Investigation on Fabricating a Chicken Eggshells Powder Mold for Metal Casting

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Abstract

Sand casting is one of the metal casting techniques that is widely used in many applications. Besides a problem on surface quality of the casting from sand mold, sand extraction from places also gives serious environmental impact. Instead of using sand, a less environmental impact material has been considered. In this study, chicken eggshells waste is investigated for applying in metal casting process. The chicken eggshells waste is cleaned, air-dried and crushed into powder form. Bentonite and water are used to help cavity formation. A design of experiment was conducted to determine a suitable composition that provided the durable mold. Results illustrated that the specimens prepared from eggshells powder mixed with bentonite 10 wt% and water 16 wt% of eggshells powder, provided the highest ultimate compressive strength of 27.05±1.17MPa. In addition, the surface roughness of the castings was 5.86µm, lying lower than the normal range of the sand casting process. With these investigated properties, the results presented the potential of using the chicken eggshells waste in this application.

Keywords: Chicken, Waste, Eggshells, Metal Casting, Mold

Introduction

Metal casting is an important manufacturing process that a solid metal is heated to a suitable temperature and subsequently added into a mold to keep the molten metal in a desired form during solidification. Due to a variety of metals and casting techniques, it is widely used in several industries, e.g., automotive, machinery, aerospace and electronics. Sand casting is one of the well-known metal casting techniques that the mold is made from sand. The building principle of the sand casting process is illustrated in Figure 1. The process starts from preparing the mold material by mixing dry sand with a binding agent, normally bentonite and water. The cavity profile is created by placing a physical pattern in the mold material. After removing the pattern, the cavity is then filled with the molten metal and allowed the metal to cool down for solidification.

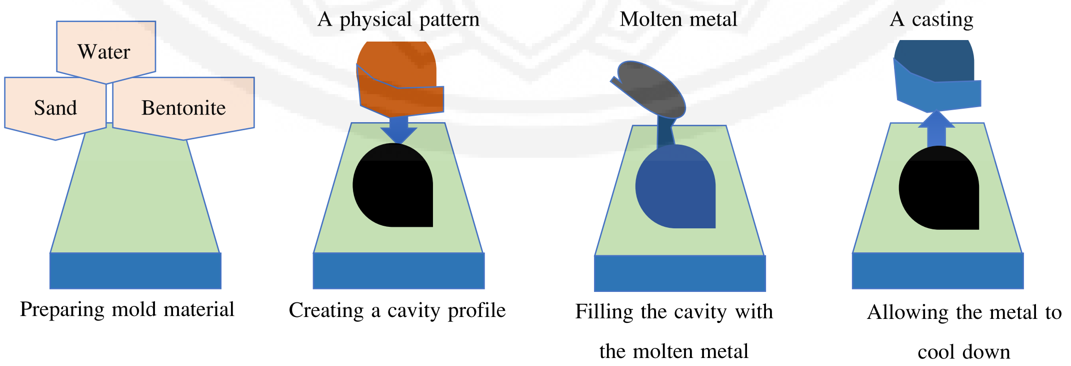


Figure 1 The building principle of the sand casting process

Comparing with the other casting techniques, the sand casting technique is quite inexpensive and can be applied to several metals. However, surface quality of the casting is not visually appealing or smooth due to particle size of the sand. As a result, post-machining processes are often required. Crushing the sand to lower its particle size is quite difficult because of its high mechanical strength. In addition, sand extraction from places, e.g., rivers, beaches and ocean floors, might give a serious environmental impact (Ashraf et al., 2011; Masalu, 2002; Carter & Bartlett, 1990). To find a new mold material that can reduce the environmental impact is an interesting issue to be addressed.

Everyday chicken eggshells waste is made around the world at many tons per day from both food processing industries as well as household usages. The disposal of this enormous amount is a challenge (Oliveira, Benelli & Amante, 2013). To promote circular economy, this waste can be considered as a raw material for manufacturing purpose (Dwivedi, Sharma, & Mishra, 2017; Bootklad & Kaewtatip, 2013). The chicken eggshells compose of three layers, including (1) cuticle on outer surface, (2) a spongy (calcareous) layer and (3) an inner lamellar (or mammillary) layer (Stadelman, 2000). For the outer surface, it contains about 95% crystalline calcium carbonate in the form of calcite that is a ceramic material (Shuhadah, Supri & Kamaruddin, 2008; Toro et al., 2007; Tasai et al., 2006; Arias et al., 1993). Melting temperature of calcite is 1339°C (Centers for Disease Control and Prevention, 1995). Due to the large amount of the ceramic in the chicken eggshells, it is possible to apply this material as an alternative mold material for metal casting. Presented in this study is an attempt to investigate the possibility to fabricate the metal casting mold from the chicken eggshells powder. In order for the chicken eggshells powder mold to be considered in this application, the fabricated mold should provide sufficient mechanical strength and acceptable surface quality of the casting.

Methods and Materials

Materials

Waste chicken eggshells were collected and cleaned by using washing-up liquid. The chicken eggshells were air-dried for 10hrs and mechanically grinded to control the particle size to be less than 149μm by sifting with a sieve no.100. Figure 2(a)-2(d) show the steps for preparing the chicken eggshells powder. Figure 3(a)-3(b) show the micro-structure of the powder examined by SEM test under a vacuum condition at 15 kV. The powder was prepared with sputter coating of gold to make the powder conductive. SEM images were captured with magnification of 2kX and 10kX. Results illustrate that the particle is porous, i.e., plenty of micro-holes that allow the steam and other gases to release from the mold. This property is an important requirement for the mold material. With the main purpose for forming the metal casting mold, an important requirement for mold material is ability to maintain the cavity shape with no collapse during the process. Therefore, a binding agent was required, bentonite and water were selected for this purpose.

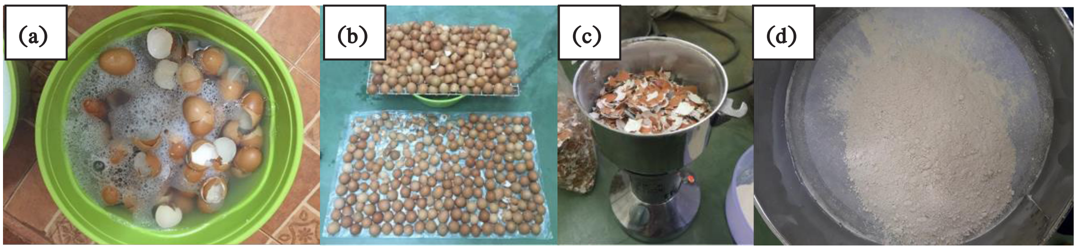


Figure 2 Steps for preparing chicken eggshells powder (a) cleaning (b) air-drying (c) grinding (d) sifting

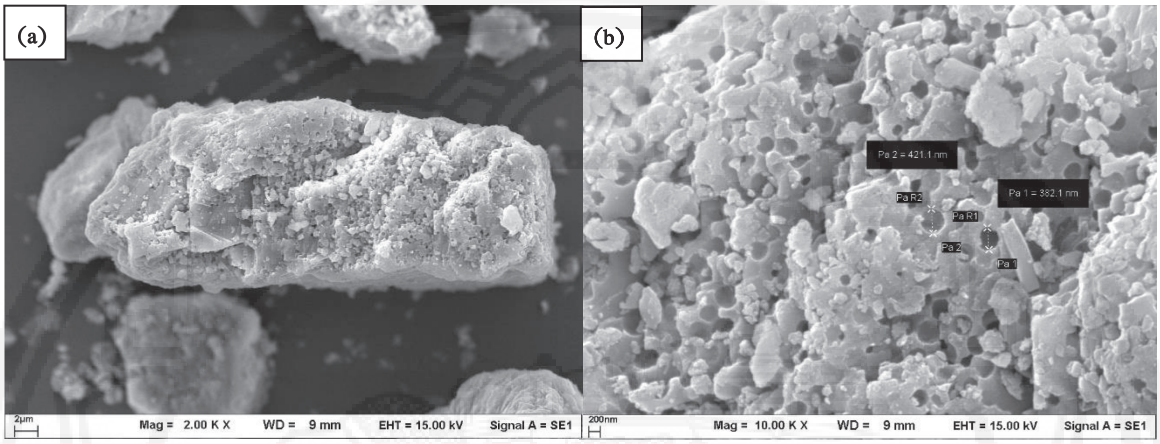


Figure 3 SEM images of chicken eggshells powder on magnification of (a) 2kX with 2μm scale bar (b) 10kX with 200nm scale bar

Methods

Experiments were conducted to check the possibility of using chicken eggshells powder to form the metal casting mold and determine the suitable composition of this new mold material. As shown in Figure 4(a)-4(c), steps for mold material preparation are as follows: (1) dry-mix 100g chicken eggshells powder with three levels of bentonite (6, 8 and 10g), (2) fill three levels of water (15, 16 and 17g) into the mixture and (3) gently crumble and keep it in a close container for 1min to reach homogeneity of water content. The particle size of the bentonite was also less than 149 μm by sifting with a sieve no.100. Table 1 shows all nine testing conditions. Each material condition, three cube specimens were created by using a steel mold of triple 50mm-cube cavities. As shown in Figure 5(a)-5(d), steps for specimens fabrication are as follows: (1) fill the mold with the prepared mold material, (2) tamp with a square rod, (3) leave the specimens in the mold for 10min before testing and (4) remove the mold.

Figure 4 Steps for preparing mold material (a) mixing with bentonite (b) filling water (c) gently crumbling

On each testing condition, compression tests were conducted on three specimens by using a universal testing machine with 1,000-kN load-cell. After a preload was applied, each green specimen was compressed at the crosshead speed of 10 mm/min until the specimen failed completely. Peak load data were recorded and used to determine the ultimate compressive strength (UCS) for the three specimens. A criterion for evaluation was the highest average UCS since the mold must have sufficient strength to maintain its shape during the metal casting process. The testing condition that provides the highest average UCS will be further investigated for the surface quality of the obtained casting by using a surface roughness tester (INSPEX : IPX-104) with measuring range 0.03-6.35μm and resolution 0.01μm.

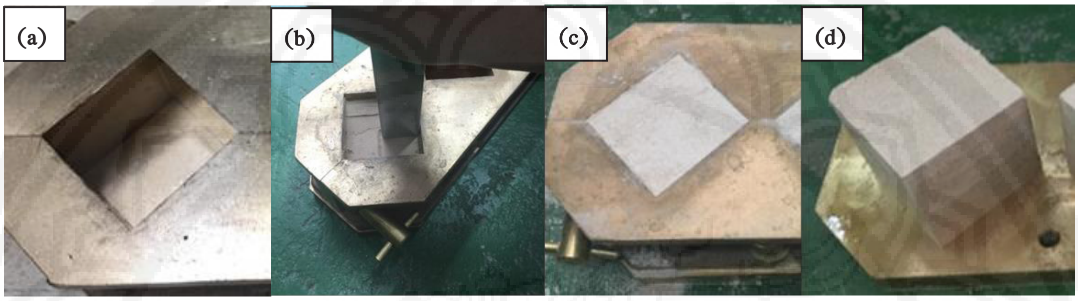


Figure 5 Steps for preparing specimens from the chicken eggshells powder (a) filling mold material (b) tamping (c) leaving for 10min (d) removing the mold

Results and Discussion

All 27 specimens were fabricated according to the testing condition. Table 1 presents the average UCS obtained from each testing condition. Two-ways ANOVA was conducted to ensure effects of bentonite, water and their interaction on UCS of the new mold material. Figure 6(a) shows that key assumptions were achieved therefore ANOVA could be applied. The results were obtained from Minitab (v.14) by using 95% confidence level (α = 0.05). A factor had significant effect on an investigated property when $F > F_{Critical\ value}$ or $P < \alpha$. Figure 6(b) illustrates that the interaction affected UCS due to $P_{interaction} < \alpha$. Therefore, this statistical analysis illustrated that both bentonite and water were required in order for the chicken eggshells mold could maintain its shape during the metal casting process. The optimum condition was considered from the condition that provided the highest UCS. As a result, the condition using 10g of bentonite and 16g of water gave the highest average UCS of 27.05 ± 1.17 MPa. A confirmation test was performed on five specimens to investigate whether the obtained UCS under the optimum condition is within the confident level. The sample size was determined by using power analysis approach to detect the difference of 2 with a power of 80% (Figure 7). The results were 26.25, 26.03, 27.11, 27.97, and 25.54 MPa. A one sample t-test was conducted with 95% confidence level (α = 0.05). Figure 8 shows that average UCS obtained from the optimum condition lying within range of the confidence interval, 25.39 to 27.78 MPa. Therefore, this could be accepted that the selected condition was reliable.

Table 1 The average UCS of the specimens on each testing condition (MPa)

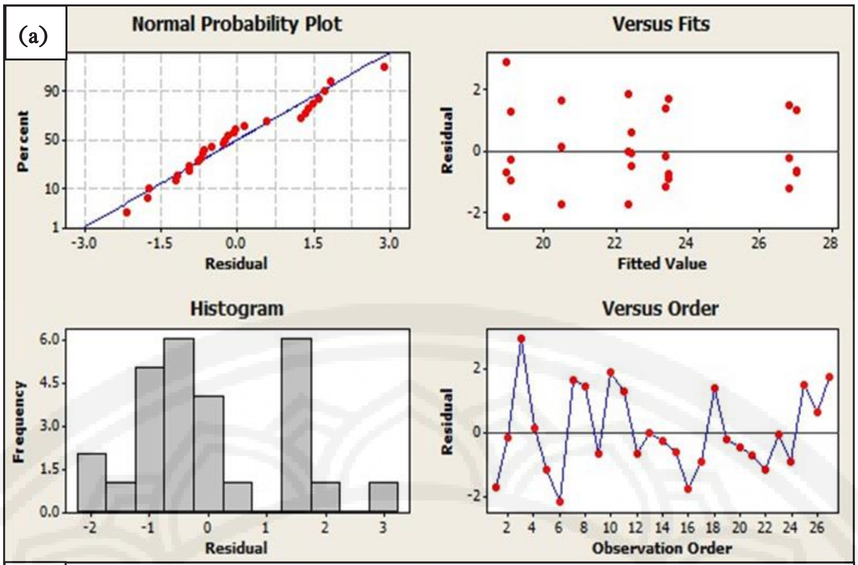
		Water (g)*		
		15	16	17
Bentonite (g)*	6	20.48 ± 1.69	22.35 ± 1.82	26.84 ± 1.37
	8	23.39 ± 1.32	19.07 ± 1.14	22.44 ± 0.56
	10	18.93 ± 2.63	27.05 ± 1.17	23.47 ± 1.49

**unit in g per 100g of the chicken eggshells powder*

A specimen of 30x40x8 mm^3 was created for checking the surface quality of the part made by using the chicken eggshells powder mold. Similar to the sand casting process, the specimen fabrication steps are as follows: (1) prepare the mold material with the optimum condition, (2) create the two pieces mold, cope and drag, (3) prepare the molten tin alloy, (4) fill the mold cavity with the molten tin alloy, and (5) extract the casting and remove the excess materials. The specimen was tested for average surface roughness (Ra) by the surface roughness tester. Figure 9(a) and 9(b) show the specimen and instrument setup. The specimen was measured for Ra at three position as shown in Figure 9(c). The cut-off and evaluation length were set at 2.50 mm and 3 mm. The results were 6.30, 5.40, 5.88μm respectively that were lower than the normal range of sand casting process, 6.30-50μm, according to ASME B46.1-1985.

According to the obtained mechanical strength of the specimens and the surface quality of the casting, applying the chicken eggshells powder was applicable for the metal casting application. In addition, the internal quality of the alloy part casted by this new mold material should be further studied to compare with the casted by the traditional sand mold. Because the internal quality of the casting is determined by heat dissipation in the solidification process, which is closely relate to the ability to the heat transfer of the mold material.

Due to the high mechanical strength, the chicken eggshells powder has been further investigated for additive manufacturing application. Typically, there are three types of additive manufacturing techniques: (1) powder-based, (2) liquid-based, and (3) solid-based techniques. The materials used in each technique must meet their requirements in shape forming method therefore the material composition identified in this paper might be revisited and adjusted. Figure 10 shows our on-going research to apply this green material in this application that the material composition was adjusted to be bentonite 35wt% and water 80wt% of the chicken eggshells powder. The build material was able to extrude through a nozzle consistently but the adhesion among the chicken eggshells powder still needed further improvement. Besides using as building material, the chicken eggshells powder was also applied as reinforcement material in concrete printing (Shakor, Nejadi & Paul, 2020; Shakor et al., 2017).



(b)

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General Linear Model: compressive strength versus Water, Bentonite

Factor     Type   Levels  Values
Water      fixed       3  15, 16, 17
Bentonite  fixed       3  6, 8, 10


Analysis of Variance for compressive strength, using Adjusted SS for Tests

Source           DF   Seq SS   Adj SS  Adj MS      F      P
Water             2   49.887   49.887  24.943  10.27  0.001
Bentonite         2   14.522   14.522   7.261   2.99  0.076
Water*Bentonite   4  144.622  144.622  36.156  14.88  0.000
Error            18   43.734   43.734   2.430
Total            26  252.765


S = 1.55873   R-Sq = 82.70%   R-Sq(adj) = 75.01%
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Figure 6 Analytical results generated from Minitab (a) residual plots for UCS (b) two-ways ANOVA for UCS

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Testing mean = null (versus not = null)
Calculating power for mean = null + difference
Alpha = 0.05  Assumed standard deviation = 1.17


             Sample  Target
Difference     Size   Power  Actual Power
         2        5     0.8      0.811766
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Figure 7 Power analysis for the sample size determination

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One-Sample T: Repeat the experiment

Test of mu = 27.05 vs not = 27.05


Variable               N    Mean  StDev  SE Mean       95% CI            T
Repeat the experiment  5  26.580  0.963    0.430  (25.385, 27.775)  -1.09

Variable                   P
Repeat the experiment  0.336
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Figure 8 Analytical results generated from Minitab : one sample t-test for confirmation test

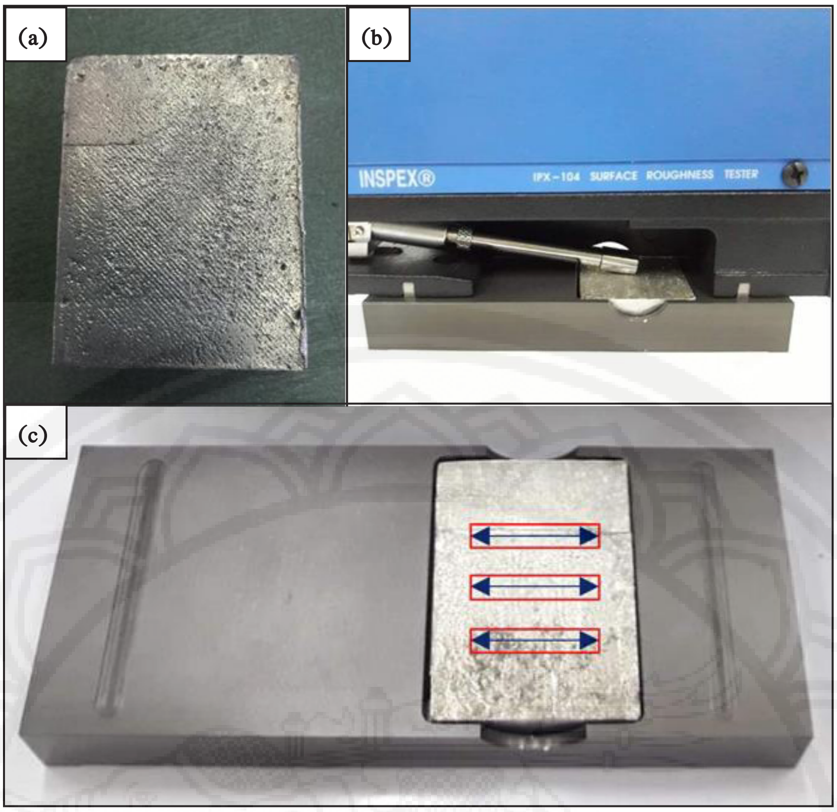

Figure 9 Surface roughness test (a) specimen (b) instrument setup (c) checking positions

Figure 10 The results obtained from the initial investigated on adjusting the material composition for additive manufacturing application

Conclusion and Suggestions

Chicken eggshells waste was investigated for the possibility of applying as new mold material for metal casting application. The chicken eggshells waste prepared in powder form was mixed with bentonite and water respectively. Experimental results showed that mixing bentonite 10wt% and water 16wt% of the chicken eggshells powder provided the highest UCS. With this mold composition, the obtained casting was further investigated for its surface quality. The testing results showed that Ra was in the lower range of sand casting process, i.e., the casting had good surface quality relative to the part made from sand mold. The investigated results demonstrated that the chicken eggshells waste could be applied for this application. Future studies will be on testing of (1) the chemical compositions of the mold material and (2) the internal quality of the alloy casted by this new mold.

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References

Arias, J. L., Fink, D. J., Xiao, S. Q., Heuer, A. H., & Caplan, A. I. (1993). Cell-mediated acellular compartments of mineralized extracellular matrix. *International Review of Cytology, 145,* 217-250.

Ashraf, M. A., Maah, M. J., Yusoff, I., Wajid, A., & Mahmood, K. (2011). Sand mining effects, causes and concerns: A case study from Bestari Jaya, Selangor, Peninsular Malaysia. *Scientific Research and Essays, 6(6)*, 1216-1231.

Bootklad, M., & Kaewtatip, K. (2013). Biodegradation of thermoplastic starch/eggshell powder composites. *Carbohydrate Polymers*, *97*, 315-320.

Carter, R. W. G., & Bartlett, D. J. (1990). Coastal Erosion in Northeast Ireland—Part I: Sand beaches, dunes and river mouths. *Irish Geography*, *23*(*1*), 1-16.

Centers for Disease Control and Prevention. (1995). *Occupational safety and health guideline for calcium carbonate.* Retrieved from https://www.cdc.gov/niosh/docs/81-123/pdfs/0090.pdf?id=10.26616/NIOSHPUB81123

Dwivedi, S. P., Sharma, S., & Mishra, R. K. (2017). A comparative study of waste eggshells, CaCO3, and SiC-reinforced AA2014 green metal matrix composites. *Journal of Composite Materials*, *51(17)*, 2407-2421.

Masalu, D. C. (2002). Coastal erosion and its social and environmental aspects in Tanzania: a case study in illegal sand mining. *Coastal Management*, *30(4)*, 347-359.

Oliveira, D. A., Benelli, P., & Amante, E. R. (2013). A literature review on adding value to solid residues: eggshells. *Journal of Cleaner Production*, *46*, 42-47.

Shakor, P., Nejadi, S., & Paul, G. (2020). Investigation into the effect of delays between printed layers on the mechanical strength of inkjet 3DP mortar. *Manufacturing Letters*, *23*, 19-22

Shakor, P., Sanjayan, J., Nazari, A., & Nejadi, S. (2017). Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing. *Construction and Building Materials*, *138*, 398-409.

Shuhadah, S., Supri, M., & Kamaruddin, H. (2008). Thermal analysis, water absorption and morphology properties of eggshell powder filled low density polyethylene composites. *Proceeding of MUCET 2008, 8-10 March 2008* (pp. 15-16). UniMAP: Kangar, Perlis.

Stadelman, W. J. (2000). Eggs and egg products. In: F. J. Francis (ed), *Encyclopedia of food science and technology* (pp. 593-599). John Wiley & Sons: New York.

Tasai, W. T., Yang, J. M., Lai, C. W., Cheng, Y. H., Lin, C. C., & Yeh, C. W. (2006). Characterization and adsorption properties of eggshells and eggshell membrane. *Bioresource Technology*, *97*, 488-493.

Toro, P., Quijada, R., Yazdani-Pedram, M., & Arias, J. L. (2007). Eggshell, a new bio-filler for polypropylene composites. *Materials Letter*, *61(22)*, 4347-4350.