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Simulation of the Moulding Process of Bentonite-Bonded Green Sand

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Abstract

Finite Element Method FEM via commercially available software has been used for numerical simulation of the compaction process of bentonite-bonded sand mould. The mathematical model of soil plasticity which involved Drucker-Prager model match with Mohr-Coulomb model was selected. The individual parameters which required for the simulation process were determined through direct shear test based on the variation of sand compactability. The novelty of this research work is that the individual micro-mechanical parameters were adopted depend on its directly proportional to the change of sand density during the compaction process. Boundary conditions of the applied load, roller and fixed constraint were specified. An extremely coarse mesh was used and the solution by time-dependent study was done for investigation of material-dependent behaviour of green sand during the compaction process. The research implemented also simulation of the desired points in sand mould to predict behaviour of moulding process, and prevent failure of the sand mould. Distance-dependent displacement and distance-dependent pressure have been determined to investigate the effective moulding parameters without spent further energy and cost for obtaining green sand mould. The obtained numerical results of the sand displacement show good agreement with the practical results.

Keywords: Green sand mould, Moulding process, COMSOL Multiphysics, Time-dependent study

1. Introduction

The soil consists mainly from three-parts which includes solid, liquid and gas. The first one is a complex set of organic and inorganic materials whose arrangement, quantity and quality determine its physical characteristics such as density, porosity, etc.… [1]. Moulding of soil is the measurable statement of soil behaviour under compaction process which is defined as a density change, the degree of porosity, and soil strength [2]. One important factor which influence on the moulding of soil is the size of the particles [3]. Moulding process improves density of the mould by connecting particles of a soil together [4].

Wenzehn and Junjio, were used practical results of sand properties to developed mathematical model of the sand moulding process. In these models nonlinearity of the material, geometrical, and connection between flask and sand were taken into account. These models were coupled with the commercialized ANSYS software for numerical simulation of the moulding process of the sand and forecasting of the mould hardness distribution [5]. E Hovad et. al, used Discrete Element Method DEM to simulate the dynamics flowability of the sand through manufacturing of the green mould by using moulding machine DISAMATIC [6]. Li Hua et.al, used Drucker – Prager / Cap model for simulating squeezing process (nonlinear features) for moulding sand (discrete materials). ABAQUS software used to solve the associated nonlinearity by simulation of growth of dynamic load/displacement through the squeezing process [7]. A lot of scientific obstacles can be defined by Partial Differential Equations PDEs. Many programs were developed to obtain the analysis of simulation process in brief time. Commercially available software code COMSOL Multiphysics is developed for solving any system of Partial Differential Equations PDEs until 32 self-sufficient variables. Partial Differential Equations PDEs may be time-dependent, non-linear, and act on a one, two or three dimensions. Meshing is used for partition PDEs troubles and altered for enhancing analysis preciseness. To solve objectives for specific PDEs problems, COMSOL involves definite solvers such as linear, non-linear, static and dynamic solvers [8].

In this research, a program of COMSOL Multiphysics used for simulation of the sand moulding process. 2D geometry, solid Mechanics- model of soil plasticity and time-dependent study were selected. Properties of sand samples which required for numerical simulation were determined as a functions of the density variation. Steps of FEM via COMSOL Multiphysics involves drawing geometry of sand sample and die, assigning material data, create mesh, computation of time –dependent study, viewing and analysis of post processing results.

2. Experimental procedure

Characterization of the moulding material is required for simulation of the compaction process of the green sand mould. Parameters that describe the plastic region are the angle of internal friction φ, cohesion c, and the dilatation angle ϕ. It can be assumed that the mechanical properties of the moulding material are considered by these two strength parameters. Cohesion and internal angles of friction are describe the micro-mechanical properties of the moulding material. The cohesion (also indicated to adhesion strength or shear strength) is the cohesive force in porous, binding media, moulding mixtures and powders. The cohesion ensures the interior cohesion of the individual particles of the medium. These cohesive forces are liable for flowability behaviour of the particles through the moulding process. The angle of internal friction is an angle between shear stress and the normal tension meanwhile of shear fracture. The angle of internal friction is dependent on the:

1. The shape and size of the particles,
2. Distribution of grain size,
3. The degree of condensation and,
4. The moisture content [9, 10].

Cohesion and angle of internal friction can be determined by Mohr–Coulomb's fracture criterion as is shown in figure 1, where τ is the shear stress, σ is the normal stress, σ_1, σ_2 are the principle stresses, c is cohesion, and φ is the angle of internal friction.

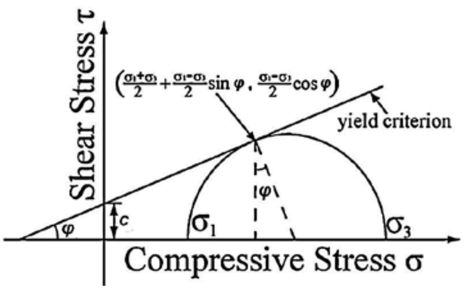

Fig 1: Mohr–Coulomb's fracture criterion [11]

Besides the effect of static pressure, the characteristics of Mohr-Coulomb's fracture criterion takes into account the influence of the dilatation angle on the yield criterion. The dilatation angle represents the soil characteristics when shear deformation occurs, which involves the change in soil volume due to the change in the arrangement of the soil particles themselves. The dilatation angle can be determined according to Eq. 1 [12], where ϕ is the dilatation angle, and φ is the angle of internal friction.

$$\phi = \frac{\varphi}{3} \tag{1}$$

Properties of the green sand were determined by using direct shear test and uniaxial compression test of the standard samples. Analysis of various factors of density and compactability of green sand was done to investigate the impact of individual parameters on the full structure.

Strength parameters of the moulding sand cohesion and angle of internal friction were calculated by using a calibrated shearing instrument. Fundamental working of the shearing machine is described in figure 2, there is a horizontal movement of the lower base is performed by the engine at constant velocity.

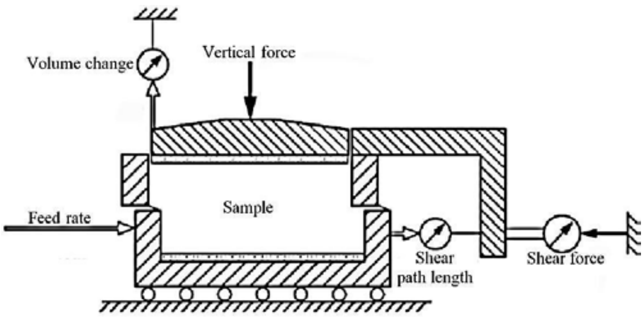

Fig 2: Principle of direct shear test [12]

The sample is subjected to the load through a constant vertical pressure. Change of the sample height is recorded by a displacement gauge which installed on the piston of shearing machine. A standard cylindrical specimen with a circular cross-section is used as is shown in figure 3.

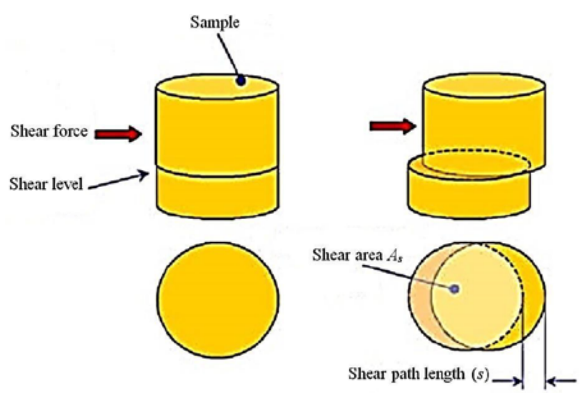

Fig 3: Shear area during shearing process [12]

Shearing surface decreases radially with feeding (shear path). Shear stress was determined by dividing shear force to the area which is variable by horizontal movement.
For calculating the current shear stress during shearing process, the current shear area A_s is required. Calculation of A_s is performed by the following mathematical equation [12]. where: *D*: diameter of the sample (50*mm*), and *s*: shear path (feeding) (*mm*).

$$A_s = \left(\frac{\pi}{4}D^2\right) - \left(\frac{(D-s)}{2}\sqrt{2sD - s^2} - \frac{D^2}{2}arccos\left(\frac{D-s}{D}\right)\right) \quad (2)$$

There is a problem in the determination of shear path length (*s*) to calculate the shear stress, because until now there are no such examinations were done in the field of sand moulding process. Therefore, the shear path length (*s*) was determined according to DIN-18137-3 [12]. Parameters that required to express the behavior of the elastic region are Poisson's ratio *v* and Young's modulus *E*.

Determination of the Poisson's ratio through Eq. 3, is based on the coefficient of earth pressure K_0, which depends on the angle of internal friction. The value of earth pressure coefficient does not exceeds 1, and it can be obtained through Eq. 4. [13].

$$v = \frac{K_0}{1 + K_0} \quad (3)$$

$$K_0 = 1 - sin\varphi \quad (4)$$

Young's modulus *E*, is determined from the stiffness modulus E_s which its determination based on stress-strain curve of compression test as is shown in figure 4. For uniaxial pressure tests with restricted lateral elongation $\varepsilon_{yy} = \varepsilon_{xx} = 0$, $\sigma_{yy} = \sigma_{xx} \neq 0$. Therefore, Young's modulus can be determined by the stiffness modulus through Eq. 5 [12].

$$E = E_s \frac{(1 - 2v^2 - v)}{(1 - v)} \quad (5)$$

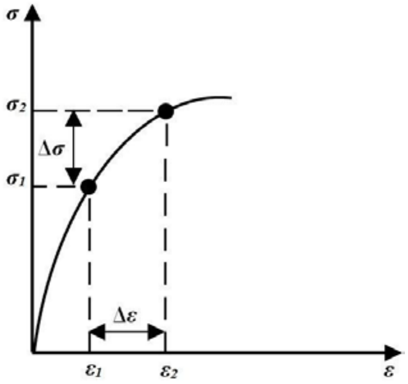

Fig 4: Stress (σ) - strain diagram (ε)

The uniaxial test is an unconfined compression test usually used to determine the modulus of elasticity of sand samples. During which this test, the load is applied through the uniaxial compression machine on the sand sample and gradually increased until the sample was a failure [14]. Modulus of elasticity have been determined for different density of sand samples based on slope of the stress-strain diagram. It has detected that high density of sand sample gives high value of the modulus of elasticity and vice versa.
The green sand is pressed by using 1MPa pressure through pressing machine for getting series of sand samples have (100 mm height and 50 mm diameter) same dimensions and (1.36, 1.46 and 1.56 g/cm^3) different densities. The Individual parameters listed in the tables 1-3, have been obtained through direct shear test and uni-axil compression test of bentonite-bonded green sand which have 30%, 40%, and 50% compactabiliy respectively.

Table 1.
Characteristics of green sand @ 30% compactability

ρ (g/cm³)	*φ* [°]	***c* [kPa]**	***v***	***E [MPa]***	***ϕ* [°]**
1.36	10	28	0.45	2.32	3.33
1.46	18	50	0.41	4.01	6
1.56	32.5	86	0.32	6.51	10.83

Table 2.
Characteristics of green sand @ 40% compactability

ρ (g/cm³)	*φ* [°]	***c* [kPa]**	***v***	***E [MPa]***	***ϕ* [°]**
1.36	12.5	30	0.44	3.62	4.17
1.46	22	56	0.38	6.03	7.33
1.56	37	86	0.28	8.99	12.33

Table 3.
Characteristics of green sand @ 50% compactability

ρ (g/cm³)	*φ* [°]	***c* [kPa]**	***v***	***E [MPa]***	***ϕ* [°]**
1.36	13.7	36	0.43	4.15	4.57
1.46	24.7	60	0.37	6.98	8.23
1.56	39.1	89	0.27	9.78	13.03

3. Numerical simulation of the compaction process

For verifying that the moulding process of green sand is a dynamic process and to make a statement about behavior of the real system through the compaction process. Simulation process was done by using program of COMSOL MULTIPHYSICS. Finite element software code COMSOL Multiphysics offers a realistic simulation of scientific problems with elements of multiphysics such as heat, particle tracing and water flow [15]. Practical problems in the field of dynamics of fluid and soil mechanics can be solved by using this program [8].
The soil was treated as an elastic-perfectly plastic material. In the elastic region, the stress-strain relationship is described by Hooke's law. The hook's law has been used successfully in soil mechanics to describe the general behavior and strength of a soil under short-term working load condition [16].

In the plastic region, the soil is yielded according to the Drucker Prager criterion match with Mohr-Coulomb yield criterion. Model of soil plasticity with a constitutive relation given by a combination of these two models was used for modelling of the moulding process of green sand. The well-known Mohr-Coulomb model and Drucker-Prager model can be considered as a first order approximation of the clay-bonded moulding sand behaviour. These models are preferred for describing the compaction process of green sand. This elastoplastic model requires five parameters for simulation process are easy to be determine. The parameters are modulus of elasticity E, Poisson's ration ν, angle of internal friction φ, cohesion c, and dilatation angle ϕ [17].
As summarized in table 4, the mathematical relationships between the individual parameters and variation of initial density of the sand samples have been adopted for simulation process. It is mentioned that the individual Parameters which required for simulation of sand moulding are correspond to variation of density. Selection of input parameters and its range to show effect variation of sand density and compactability on behavior of green sand mould during moulding process. Variation of sand density occur during the compaction process, this has an influence on cohesion and angle of internal friction so on mechanical properties of the sand mould.

Table 4.
Correlations between sand properties and density

Sand properties	***Compactability %***		
	30%	**40%**	***50%***
φ [°]	$\varphi = 112.5\rho - 144.08$	$\varphi = 122.5\rho - 155.02$	$\varphi = 127\rho - 159.59$
***c* [k*Pa*]**	$c = 290\rho - 368.73$	$c = 280\rho - 351.47$	$c = 265\rho - 325.23$
ν	$\nu = -0.65\rho + 1.34$	$\nu = -0.8\rho + 1.53$	$\nu = -0.8\rho + 1.52$
E [MPa]	$E = 20.95\rho - 26.31$	$E = 26.85\rho - 32.99$	$E = 28.15\rho - 34.13$
ϕ [°]	$\phi = 37.5\rho - 48.03$	$\phi = 40.8\rho - 51.62$	$\phi = 42.3\rho - 53.15$

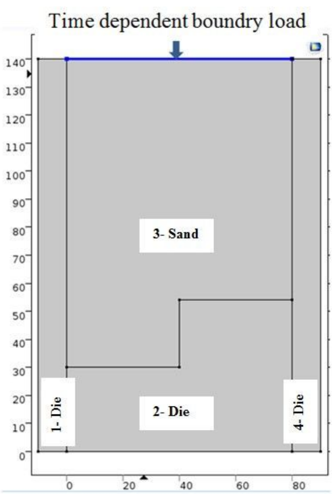

Fig 5: Geometry of the sand sample and die

Geometry of the sand sample and die are shown in figure 5. Time-dependent study has been used by applying 1 MPa load (*P*) on the top surface, and the compaction time (t) is 3 seconds to compact the sand in the y-axis direction. An interpolation function *P(t)* has been used to define the time-dependent boundary load. The die is fixed constraint, and the piston that used for sand compaction does not modelled.

4. Results and Discussion

Figure 6a and b shows 2D cut points, where the first point is located on the bottom level of the sand sample and the second point is located on the upper level of the sand sample. These two desired points are located on the sand sample have been selected to investigate time-dependent variation of distance-dependent displacement and distance-dependent pressure.

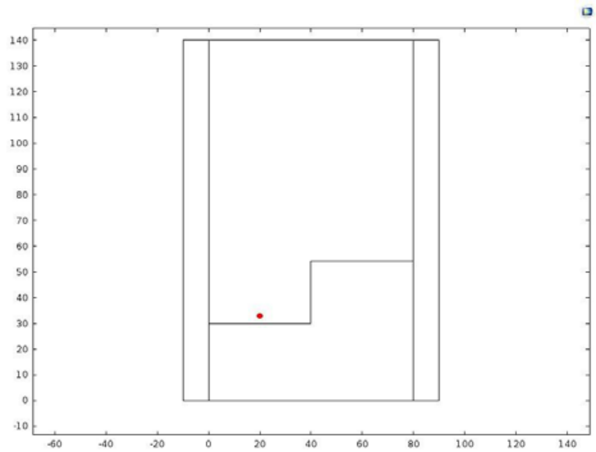
Fig 6a: Location of desired point on the bottom level

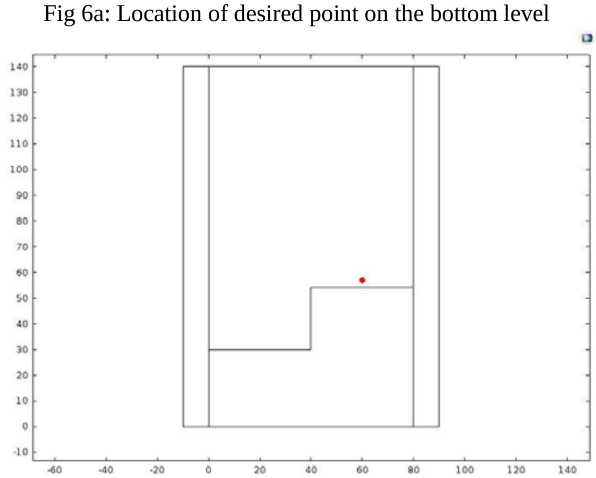
Fig 6b: Location of desired point on the upper level

Simulation of the desired points in the sand sample allows predicting material flow at the complex positions on the pattern. Variation of distance-dependent displacement, and distance-dependent pressure as a function of time at the desired points

during compaction the sand sample which has 30% compactability were shown in figures 7 & 8 respectively.
The blue legend (20, 33) referred to the position of the bottom point, while green legend (60, 57) referred to the position of the upper point. It is found that both distance-dependent displacement, and distance-dependent pressure decrease as a result of increase compactability of green sand.

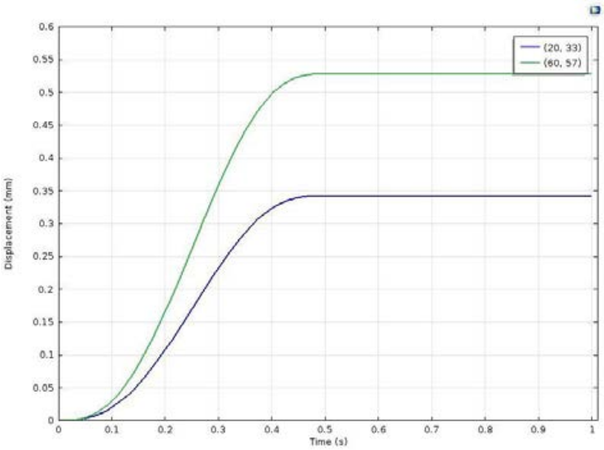

Fig 7: Distance-dependent displacement VS time

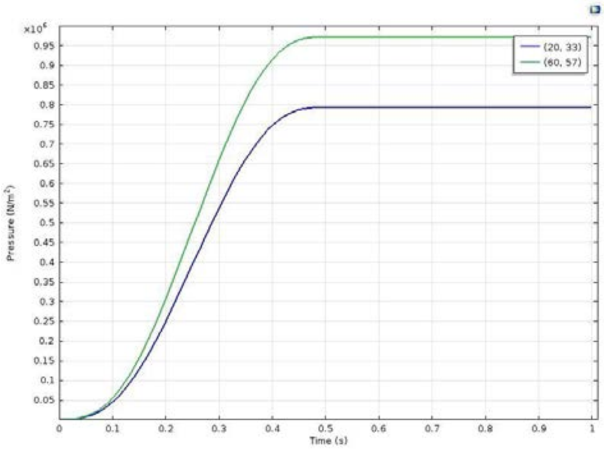

Fig 8: Pressure-dependent displacement VS time

Maximum values of distance-dependent displacement are 0.34*mm*-0.53*mm*, 0.27*mm*-0.42*mm*, and 0.24*mm*-0.39*mm* at the bottom and upper levels of the green sand samples which have different compactability 30%, 40%, and 50% respectively. Maximum values of distance-dependent pressure are 0.8*MPa*-0.97*MPa*, 0.74*MPa*-0.92*MPa*, and 0.7*MPa*-0.9*MPa* at the bottom and upper levels of the green sand samples which have different compactability 30%, 40%, and 50% respectively. Results of time-dependent stress concentration and time-dependent displacement at different intervals 0.01*sec* & 0.5*sec* during compaction the sand sample which has 30% compactability are shown in figure 9(a & b) and figure 10(a & b) respectively. The stress concentration is existed at the sharp edge of the pattern. The stress concentration is expanded during compaction process, and dividing the green sand sample into two different regions at the left and right sides. This behavior contributes to reduce the material flow especially towards left bottom region. Selection of time-dependent study show that the moulding process of green sand is dynamic process. Density variation which occur during the moulding process has an influence on properties of the sand mould. The voids between sand particles decrease as a result of compaction process, this has an effect on angle of internal friction and cohesion.

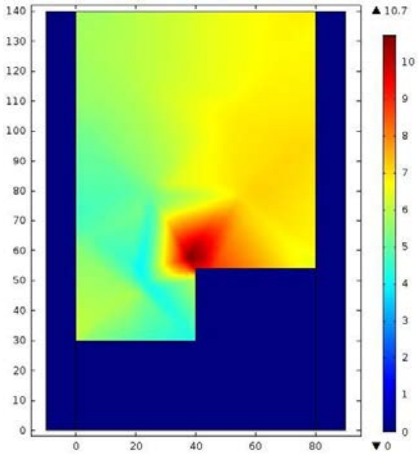

Fig 9a: Stress concentration of sand sample @ 0.01sec

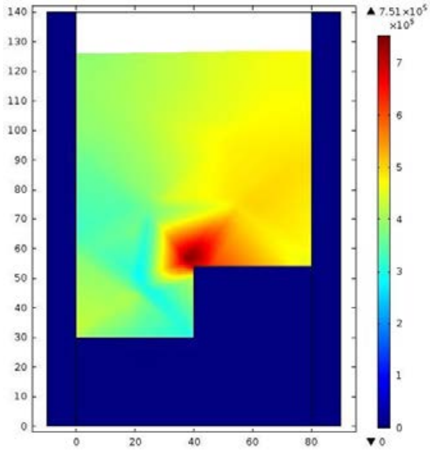

Fig 9b: Stress concentration of sand sample @ 0.5sec

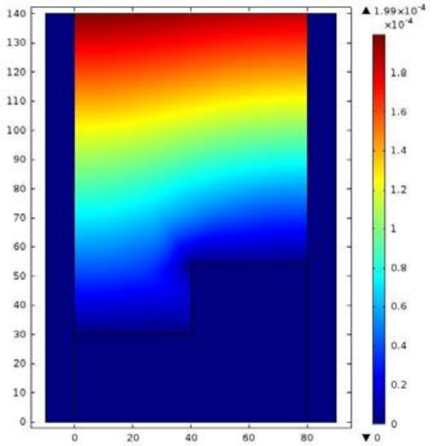

Fig 10a: Displacement of sand sample @ 0.01sec

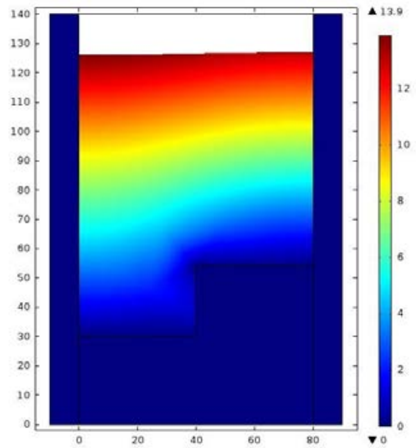

Fig 10b: Displacement of sand sample @ 0.5sec


Fig 11: Displacement measurement of sand sample

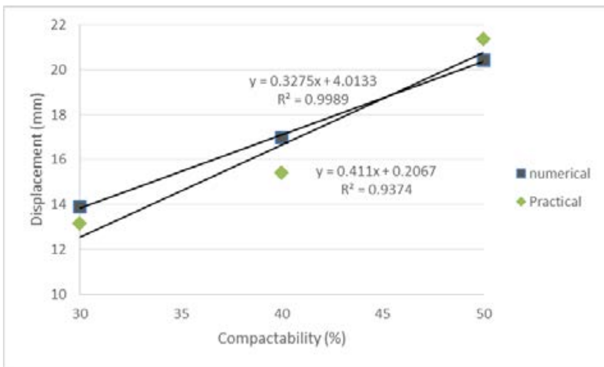

Fig 12: Comparison between numerical and practical results

As comparison to numerical simulation, practically, three different series (30%, 40%, and 50%) compactability of green sand have been used. The tube test (80 mm diameter, 140 mm height) placed on graded pattern and filled with the green sand. The sand is subjected into 1MPa preesure through pressing machine. Figure 11 shown displacement measurement of sand sample , the obtained results of the actual tests of three series of sand samples has been compared with the simulation results as shown in figure 12. There is good tendency between the numerical simulation and practical results. It is found that compactability of green sand has an influence on the flow and displacement of green sand. Increment compactability percentage of green sand contributes to increment displacement of the sand sample. This behavior related into that the sand become soft which contribute to increase of sand movement as a result of increase of compactability of green sand.

5. Conclusions

Time-dependent study of the moulding process of green sand shown nonlinearity dynamically behavior. Variation of stresses and displacement distribution during compaction process enhanced this concept. This ability depends on the mathematical relationships between elasto-plastic properties and variation of density of the green sand. The angle of internal friction and cohesion are directly proportional to density change of green sand during the moulding process. Measurement of distance-dependent displacement and distance-dependent pressure contribute for determining the available compaction time without losses efforts and energy, as well as determining the available sand, bentonite and water content. It is found that the maximum values of displacement and stress concentration at 0.5sec of compaction process are 13.9*mm*, 10.9*mm*, and 10.4*mm* 0.751*MPa*, 0.862*MPa*, and 0.919*MPa* of the green sand samples which have different compactability 30%, 40%, and 50% respectively.

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