EXPERIMENTAL AND NUMERICAL STUDIES OF METAL POWDERS PRESSED BY UNIAXIAL FLOATING DIE: CASE COPPER AND BRONZE

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The densification and microhardness values of copper and bronze powders were investigated experimentally using a computer controlled uniaxial die, and numerically, using a non-linear finite element program. They, also, were analyzed statistically by establishing a hyperbolic relationship, using best fit, between density and pressure applied.

The ratios of experimentally obtained maximum density to theoretical density for copper and bronze were 91 % and 81 %, respectively, at 800 MPa pressure as used in practical applications. Microhardness values were 116 and 192 kg/mm^2 for copper and bronze powders, respectively.

The results obtained from experimental, statistical (best fit) and numerical studies were found to be in good agreement, and showed that a hyperbolic relationship existed between the density and pressure.

K e y w o r d s: copper and bronze powders, uniaxial pressing, densification, microhardness, plaxis, hardening soil model

EXPERIMENTÁLNE A NUMERICKÉ ŠTÚDIUM JEDNOOSOVO OBOJSTRANNE LISOVANÝCH KOVOVÝCH PRÁŠKOV: PRÍPAD MEDI A BRONZU

Experimentálne pomocou počítačom riadenej jednoosovej lisovnice a numericky pomocou nelineárneho programu konečných prvkov sme skúmali zhusťovanie a hodnoty mikrotvrdosti medených a bronzových práškov. Tieto vlastnosti sme analyzovali aj štatisticky a určili sme hyperbolickú závislosť medzi hustotou a aplikovaným tlakom. Pomery maximálnej hustoty určenej experimentálne k teoretickej hustote medi a bronzu boli 91 a 81 % pri tlaku 800 MPa, ktorý zodpovedá praktickým aplikáciám. Pri medených a bronzových práškoch sme namerali hodnoty mikrotvrdosti 116 a 192 kg/mm^2. Zistili sme, že

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výsledky, ktoré sme získali z experimentálnych, štatistických a numerických analýz, sú v dobrej vzájomnej zhode, pričom medzi hustotou a tlakom existuje hyperbolická závislosť.

1. Introduction

As it is known that among the various metalworking technologies, powder metallurgy (PM) is the most diverse manufacturing approach. At the same time, powder metallurgy is the art of producing commercial products from metallic powders by pressure. One attraction of powder metallurgy is the ability to fabricate high quality complex parts to close tolerances in an economical manner. Key steps include the shaping or compaction of the powder and the subsequent thermal bonding of the particles by sintering [1, 2].

In powder metallurgy different methods are used for the process of consolidation of metal powders into structural shapes. Uniaxial compaction is one of the most commonly used PM consolidation process. Uniaxial compaction is a process by which powders are consolidated inside a die cavity into a designed shape by using applied pressure acting uniaxially. This process achieves an adequate green strength of the compacted samples before this part is transferred to the sintering stage. Of all the methods, uniaxial pressing is used because of its certain advantages, material and energy saving, large geometrical shape capability, precision and repeatability, and high productivity [3, 4].

When metal powders are pressed in a die, the resulting compacts are generally strong enough so that they can be handled without breaking. The green strength will, of course, depend upon the type of metal powders – those from soft metals having higher strength – and upon the pressure being applied. For soft metal powders quite low pressures, less than 35 MPa, are sufficient to produce compacts. For harder powders higher pressures are necessary [5].

The behaviour of powder densification under pressure density is one of the fundamental characteristics of parts produced by powder metallurgy techniques. Densification of a powder body is dependent upon a number of powder characteristics. These are the material and structural features, e.g. hardness, response to plastic deformation and surface characteristics, which feature respectively during deformation, work-hardening, and adhesion of the particles [6, 7].

In recent years, the finite element simulation in powder compaction processes has been widely used and reported in the literature [8–19]. However, it is noted that there is not much literature reporting on finite element method (FEM) studies of powder compaction processes using an elasto-plastic type of hyperbolic model which is appropriate for granular materials like soils [20–21].

This investigation is concerned with assessing and modeling the response to deformation during uni-axial pressing of a selection of metallic powders, possessing different metallurgical and size characteristics. Copper and bronze powders were chosen in this study since they are the most commonly used powders in industry.

2. Physical model study

2.1 Die and die set

Floating-die compacting, which has been used in this study, is shown in Fig. 1. Floating-die compaction uses a fixed lower punch and motion of the die toward the lower punch in coordination with the upper punch motion, resulting in the same effect as double-action compaction. The uni-axial die used for compaction was made of high carbon speed steel. The diameter of the die was 10 mm with a length of 20 mm. The compacting machine used for pressing was a type 1081 Instron, 200 kN max. load capacity, compression machine. The experimental programme was carried out using the facility in the laboratory of Manchester Materials Science Centre of University of Manchester and UMIST. The experimental set-up has been used extensively for the compaction of metal powders and its main features are well documented [3].

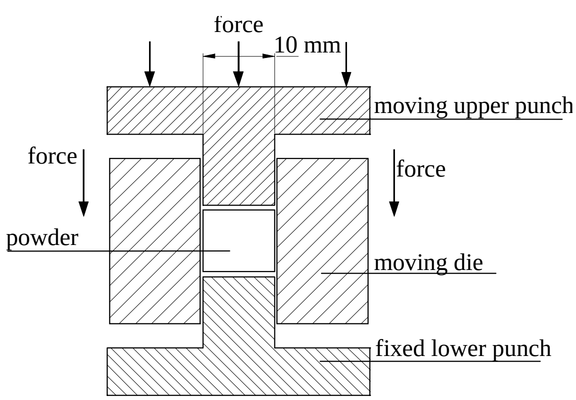

Fig. 1. Floating die used in the uniaxial pressing.

2.2 Specimen preparation and measurement of densification

Powders selected for this study are those that are commonly used in industry. The physical properties and chemical compositions of powders used are given in Table 1. The weights of copper and bronze powders used in the tests were 3.12 g

T a b l e 1. Specifications of used powders

Powders	Properties					
	Shape	Average particle size [μm]	Manufacturer	Manufacturing method	Apparent density [kN/m^3]	Fractional density [%]
Bronze	spherical	201.80	*M.M.Pow.	atomized	45–54	49.5
Copper	spherical	54.12	*M.M.Pow.	atomized	47–58	54.4
	Chemical analyze					
	Copper	Tin	Phosphorus			
Bronze	BAL	9.73	0.03			
Copper	99.58	–	0.05			

*Makin Metal Powder

and 2.99 g, respectively. The initial sample heights of 8.14 mm and 8.75 mm have been determined for copper and bronze, respectively. The particle sizes of copper and bronze powders were measured by Malvern Mastersizer E apparatus. The median particle sizes of powders were $d_{\mathrm{m}}= 54$ and 202 μm for copper and bronze, respectively. Before compacting the powders, the die wall was lubricated with the zinc stearate solution. The surfaces of both punches and die wall were coated with the solution to leave a uniform coating of lubricant. The specimens were produced in a uni-axial die up to 800 MPa. After each compaction, the die wall and punches were cleaned and relubricated for the next testing.

The morphology and microstructure of the pressed samples have been examined by using Scanning Electron Microscope (SEM). In addition, the change in micro-hardness has been measured for copper and bronze samples embedded in bakalite.

After compacting, the sample heights were reduced to values of 4.84 mm and 5.36 mm for copper and bronze, respectively. The density of the compacted powders was determined by either a weighting and dimensional measurement method, i.e. punch displacement method, that is, punch displacement was recorded continuously against increasing load. In this study, the latter method was used with the aid of computer. The maximum load was recorded with an ejection of the compact from the die; this did not include a correction for elastic springback of compact that occurs when load was released. Final compact thickness, diameter and weight were also measured after removing the compact from the die using a micrometer ($\pm$ 0.001 mm), and the mass was determined to $\pm$ 0.001 g. It was assumed that the final pressure was equal to the transmitted pressure on the compact because of the die wall lubrication and the small thickness/diameter ratio. From the displacement data the green density was calculated using the simple equation given below:

$$d = \frac{M}{V}\,, \tag{1}$$

$$V = \pi \cdot r^2 \cdot (h^{\mathrm{i}} - h), \quad (2)$$

where d is the green density at a given pressure, M is the mass of the powder, V is the volume of the green compact, r is the radius of the die cavity, h^{i} is the initial powder height, calculated from the tap density, and h is the displacement of the punch.

2.3 Micro-hardness measurement

The micro-hardness of the powder particles was determined before and after compaction using a Reichert Hardness Tester at a certain compacting pressure, separately. To determine the micro-hardness of the powder particles and specimens before and after compaction, the powders and specimens were mounted in bakelite. The indentation was made using 10 g for copper and 20 g for bronze, the average lengths of the diagonals of the indentation were measured, and the micro-hardness was determined. The recorded values represent an average of 20 readings from each powder sample. The Vickers micro-hardness value, V_{MH} was determined using Eq. (3).

$$V_{\mathrm{MH}} = \frac{1854.4 \cdot L}{d^2}, \quad (3)$$

where L is the applied load [g], and d is the base diagonal in mm.

2.4 Test results

Densification ratios and micro-hardness values of pressed powders under uniaxial pressure are given in Table 2.

Table 2. Densification ratios and microhardness values

Pressure [MPa]	Copper ($d = 8.96$ g/cm^3)		Bronze ($d = 8.78$ g/cm^3)	
	Densification [%]	Hardness [kg/mm^2]	Densification [%]	Hardness [kg/mm^2]
0	54	70.7	49	120.2
100	64	–	54	–
200	71	88.1	59	131.5
300	76	–	63	–
400	79	97.7	67	166
500	82	–	70	–
600	85	105.7	73	173.8
700	88	–	77	–
800	91	116.4	81	192.3

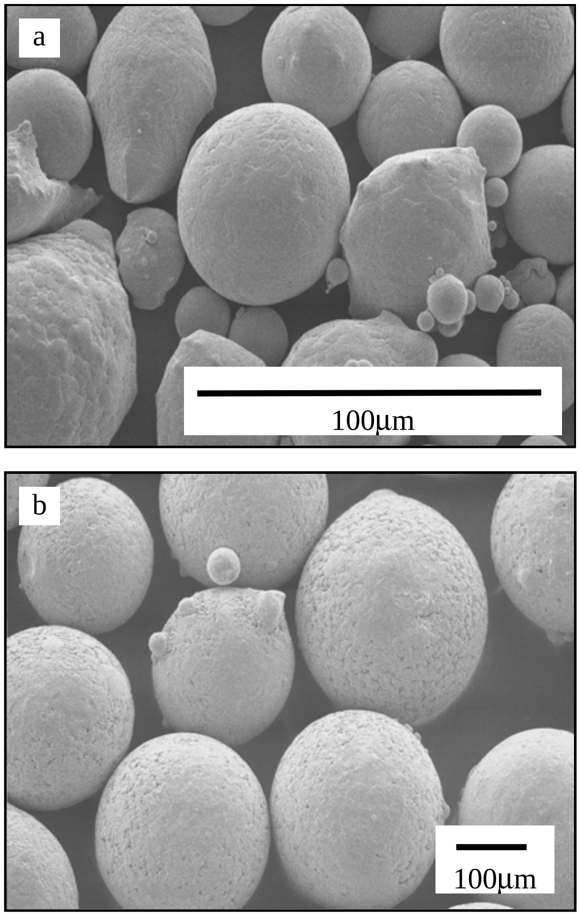

Fig. 2. The photographs of SEM before compaction a) copper and b) bronze.

Figure 2 shows the photographs of SEM of the copper (a) and bronze (b) before compaction. The photographs of SEM of the copper and bronze under 400 and 800 MPa pressure, with an uni-axial die are shown in Figs. 3 and 4, respectively. Plastic deformation is observed under these pressures which can be seen clearly in Figs. 3 and 4. In the case of medium hardness and plastic behaving copper powders, being softer than bronze powders, the maximum density is 91 %, and for bronze powders, which have higher hardness values than copper, density is 81 %, when the pressure reached 800 MPa. Micro-hardness values of copper and bronze powders are 116.4 and 192.3 kg/mm^2 under applied pressure of 800 MPa. This showed that,

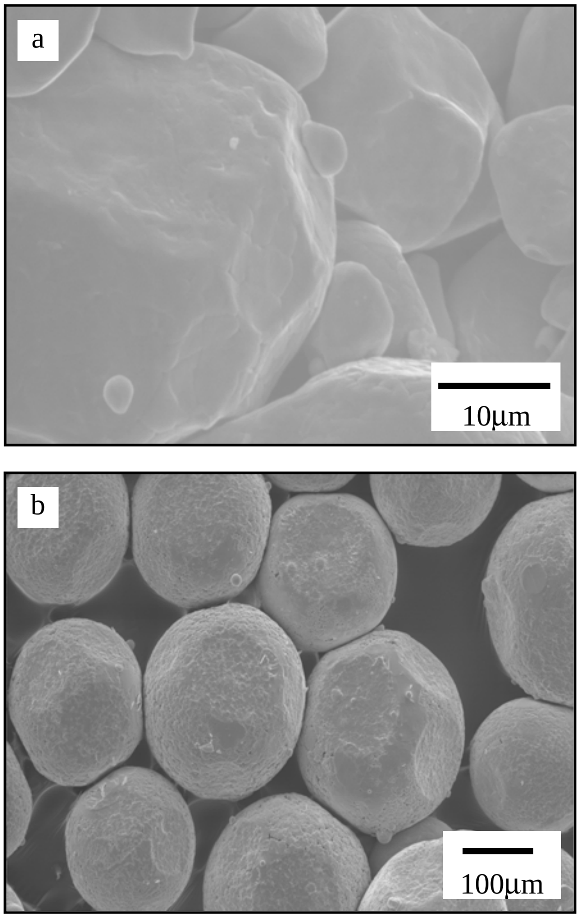

Fig. 3. The photographs of SEM under 400 MPa pressure a) copper and b) bronze.

for a given pressure, the densification of hard material was lower than that of soft material.

Figure 5 shows the relation between micro-hardness values of powders and the applied pressure. The variations of micro-hardness values with compaction pressure for bronze and copper are more or less linear. For both powders, micro-hardness values show a similar trend up to 800 MPa pressure.

The variation of fractional density with compaction pressure is shown in Figs. 6 and 7 for copper and bronze, respectively. Both graphs exhibit an initial hyperbolic behaviour to compaction, followed by an essentially linear behaviour.

Since the variations of fractional density with compaction pressure are sensibly

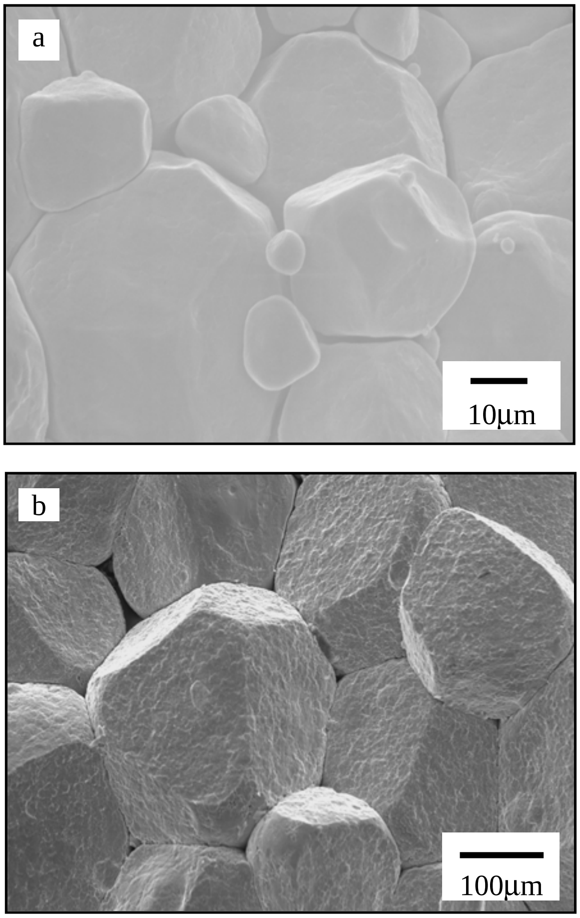

Fig. 4. The photographs of SEM under 800 MPa pressure a) copper and b) bronze.

non-linear and may be given approximately by the following hyperbolic equation:

$$D = a + \frac{b \cdot P}{c + P}\,, \qquad (4)$$

where D is the density [$\text{g} \cdot \text{cm}^{-3}$], P is the pressure [MPa], and a, b and c are constants to be obtained from the best fit. The correlation coefficients (R^2) from non-linear regression analyses were found to be better than 0.99 in both cases. The values of parameters a, b and c were 4.98, 5.15 and 546.91 for copper, and 4.38, 10.76 and 2448.31 for bronze, respectively.

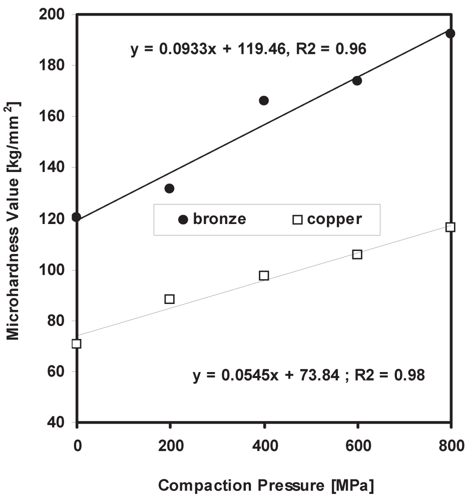

Fig. 5. The micro-hardness values of copper and bronze powders under pressure.

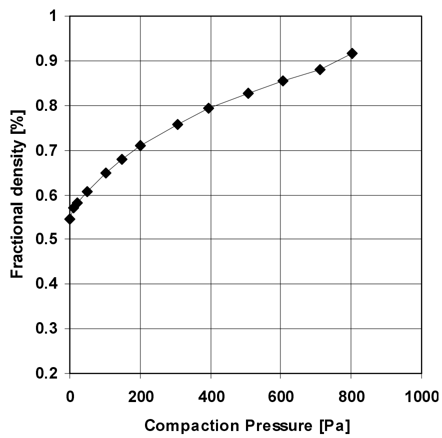

Fig. 6. Densification behaviours under the applied pressures of copper powders.

3. Discussion and presentation of FEM results

The finite element method (FEM) using the PLAXIS 7.2 software was utilized to predict the response to deformation during uni-axial pressing of metallic powders. PLAXIS is a finite element package specially intended for the analysis of deformation and stability in geotechnical engineering projects [22]. Stresses, strains and failure states of a given problem can be calculated. It was developed in 1987 at the Technical University of Delft in Holland. PLAXIS is equipped with special features to deal with the numerous aspects of complex geotechnical structures.

Axi-symmetric finite element studies of the metallic powders subjected to uni-axial pressing with the same model geometries as in the tests were carried out using PLAXIS. The finite element model of the metallic powder during the compaction process is shown in Fig. 8. Geometry of the problem includ-

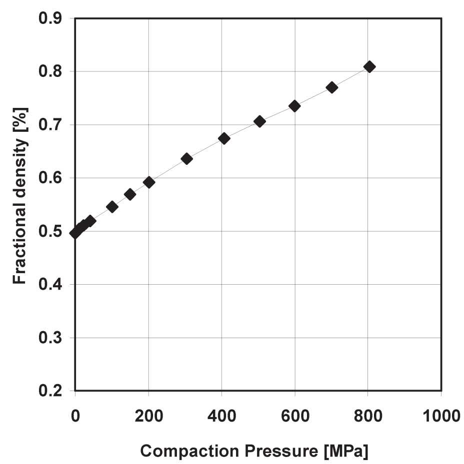

Fig. 7. Densification behaviours under the applied pressures of bronze powders.

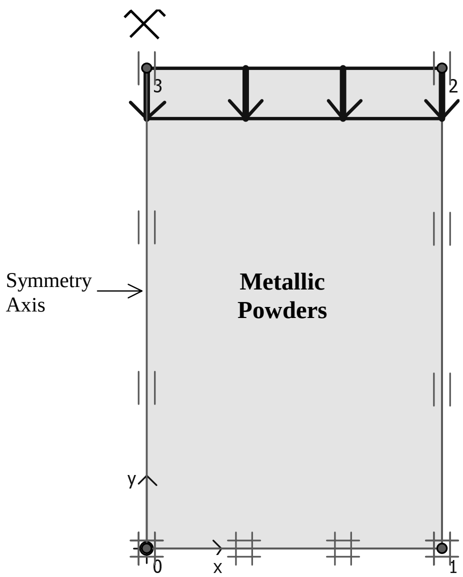

Fig. 8. The axi-symmetric finite element model of the test setup.

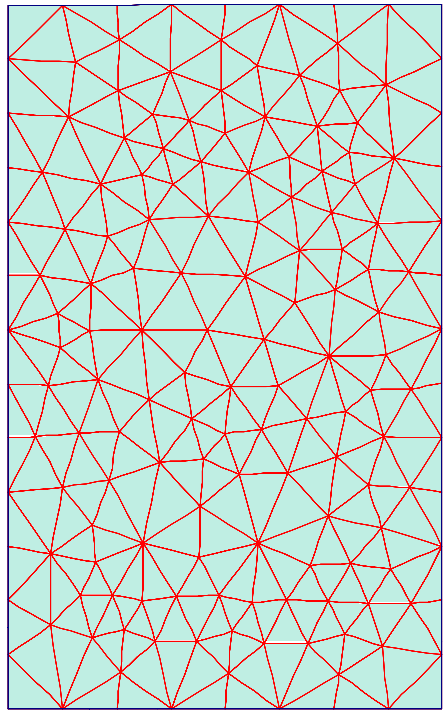

Fig. 9. The finite element mesh used for the numerical simulations.

ing boundary conditions and the finite element mesh used for the numerical simulations are illustrated in Figs. 8 and 9.

Metallic powder was modeled by using 15-node triangular elements. Different constitutive models are available in PLAXIS. In this study, an elasto-plastic type of hyperbolic model called the Hardening Soil Model (HSM) was used for non-linear metallic powder behaviour. The HSM is an advanced model for simulating the behaviour of different types of soil, both soft and stiff soils [23]. When subjected to primary deviatoric loading, material shows a decreasing stiffness, and simultaneously irreversible plastic strains develop. The observed relationship between the compactive pressure and the axial strain can be well approximated by a hyperbola. Such a relationship was first formulated by [24] and later used in the well-known hyperbolic model, which is found to be appropriate for granular matter [25]. The HSM, however supersedes the hyperbolic model by far. A basic idea for the formulation of the HSM is the hyperbolic relationship between the vertical strain and the deviatoric stress in primary tri-axial loading. The model is capable of simulating

Table 3. The values of the HSM parameters

Parameter	Unit	Copper	Bronze
Reference stress for stiffness, p^{ref}	$\mathrm{kN/m^2}$	100	100
Unit weight, γ_{n}	$\mathrm{kN/m^3}$	48.80	43.53
Secant stiffness, E_{50}^{ref}	$\mathrm{kN/m^2}$	45000	55000
Reference unloading/reloading stiffness, $E_{\mathrm{ur}}^{\mathrm{ref}}$	$\mathrm{kN/m^2}$	135000	165000
Reference oedometer stiffness, $E_{\mathrm{oed}}^{\mathrm{ref}}$	$\mathrm{kN/m^2}$	45000	55000
Power, m	–	0.50	0.50
Cohesion, c	$\mathrm{kN/m^2}$	0.21	0.21
Friction angle, ϕ	(°)	39.5	40
Dilatancy angle, ψ	(°)	9.5	10
Poisson's ratio, ν	–	0.33	0.33
K_0	–	0.364	0.357
Failure ratio, R_{f}	–	0.90	0.90

nonlinear, inelastic, stress dependent material behaviour.

The HSM represents a much more advanced model than the Mohr-Coulomb model. As for the Mohr-Coulomb model, limiting states of stress are described by means of the friction angle (ϕ), the cohesion (c) and the dilatancy angle (ψ). Soil stiffness is described much more accurately by using three different input stiffnesses; the tri-axial loading stiffness, E_{50}, the tri-axial loading, E_{ur}, and the oedometer loading stiffness, E_{oed}. In contrast to the Mohr-Coulomb model, the HSM also accounts for stress-dependency of stiffness moduli. This means that all stiffness increase with pressure. Hence, all three input stiffness relate to a reference stress, being usually taken as 100 kPa. The parameters of the HSM for the copper and bronze powders are listed in Table 3. Parameters were determined from the tri-axial compression and shear box tests on powder specimens. Values of the angle of friction ϕ for copper and bronze were 39.5° and 40°, respectively. The values of dilatancy angle ψ depend on the density and on the friction angle. For granular materials, it is suggested as $\psi = \phi - 30$ in the reference manual of Plaxis. Therefore the values of 9.5° and 10° were taken for copper and bronze powders, respectively. Although the values of cohesion, c were obtained as 0 from the tests, a small value of 0.21 $\mathrm{kN/m^2}$ was used in the analysis as it is suggested in the reference manual of Plaxis. Values of Poisson's ratio, ν, generally lay between 0.25 and 0.40, and therefore an average value of 0.33 was used in the calculations. The initial stresses in the granular material were generated using Jaky's formula stated by Eq. (5) (in PLAXIS, this procedure of generating initial soil stresses is often known as the K_0-procedure).

$$K_0 = 1 - \sin\phi, \tag{5}$$

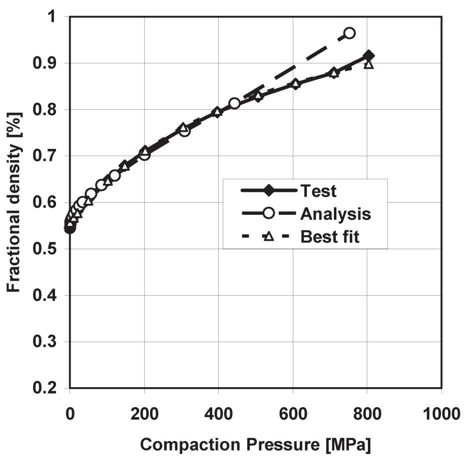

Fig. 10. Results of Test and Finite Element Analysis for copper powders.

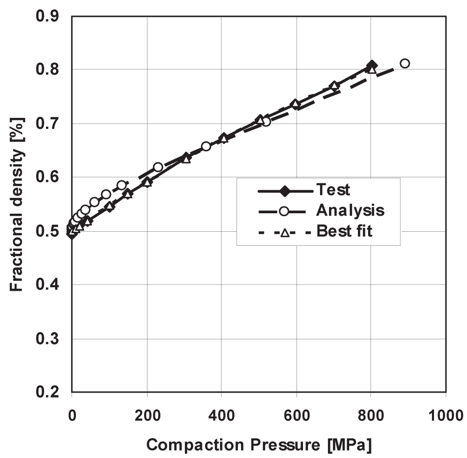

Fig. 11. Results of Test and Finite Element Analysis for bronze powders.

where K_0 is the coefficient of lateral earth pressure and ϕ the friction angle of the material.

The problems have been solved with stress control and by predicting the displacements at different stresses. Since the model tests were continued until the pressure value of 800 MPa, a suitable compaction pressure was applied incrementally in the analysis. The predicted fractional density/compaction pressure relationships for copper and bronze are presented in Figs. 10 and 11, respectively, together with the results from tests and empirical expressions. The results from the non-linear finite element analysis are in very good agreement with the experimental observations using the HSM parameters. Although, other material models, i.e. linear elastic and Mohr-Coulomb model, were used to analyze the behaviour of compacted powders, they were not presented here since the results obtained from them were not in good agreement with experimental findings.

4. Conclusions

Following conclusions were drawn from the investigation.

1. For a given pressure, the compaction ratio of hard material was lower than that of soft material.

2. In this study, an elasto-plastic type of hyperbolic model called the Hardening Soil Model was used to simulate behaviour of non-linear metallic powder subjected to uni-axial pressure. The results obtained from experimental, statistical (best fit) and numerical study were found to be in good agreement.

3. The study showed that a hyperbolic relationship existed between the density and pressure.

4. Although the observations and conclusions drawn in this study are encouraging, further validation of behaviour of metallic powder subjected to uni-axial pressure is required by additional testing and numerical calculations using some different metallic powders. Some practical applications are also required for validation.

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