

Article

Utilising Flowability Sensor for Green Sand Mould Characterisation

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ABSTRACT

In this work, an attempt has been made to improve the sand casting process by reducing the percentage of casting defects. The enhancement of the sand casting process is based on producing green sand castings with good pattern profiles and no failures at any complex points during the separation process, handling and transportation. This work introduces modified, non-destructive, direct tests for measuring sand mould properties using sensor readings. A new flowability sensor has been used to measure the time-dependent density, distance-dependent mould hardness, and distance-dependent mould strength. The sensor is able to detect sand motion at the desired points during the mould-making process. The live characterisation of the green sand mould is used to determine the optimum parameters for the compaction process, reduction of the moulding time, and spent energy, so that the cost of the moulding and casting process will be reduced. It has been found that there is a linear relationship between the properties of the green sand samples and the sensor signals. The new method facilitates the measurement of sand properties and determines the most effective moulding parameters based on the flowability sensor readings. The resultant increases in both compactibility and compaction pressure improve mould hardness and mould strength.

1. Introduction

The main challenge in foundries is obtaining bentonite-bonded green sand moulds without failures at any point of the sand moulding process, especially in the critical regions, which are shown in Figure 1. Failure usually occurs due to existing variations in the density distribution across the sand mould. Variations of sand mould density during the compaction process have an influence on the distribution of mechanical properties. Therefore, there is an urgent need to introduce a method for measuring the properties of green sand moulds during the moulding process. In previous work in this area, Bast et al. [1, 2] used density sensors to measure sand density based on the relationship between sand density and sensor signals. Similarly, Kadauw [3] utilised the Industrial Computed Tomography (ICT) method to calculate sand density by creating a relationship between ICT signals and real density.

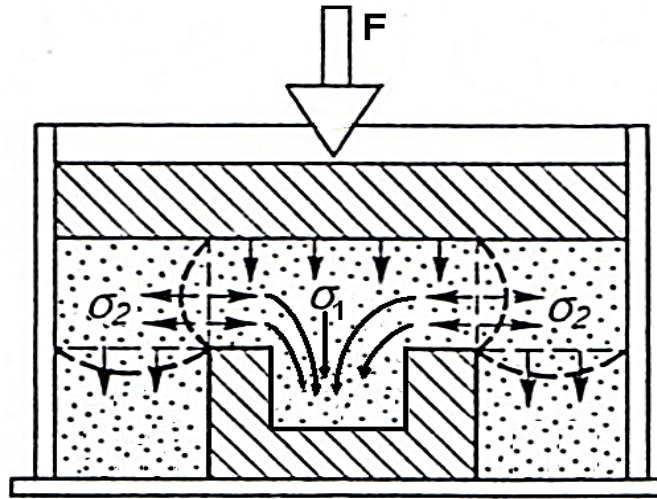


Figure 1: Distribution of stresses during sand compaction process [4].

The present method for the measurement of green sand properties is based on the flowability sensor developed by Bast [5]. Two sensors are installed in a stepped pattern with an upper and lower level. The sensor gives out signals during the compaction process of the green sand, as is shown in Figure 2, where S_u and S_o are the values of the lower and upper sensors, respectively. The sensor signals evaluate the moulding process based on the flow of material. If the sand does not move, there will be no sensor motion [6].

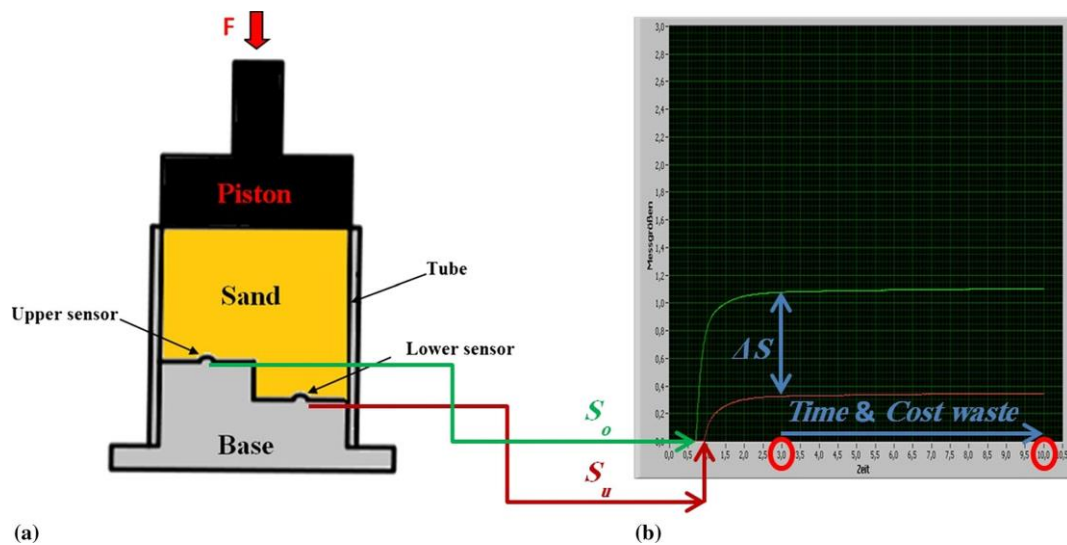


Figure 2: Compaction process of the green sand – (a) principle of the flowability test; (b) sensor signals [7].

The dynamic behaviour of the sensor signals during the sand moulding process may be related to three types of nonlinearity in the compaction process: mechanical response, structural, and contact [8]. Characterisation of the sand mould is based on the calibrated sensor signals. The validity of the calibration process is confirmed by the results from the sand samples, which could be applied to the actual sand mould making process [1]. The relationships between the sensor signals and sand properties should be measured, so that the calibration of the sensor readings allows them to accurately track the sand mould properties. This calibration process requires the production of sand samples. During this process, the properties of these samples and the sensor signals are measured simultaneously. After being calibrated, the mentioned properties of the sand mould can be determined as a function of the sensor readings [1, 6, 9, 10]. The present work is focused on evaluating the behaviour of the green sand mould during the moulding process through an economical and safe direct measurement method using the flowability sensor.

2. Methodology

To monitor time-dependent density during the mould making process, the method uses sensor signals that are related to the sand density by means of multiple linear regression models. The final sensor signals were also applied to measure distance-dependent mould hardness and distance-dependent mould strength. The usual measurements of sand properties and sensor signals are measured simultaneously. In order to validate the applicability of the developed relationships for calculating sand mould properties, several experiments have been carried out. This work used different tools, equipment, and software during the practical investigation of green sand properties. Understanding the properties of the moulding materials and the ideal parameters for the moulding process is necessary to improve the compaction systems in foundries. For this purpose, the effects of different moulding parameters on the properties of green sand mould have been studied in this research. The experiments focussed on the determination of the factors that affect density, mould hardness and mould strength (i.e. pressing forces), and compactibility. These parameters of the moulding process have been described using multi-level design experiments and Q-das software during the compaction of green sand by high-speed and low-speed compaction machines.

3. Sensor Signal-dependent Density

A multiple linear regression model has been used to investigate the relationship between time-dependent density and the corresponding sensor signals. This model describes how a single response (Y) depends on a number of predictor variables. The multiple linear regression model is a function of two or more variables (X_n) and can be written as

$$Y = F(X_1, X_2, \dots, \dots, X_n).$$

The simplest multiple regression model uses the Y function of two variables, X_1 and X_2 , so that

$$Y = F(X_1, X_2)$$

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 \quad (1)$$

The values of α_0 , α_1 , and α_2 are regression coefficients that are determined by the solution of the following matrix [11]:

$$\begin{bmatrix} n & \sum_{i=1}^n X_{1,i} & \sum_{i=1}^n X_{2,i} \\ \sum_{i=1}^n X_{1,i} & \sum_{i=1}^n X_{1,i}^2 & \sum_{i=1}^n X_{1,i} X_{2,i} \\ \sum_{i=1}^n X_{2,i} & \sum_{i=1}^n X_{1,i} X_{2,i} & \sum_{i=1}^n X_{2,i}^2 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^n Y_i \\ \sum_{i=1}^n X_{1,i} Y_i \\ \sum_{i=1}^n X_{2,i} Y_i \end{bmatrix}$$

where n is the number of sensor readings, and $i = 1, \dots, n$.

The usual measurements of density (ρ_r) were taken during the compaction process using a displacement sensor, which was accompanied by the pressing machine. The matrix above can be rewritten in terms of S_u and S_o as described below:

$$\begin{bmatrix} n & \sum_{i=1}^n S_{u_i} & \sum_{i=1}^n S_{o_i} \\ \sum_{i=1}^n S_{u_i} & \sum_{i=1}^n S_{u_i}^2 & \sum_{i=1}^n S_{u_i} S_{o_i} \\ \sum_{i=1}^n S_{o_i} & \sum_{i=1}^n S_{u_i} S_{o_i} & \sum_{i=1}^n S_{o_i}^2 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^n \rho_{r,i} \\ \sum_{i=1}^n S_{u_i} \rho_{r,i} \\ \sum_{i=1}^n S_{o_i} \rho_{r,i} \end{bmatrix}$$

where

$\rho_r(g/cm^3)$ = the usual measurement of density

A mathematical relationship between the usual measurements of density and the sensor signals was investigated to determine the sensor signal-dependent density [$\rho_s(g/cm^3)$]:

$$\rho_s = \alpha_0 - \alpha_1 S_u + \alpha_2 S_o \quad (2)$$

The moulding material used to investigate mould density, hardness, and strength was 10% bentonite-bonded natural sand (NS). The grain size distribution of the natural sand is listed in Table 1. Additionally, the mechanical properties of bentonite-bonded green sand are provided in Table 2, where σ_c , σ_t , σ_s are compressive strength, tensile strength, and shear strength, respectively.

The experiments investigating density were carried out using a high-speed pressing machine, which has a maximum pressing speed of 36mm/sec and 0.4Mpa pressure. A displacement gauge was installed on the pressing machine, as shown in Figure 3, to record the changes in the sand sample length during the compaction process. The weight of the sand sample was inputted through the LabVIEW software. The volume of the sand sample and the variation of density were recorded during the compaction process. At the same time, the sensor emitted signals, which were transported by transducers to a data-acquisition system.

Table 1: Grain size distribution of sand NS [7].

Mesh (mm)	0.315	0.2	0.16	0.125	0.1	0.08	0.063	0.063
(Residue / sieve) (g)	0.60	0.8	1.2	2.2	8.6	29.2	26.4	12

Table 2: Characteristics of bentonite bonded green sand NS [7].

Compactibility (%)	35	40	45
H ₂ O (%)	4.17	4.67	4.81
σ_c (N/cm ²)	14.88	16.92	17.75
σ_t (N/cm ²)	1.47	1.66	1.76
σ_s (N/cm ²)	2.91	3.07	3.94



Figure 3: High-speed pressing machine.

The factors and their levels in the density test are listed in Table 3 and the design of these experiments are mentioned in Table 4.

Table 3: Variables and their levels.

Factors	Compactibility	Compaction Pressure
Symbol	Co	P
Units	%	MPa
Main level (0)	40	0.3
Higher level (+1)	45	0.4
Lower level (-1)	35	0.2
Interval	5	0.1

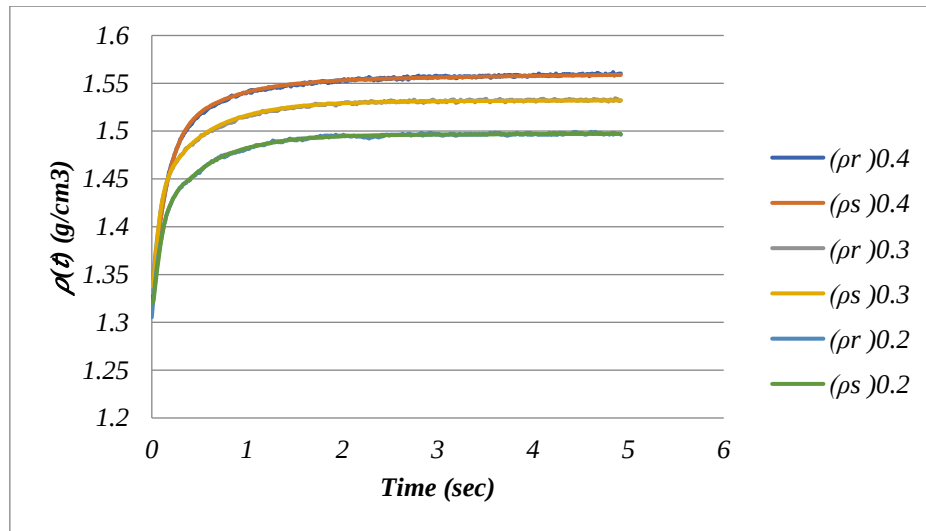
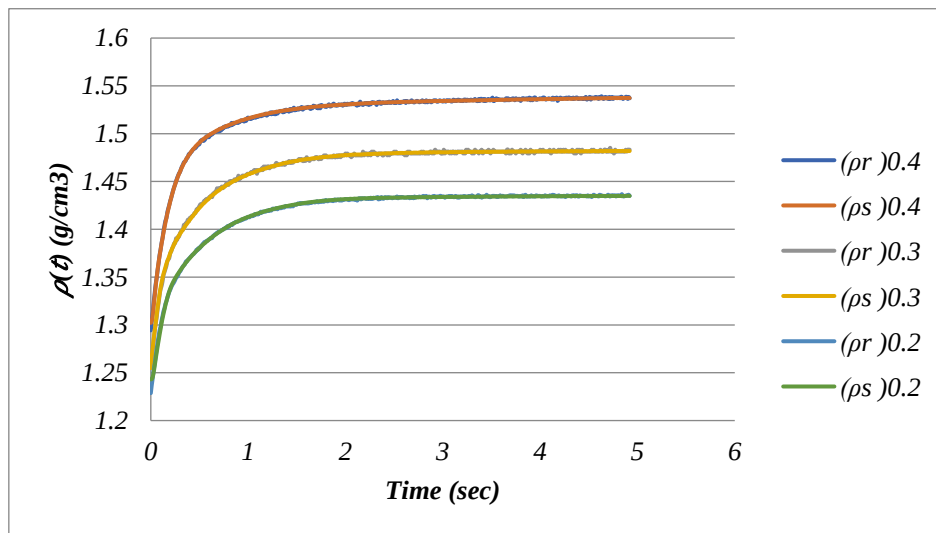
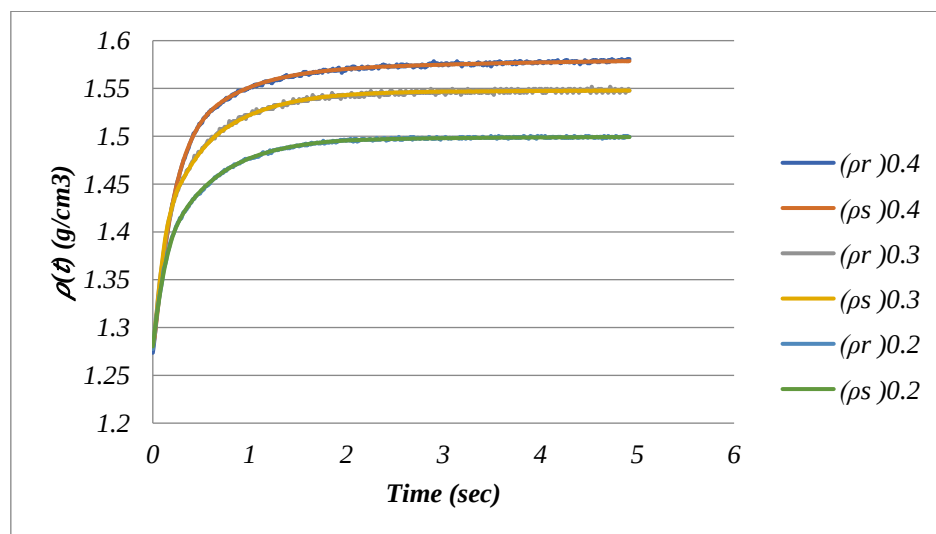
Table 4: Design of experiments during compaction by high-speed pressing machine.

Number of experiments	Variables		Final response by sensor	
	Co %	P (MPa)	S _u (mm)	S _o (mm)
1	-1	-1	0.469	0.930
2	0	-1	0.420	0.946
3	+1	-1	0.376	1.032
4	-1	0	0.584	1.037
5	0	0	0.637	1.201
6	+1	0	0.767	1.668
7	-1	+1	0.819	1.118
8	0	+1	0.817	1.326
9	+1	+1	0.834	1.547

Table 5 shows the mathematical equations for sensor signal-dependent density for all experiments that were listed in Table 4. The matrices and regression parameters α_0 , α_1 , and α_2 have been solved using Matlab software, where α_0 indicates the initial density of the sample. Figures 4–6 show drawings of these equations and comparisons between the usual measurement of density (ρ_r) and the sensor signal-dependent density (ρ_s). It finds a good agreement between the two. The calculated dynamic density assists in the calculation of a sufficient compaction time without any waste of energy, resulting in an economical moulding process. In this work, the effects of different compactibilities and pressures on the material-dependent density of green sand has been studied. The obtained results show that this non-destructive method allows the ability to determine the most effective parameters for the moulding process. The new method, which is based on the detection of sensor signals, shows that density is inversely proportional to compactibility and directly proportional to pressing force. The results show that this new approach reduces the time needed to monitor sand properties and improves the accuracy of the measured properties.

Table 5: Relationships between density and sensor signals.

Ex. No	Mathematical relationships
1	$\rho_s(t) = 1.3195 - 0.0679 S_u(t) + 0.2251 S_o(t)$
2	$\rho_s(t) = 1.2431 - 0.0606 S_u(t) + 0.2297 S_o(t)$
3	$\rho_s(t) = 1.2802 - 0.0369 S_u(t) + 0.2257 S_o(t)$
4	$\rho_s(t) = 1.3376 - 0.0985 S_u(t) + 0.2430 S_o(t)$
5	$\rho_s(t) = 1.2548 - 0.0580 S_u(t) + 0.2200 S_o(t)$
6	$\rho_s(t) = 1.2843 - 0.0483 S_u(t) + 0.2479 S_o(t)$
7	$\rho_s(t) = 1.3325 - 0.1761 S_u(t) + 0.3315 S_o(t)$
8	$\rho_s(t) = 1.3021 - 0.0887 S_u(t) + 0.2325 S_o(t)$
9	$\rho_s(t) = 1.2835 - 0.0764 S_u(t) + 0.2323 S_o(t)$

Figure 4: Comparison between ρ_r and ρ_s @ 35% Co.Figure 5: Comparison between ρ_r and ρ_s @ 40% Co.Figure 6: Comparison between ρ_r and ρ_s @ 45% Co.

4. Distance-dependent Mould Hardness and Mould Strength

The new measurement method is based on the calibration of distance-dependent hardness and distance-dependent mould strength as a function of sensor signals. Hardness and mould strength are able to be measured by preparing green sand samples that have different densities. The same procedure that has been used for determining time-dependent density can be used for the calibration of mould hardness or strength as a function of sensor signals. The following equations are the relationships between mould hardness and mould strength and the final values $S_{u_{end}}$ of the bottom sensor and the upper sensor $S_{o_{end}}$, respectively.

$$H_u = i + i_1 * S_{u_{end}} \quad (3)$$

$$H_o = j + j_1 * S_{o_{end}} \quad (4)$$

$$\sigma c_u = u + u_1 * S_{u_{end}} \quad (5)$$

$$\sigma c_o = v + v_1 * S_{o_{end}} \quad (6)$$

where H_u , H_o , σc_u , and σc_o are values of the mould hardness and mould strength within the lower and the upper sensor, respectively; i , j , u , and v are intercepts; and i_1 , j_1 , u_1 , v_1 are slopes. The precision of the sensor signals is used to obtain precise data on the mould hardness and mould strength in the complicated areas of the green sand mould. To determine the interaction between the sensor signals and the usual measurement of hardness/strength of the sand mould, several samples of bentonite-bonded green sand were prepared. A low-speed pressing machine, as illustrated in Figure 7, with a $2mm/sec$ maximum pressing speed was used to prepare sand samples for this purpose. The variables and their levels of work plan are listed in Table 6.



Figure 7: Low-speed pressing machine.

Table 6: Variables and their levels.

Factors	Compactivity	Compaction pressure
	%	(MPa)
Symbol	C_o	P
Units	%	MPa
Main level (0)	40	0.8
Levels Higher level (+1)	45	0.9
Lower level (-1)	35	0.7
Interval	5	0.1

The initial densities of the prepared sand samples were 0.95g/cm^3 , 1.01g/cm^3 , and 1.08g/cm^3 . A density change in the sand moulds usually occurred during the moulding process. The variation in sand density had an influence on the mould hardness and mould strength. The plan used for measuring the properties of different densities of sand samples is given in Table 7.

Table 7: Design of experiments.

Ex. No	0.95 (g/cm ³)		1.01(g/cm ³)		1.08 (g/cm ³)	
	Co%	P(MPa)	Co%	P(MPa)	Co%	P(MPa)
1	-1	-1	-1	-1	-1	-1
2	0	-1	0	-1	0	-1
3	+1	-1	+1	-1	+1	-1
4	-1	0	-1	0	-1	0
5	0	0	0	0	0	0
6	+1	0	+1	0	+1	0
7	-1	+1	-1	+1	-1	+1
8	0	+1	0	+1	0	+1
9	+1	+1	+1	+1	+1	+1

4.1 Usual Measurement Method of Mould Strength

A digital portable durometer from DISA Georg Fisher type 8931 PFP was used to measure mould strength at different points of the process, as is illustrated in Figure 8. This mould strength tester has a measurement range of 0.2 N/cm^2 to 34.5 N/cm^2 . The durometer involves the use of a pressure pin. When the pin is pushed into the desired position within the mould, the strength value appears on the durometer's digital screen.



Figure 8: Digital durometer for mould strength measurement.

4.2 Usual Measurement Method of Mould Hardness

A scalar portable durometer was used to measure mould hardness at different points, as shown in Figure 9. The durometer uses a pressure pin, which is pushed into the desired position in the mould. The indicator then moves around the scalar circle equipped to the durometer. When the indicator is stable in value at the scalar circle, it indicates the hardness of the mould at a desired position. The maximum capacity of this durometer is 100 arbitrary unit (a. u). This is referred to as 'high hardness', whereas a measurement of zero indicates that the mould is weak.

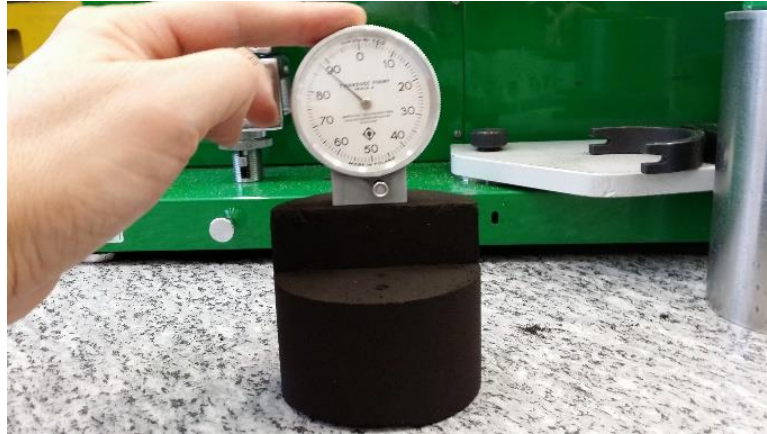


Figure 9: Scalar durometer for mould hardness measurement.

After this, the final sensor signals were recorded, and the properties of the sand samples were measured. For each experiment that was listed in the plan shown in Table 7, the results of three samples with differing densities were used to identify the relationship between sensor readings and the measured properties of hardness and strength. The calibration between the sensor signals and the usual measurements of sand mould properties was then determined. A linear relationship exists between the sensor signals and the properties of the sand samples. Comparison between the usual measurements of sand properties and the sensor signal-dependent sand properties is summarised in Table 8.

Table 8: Comparison between usual measurements of sand properties and sensor signal-dependent sand properties.

Ex. No	Usual measurement of sand properties		Sensor signal-dependent sand properties		Usual measurement of sand properties		Sensor signal-dependent sand properties	
	H_u	H_o	H_u	H_o	σc_u	σc_o	σc_u	σc_o
1	67.65	73.11	67.56	74.35	3.2	11.91	3.19	12.41
2	70.93	75.55	71.32	75.37	3.76	13.22	3.99	12.30
3	71.04	75.33	71.08	74.82	4.5	12.08	4.41	11.86
4	70.70	74.78	70.98	74.97	3.84	13.89	3.99	14.28
5	71.49	78.86	70.54	87.16	4.1	15.85	3.79	26.69
6	71.78	76.11	72.11	74.18	5.42	14.67	5.41	14.83
7	72.58	76.41	71.79	76.86	4.73	14.82	4.88	15.47
8	71.81	77.89	71.85	79.22	4.88	15.79	4.87	18.50
9	73.18	78.7	73.2	76.25	6.1	16.69	6.1	15.42

Despite the manual measurement of hardness and mould strength, there is a good relationship between the usual measurements of sand properties and the sensor signal-dependent sand properties. It was found that the increase of both compactibility and compaction pressure improves the values of mould hardness and mould strength. The sensor signal-dependent sand properties had more accuracy than the usual measurements of mould strength and less accuracy than the usual measurements of mould hardness [12].

An explanation for this could be that the usual measurement of mould strength was performed manually by digital durometer, as shown in Figure 8, while the usual measurement of mould hardness was performed manually by scalar durometer, as shown in Figure 9. The digital durometer is more accurate than the scalar durometer. The new method of measuring sensor signal-dependent sand properties eliminates the complexity that exists in a foundry and determines the desired values of these properties without an extensive process.

5. Conclusions

A linear relationship between the properties of the green sand samples and the sensor signals was discovered. Comparison between the usual measurements of sand properties (time-dependent density, distance-dependent mould hardness, and distance-dependent mould strength) and sensor signal-dependent sand properties showed

a good agreement. The new method facilitates the measurement of sand properties and determines the most effective moulding parameters based on the flowability of sensor readings. Furthermore, it was found that an increase in both compatibility and compaction pressure improves mould hardness and mould strength. Another finding was that initial density had an influence on the displacement of the green sand samples during the compaction process. Also, variation in sand displacement mainly affects mechanical properties, including mould strength and mould hardness.

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