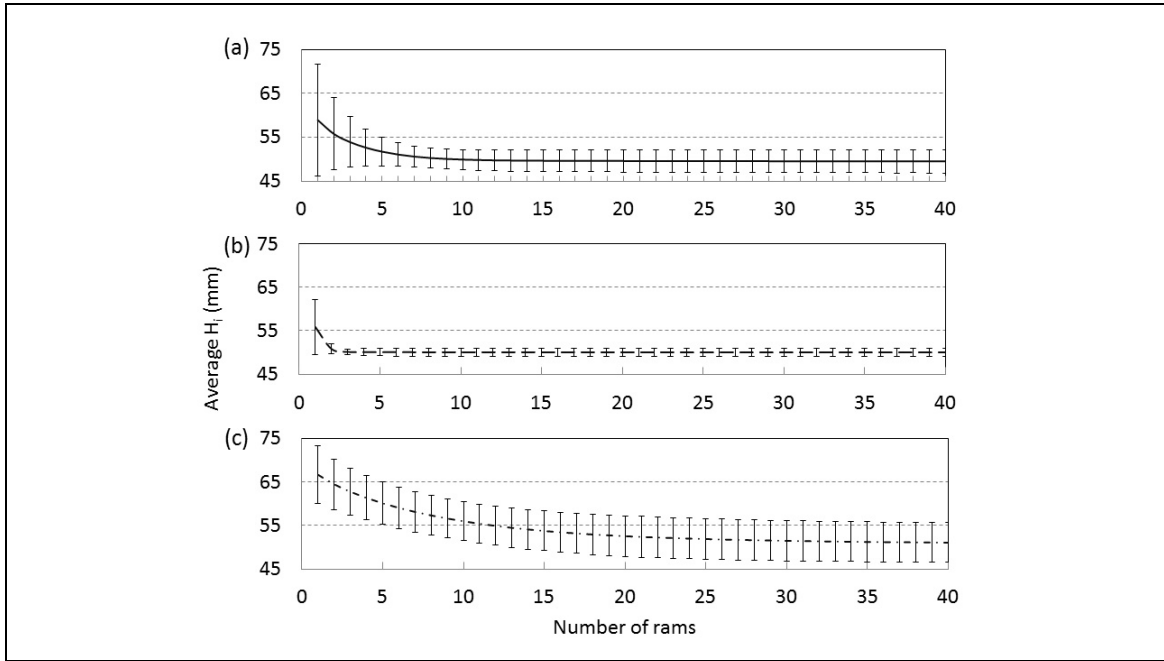


Figure 8: Average sample height as a function of number of rams determined for (a) clay A, (b) clay B, and (c) clay C, using the automated sand-rammer. Error bars indicate the 95% confidence interval on the average (clay A: 6 data points, clay B: 5 data points, and clay C: 5 data points).

The effect of the delayed stabilization in height on the workability index is illustrated in Figure 9(a). An extended workability index was calculated for each subsequent ram according to Equation [4]. As for Equation [3], H is the initial height of the sample. H_i is the height of the sample at each ram, starting at 3 rams (as per the standard) and followed by 4, 5, 6 rams, etc. Figure 9(b) indicates the ratio of the extended workability index per ram to the workability index determined after 3 rams, for each clay. As expected, the extended workability index remained constant at 10% for clay B. For clay A, it stabilised at 16%, nearly double the value reported after 3 rams, and for clay C at 24%, which was four times higher.

$$ExtendedW_i = \frac{100(H - H_i)}{H} \quad [4]$$

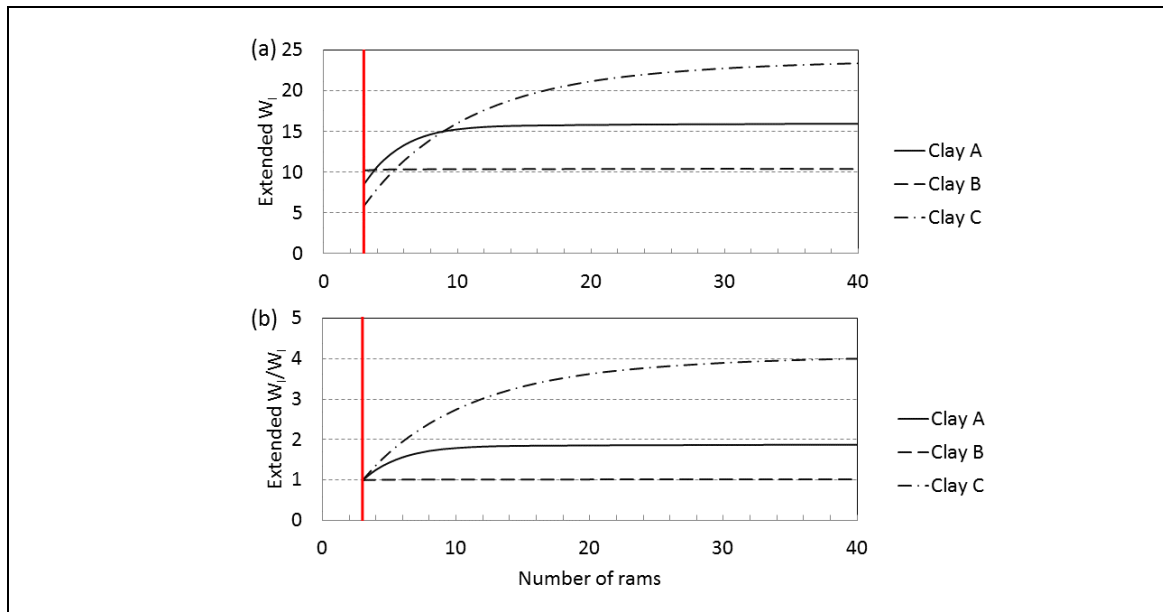


Figure 9: (a) Extended workability index per type of clay calculated for results in Figure 8 using Equation [4]; (b) ratio of extended workability index to workability index for each type of clay

The effect of delayed stabilization in height is illustrated by the effect on calculated density (ρ in g/cm^3 in Figure 10(a)), or the ratio of density after any given ram to the density after 100 rams (Figure 10(b)) per ram, for each of the clays. Again, the density of clay B remained constant after 3 rams, with that of clay A and clay C increasing with the number of rams. If compared after 3 rams, clay C is less dense than clay B, but once stabilised, the density was higher.

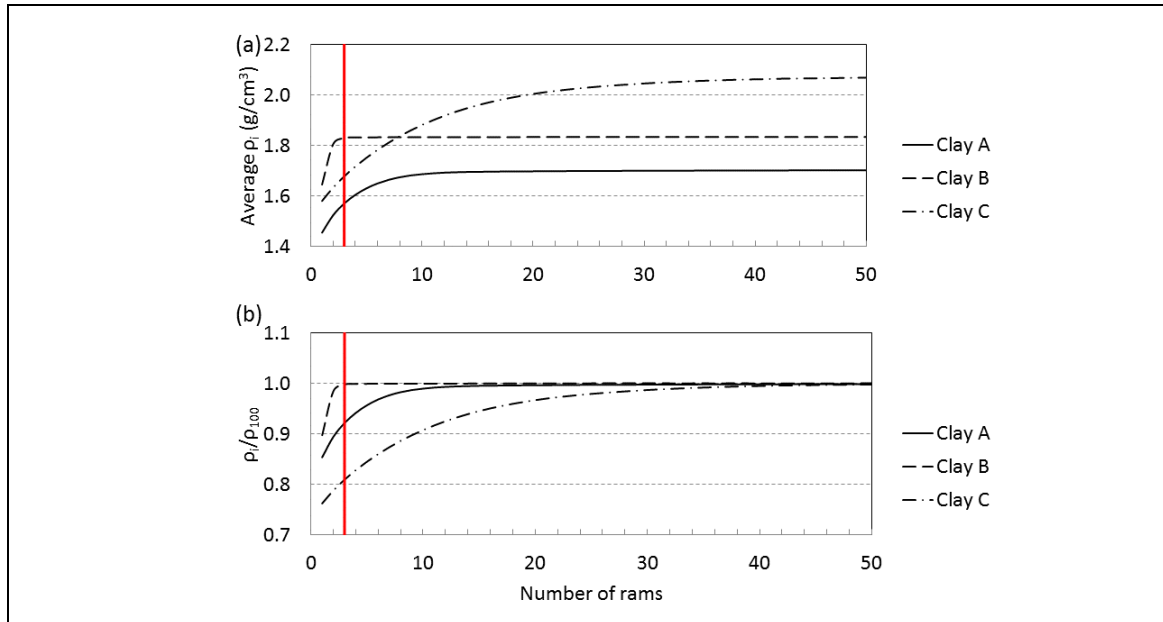


Figure 10: (a) Average density per type of clay calculated for results in Figure 8
(b) Ratio of density after a specific number of rams to density after 100 rams, per type of clay

What these differences in workability indexes mean in terms of clay-gun operation, will be determined in a subsequent phase of the study. To quantify the forces needed to push the clay from the clay-gun, a pressure sensor will be installed in-line (vii in Figure 2). Such an installation will allow for the quantification of the effect of differences in workability indexes on the pressure required to push the clay from the clay-gun.

The effect of differences in tap-hole clay densities on clay-gun operation can be illustrated as follows: when using the sample masses obtained through experiment, the density of each of the clays was calculated. The assumption was made that the final sample diameter was 50 mm and the height was 50 mm after ramming. Using the results obtained, and assuming that the tap-hole dimensions of a newly installed, industrial-scale tapblock are 100 mm in diameter and 1300 mm in length (Steenkamp *et al.*, 2015), the mass of clay required to fill the tap-hole was calculated for each clay – see Table I. As tap-hole clay is typically sold by mass, 1.1 times more of clay B will be required compared to clay A, and 1.4 times more of clay C.

Table I: Summary of results

	Comment	Clay A	Clay B	Clay C
Sample mass (g)	Manual sand-rammer #1	165	178	250
	Manual sand-rammer #2	165	175	230
	Automated sand-rammer	165	180	235
WI₃	Manual sand-rammer #1	10	2	3
	Manual sand-rammer #2	10	8	5
	Automated sand-rammer	10	10	5
Extended WI₁₀₀	Automated sand-rammer	16	10	24
ρ_{100} (g/cm³)	Automated sand-rammer	1.70	1.83	2.07
Calculated ρ (g/cm³)	All sand-rammers	1.68	1.81	2.43
Calculated mass of clay required to plug industrial tap-hole (kg)	Based on calculated ρ (g/cm ³), tap-hole dimensions being 100 mm in diameter and 1300 mm in length	17	18	25

CONCLUSIONS

1. Plasticity of tap-hole clay plays a role in the performance of clay-guns, and the quality of the seal produced when plugging a tap-hole. The workability index is a way of quantifying the plasticity of tap-hole clays for which standard methods, *i.e.*, ASTM-C180 (2011) and ISO 1927-3 (2012), exist.
2. A method, based on ISO 1927-3 (2012), was developed in South Africa to quantify the workability index of tap-hole clays using a manual sand-rammer. Results obtained for three different tap-hole clays were validated against results obtained for the same clays at a laboratory in Norway, all within the shelf-life of the clay. In Norway, a manual sand-rammer and an automated sand-rammer were applied. Ranging between 2 and 10, the workability index results obtained were significantly lower than those reported on datasheets for other industrial tap-hole clays (ranging between 22 and 70). Interestingly enough, the automated sand-rammer displayed the largest variability in measurements, and the two manual methods produced very similar results. To improve the method developed in South Africa, systems will be put in place to ensure the ISO standard is applied consistently.
3. Once a validated method is available, the effect of clay design parameters (*i.e.*, aggregate type, morphology, and size; and binder type) or process parameters (*i.e.*, clay temperature or shelf-life) on the plasticity of clay will be investigated.

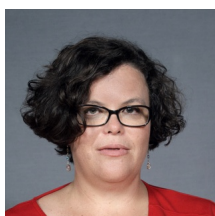
4. As the next phase in the study, the effects of variations in workability index on clay-gun operation will be investigated by quantifying the force exerted by the clay-gun piston on the tap-hole clay during extrusion.

ACKNOWLEDGEMENTS

This paper is published with the support and permission of Mintek and Elkem Ferrovel. The assistance of our colleagues is gratefully acknowledged.

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Joalet joined Mintek in 2014 after completing her PhD studies. Prior to that, she had 12 years' experience in industry – operations, projects, and research environments (steelmaking, ilmenite roasting and smelting, and manganese ferro-alloy production) – and 3 years' experience in academia where she taught courses in pyrometallurgy at both undergraduate and postgraduate level. Her main research interests are furnace tapping, and production of manganese ferro-alloys. She mainly conducts industrial research, for which she was recognised by professional bodies both locally and abroad. Joalet holds B.Eng., B.Eng.Hons., M.Eng., and Ph.D. degrees in Metallurgical Engineering, all conferred by the University of Pretoria in South Africa. She is a Fellow of the Southern African Institute of Mining and Metallurgy (SAIMM) where she was the founder of the series of Schools on Production of Manganese Ferro-alloys, and the series of Conferences on Furnace Tapping. Joalet is also a member of The Minerals, Metals & Materials Society (TMS) and a registered professional engineer (Pr.Eng.) with the Engineering Council of South Africa (ECSA). Joalet is married, and blessed with two children. Her hobbies include photography (her furnace photography received international recognition), reading, gardening, hiking, and travelling.
