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POROSITY AND STRENGTH PROPERTIES OF GYPSUM BONDED INVESTMENT USING TERENGGANU LOCAL SILICA FOR COPPER ALLOYS CASTING

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Abstract

In this study, several formulations of gypsum bonded investment (GBI) as a mould for copper alloy casting has been developed and their properties had been investigated. The mould was developed using Terengganu local silica sand with the average particle size of 220–250 μm, acted as a refractory and Plaster of Paris (POP) as a binder. The formulations used were 75% local silica, 25% plaster and various amounts (31–37%) of water. The compressive strength, tensile strength, porosity, core hardness and mould hardness properties of the prepared GBI were studied. It has been found that both compressive strength and tensile strength reduced with water content due to an increment of mould porosity which was confirmed via Scanning Electron Microscopy analysis. The mould hardness was found unchanged, but the core hardness was slightly reduced with the increment of water. The compressive strength of GBI moulds developed in this work was in the range of 600–1100 kN/m^2, which was sufficient for copper alloy casting.

Keywords: Copper alloys casting, Compressive strength, Hardness, Gypsum bonded investment.

1. Introduction

Gypsum bonded investment (GBI) casting is widely used in jewellery and dental casting and the investment usually consist of refractory material and a binder. Typically, the refractory material is silica (quartz or cristobalite) and the binder may include gypsum or phosphate. Various brands and types of GBI are readily

Nomenclature

P	Porosity
W_i	Dry weight of specimen, g
W_f	Green weight of specimen, g

Abbreviations

GBI	Gypsum Bonded Investment
GF	George Fisher
GFN	Grain Fineness Number
HPG	High Pressure Gauge
JB	Jambu Bongkok
KA	Kuala Abang
POP	Plaster of Paris

available in the market, nevertheless, further study needed to be done in order to obtain cheaper and reliable materials for GBI especially at high temperature [1-3]. Currently, in titanium-based alloys casting, the magnesium oxide-based investment casting has been favoured where the magnesium oxide can act both as refractory material and binder [4].

In all casting processes, compressive strength evaluation is very important. The compressive strength is the capacity of a material or structure to withstand axially directed pushing forces, thus, when the limit of strength is reached, brittle materials are crushed. Therefore, the mould should be able to withstand the flow and pressure of the metal at high temperature during the pouring process. According to Chew et al. [4], the compressive strength of GBI was between 4–5 MN/m^2 which had been found adequate to withstand casting pressure, yet permitted easy casting retrieval.

The porosity of GBI is also an important factor to be studied to ensure that gas porosity defect in casting can be minimised. A study done by Asaoka et al. [5] showed that the porosity increased with water content and it was generated due to evaporation of water from calcium sulphate dihydrate. Hydration of hemihydrate calcium sulphate or commercially known as Plaster of Paris (POP) is a highly exothermic reaction and occurs as shown in Eq. (1).

$$CaSO_4.0.5H_2O + 1.5H_2O \rightarrow CaSO_4.2H_2O + Q \quad (1)$$

where Q is the amount of heat evolved [6]. During the hydration, gypsum crystallisation takes place and develops strength.

Furthermore, little is known on the hardness of GBI. Earnshaw [7] had studied the compressive strength of ten commercially available GBI at room temperature, 2 hours after mixing and after heating at 700°C. He reported that the investment containing boric acid showed an increment of 40 to 55% of the compressive strength. The main objective of this study is to optimize the formulation of GBI using local silica (Terengganu, Malaysia) and determine the properties of GBI for copper alloy casting. It is anticipated that by using local materials, the cost of GBI is significantly reduced without compromising the product quality.

2. Experimental Method

2.1. Materials, formulations and mould characterizations

The silica was taken from two (2) locations; Kuala Abang (KA) and Jambu Bongkok (JB) which located in the state of Terengganu, east coast of peninsular Malaysia. The silica obtained from both locations contained 220–250 μm average grain size or 50–60 grain fineness number (GFN) was found suitable to be developed as the refractory material for copper alloy and aluminium alloy casting [8]. Two types of POP were used. They are Eurochemo POP and Cast-C POP. Several formulations of GBI consist of 75% silica, 25% POP and 31-37% water were developed. Table 1 depicts the sample of formulations and its abbreviation used in this work. The GBI samples were made into a cylinder with dimension of 50 mm diameter and 50 mm height using a specimen mould. The samples were left to harden at room temperature before the specimen mould was detached for further characterization. The strength, porosity and hardness test were carried out for every mould formulation.

Table 1. The GBI Formulations and its Abbreviation used in this Work.

Sample	KA Silica (%)	JB Silica (%)	Eurochemo POP (%)	Cast-C POP (%)	Water (%)
KA1	75	0	25	0	31
KA2	75	0	25	0	33
KA3	75	0	25	0	35
KA4	75	0	25	0	37
KA5	75	0	0	25	31
KA6	75	0	0	25	33
KA7	75	0	0	25	35
KA8	75	0	0	25	37
JB1	0	75	25	0	31
JB2	0	75	25	0	33
JB3	0	75	25	0	35
JB4	0	75	25	0	37
JB5	0	75	0	25	31
JB6	0	75	0	25	33
JB7	0	75	0	25	35
JB8	0	75	0	25	37

The strength test was carried out using George Fischer (GF) Universal Strength Machine type PFG with compressive and tensile strength accessories (inserts) and high pressure gauge (HPG). For the strength and hardness test, the samples were inserted into a furnace at room temperature. The temperature then rose at 11^{o}C/min until the testing temperature was reached. Then the samples were heat soaked at 500^{o}C for 2 hours. The strength and hardness test was carried out immediately after the samples were taken out from the furnace which represents the actual casting process. The surface hardness was measured by a method similar to the Brinell hardness test using green hardness B scale. A spring loaded steel ball with a mass of 0.9 kg had been indented onto the samples and the depth of indentation was measured. The core hardness of the mould was measured

using core hardness tester (0-100) in order to determine the hardness of the sub-surface of the moulds. This instrument has a four-point penetrator for abrading the surface of the samples. The depth of penetration was registered directly onto a gauge which represents numerically the hardness of the core. For porosity evaluation, drying process of the samples was done in a furnace at 500°C for 2 hours. The porosity was defined as a percentage and it was calculated by obtaining the differentiation in the weight of green and dried samples. The calculation is shown as follows:

$$P = \frac{W_i - W_f}{W_i} \times 100 \quad (2)$$

where P is the porosity (%), W_f is the weight of the specimen after oven dry, (g) and W_i is the green weight of the specimen, (g).

2.2. Casting processes

Prior to the moulding process, wax pattern was made by injecting liquid wax into the aluminium die. The wax was left to solidify and the die was released to remove the pattern. The wax injection machine was set to 78°C wax temperature, 50 kN/m^2 injection pressure and 2 second injection time. The wax pattern was attached to the gating system which consists of pouring cup, runner and ingate (later to be known as wax tree). The schematic diagram of the wax tree is shown in Fig. 1. Later, the wax tree was placed on a plate and encircled with a metal flask. The best GBI mixture (obtained from the previous characteristics) consists of local silica, POP and water were mixed until a creamy and thick slurry was obtained. Then the slurry was poured into the flask and permitted to solidify by chemical reaction forming a block mould. The schematic diagram of the mould is shown in Fig. 2. The optimum slurry viscosity was essential to ensure the wax pattern was able to be fully invested. Over-mixing had made the slurry thickened thus foil the investment process of the wax tree, meanwhile, insufficient mixing time resulted in separation of moulding material.

After six hours, the moulds were placed in the furnace for de-waxing and preheating process. Initially, it was heated at 170°C with a rate of 1.6°C/min and held at this temperature for 3 hours. Then the temperature was increased to 750°C with a rate of 1.9°C/min and held at this temperature for 5 hours. At this stage, burn-out process was expected to occur in order to ensure that all the wax in the mould was completely eliminated. After the burn-out process the mould was cooled in the furnace to the desired casting temperature. In this study, the mould pouring temperature was set at 500°C. The melting process of copper alloy with the main composition of 60% copper and 38% zinc was carried out using a gas fired furnace. Graphite crucible had been used and the furnace firing was controlled by a valve in the gas piping. The melting process took about 45 minutes. After the molten metal reached the pouring temperature, slag was removed and the mould was taken out from the de-waxing furnace. The molten brass was poured at temperature of 970°C and was left to solidify and cooled down for 12 hours.

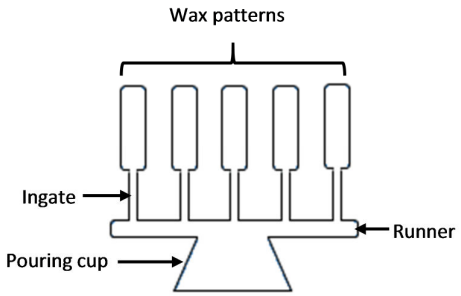

Fig. 1. The Wax Pattern with Gating System (Wax Tree).

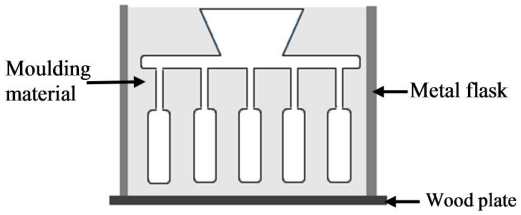

Fig. 2. The Wax Tree Embedded in the Moulding Materials.

3. Results and Discussions

3.1. Mould porosity

Figure 3 shows the porosity of the mould as a function of water content for both silica and both types of POP. From the Fig. 3, it can clearly be seen that the porosity increased with the increment of water content. To support these results, microscopic study was done using Scanning Electron Microscope (SEM) analysis. Figure 4 depicts the SEM of the mould at different water content. The needle shape structures were the calcium sulphate crystals and the dark area in between was the empty space (pores) which was filled with water when hydrated and filled with air when it was dried. Similar observation was obtained by Ingo et al., [9] which reported that the investment material was composed of calcium sulphate crystals, pores and silica particles. From Fig. 4, it can be observed that as the water content increased the percentage of dark area was also increased indicates that the mould had become more porous.

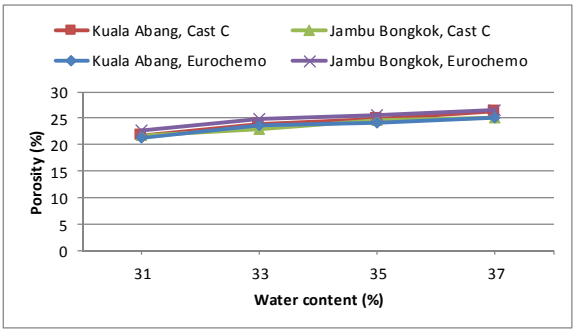

Fig. 3. Mould Porosity against Water Content.

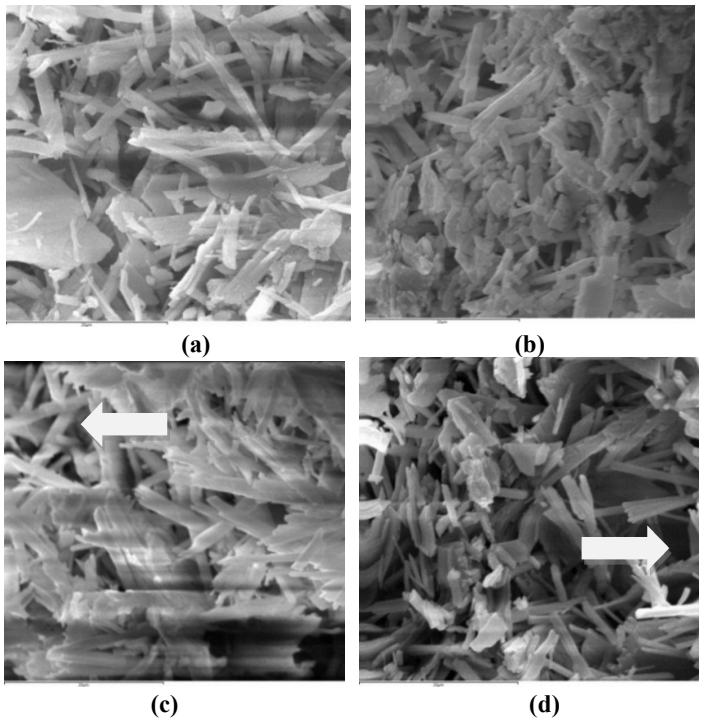

Fig. 4. SEM Micrograph of the Mould with (a) 31%, (b) 33%, (c) 35% and (d) 37% Water Content with the Arrows Showing the Mould Porosity at 3500X Magnification.

3.2. Compressive strength

Figure 5 shows the compressive strength of the mould with 25% Eurochemo plaster. It can be observed that the compressive strength of Kuala Abang's silica decreased as water content increased to 33%. Similarly, at 35% water, the strength decreased slightly and this trend continued to 37% water content. The same trend also can be observed for Jambu Bongkok's silica and the lowest compressive strength was found in the mould formulation with 37% water. Similar results were also observed for Cast-C POP where compressive strength decreased with water content as illustrated in Fig. 6. These results showed a similar trend behaviour obtained by previous researchers [10]. The influence of the water content on the strength of the gypsum showed that, when the water amounts increased the void fractions of the generated gypsum were also increased. These void fractions were believed to cause weaker bond between the gypsum crystals thus affected the mould strength. Therefore, it can be concluded that for both types of the developed GBI, at higher water ratio, the void fractions had become larger, hence reduced the resistance to compressive forces. These resulted in a weaker and more brittle mould. According to Lux and Darvel [11] the commercial GBI had the strength of 1–6 MN/m^2 depending on the type of silica used. From their study, the investment mould formulated using 30% water and silica powder in quartz form had the strength of 5 MN/m^2.

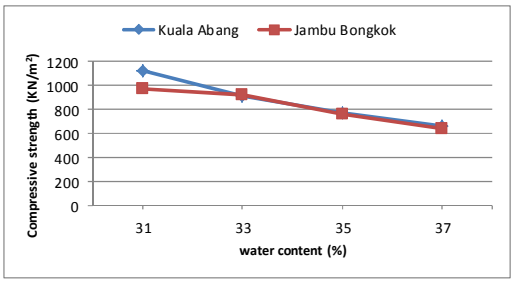

Fig. 5. Compressive Strength as a Function of Water Content (Eurochemo POP).

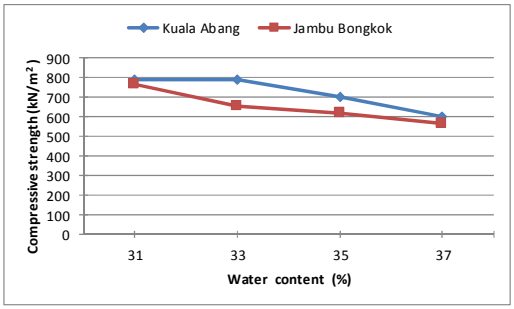

Fig. 6. Compressive Strength as a Function of Water Content (Cast-C POP).

3.3. Tensile strength

The results of tensile strength as a function of water content using Eurochemo POP as a binder is shown in Fig. 7. Figure 8 depicts the plot of tensile strength versus water content for the formulation of Cast-C POP. It can clearly be seen that the tensile strength for both silica was slightly reduced with the water content. As discussed earlier, the mould porosity and void fractions were the main reasons of a reduction in tensile strength. Besides porosity, tensile strength was also closely related to the amount of gypsum crystals, interlocking points between crystals and contact points between the crystals and the sand grains. At higher porosity, the number of crystals was lessened, thus reduced the interlocking and contact points between sand grains. These resulted in a weaker bond between moulding materials and as a consequence the tensile strength reduced [10].

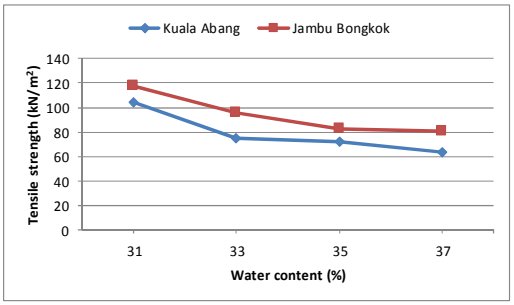

Fig. 7. Tensile Strength against Water Content (Eurochemo POP).

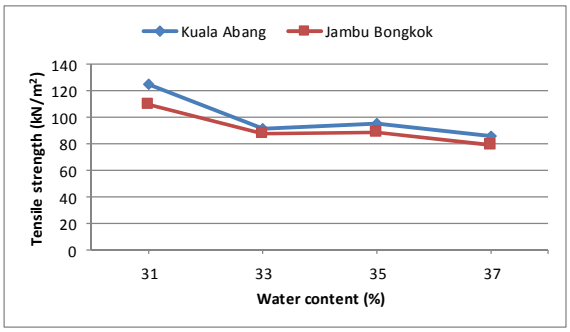

Fig. 8. Tensile Strength against Water Content (Cast-C POP).

3.4. Core hardness

Figures 9 and 10 show the core hardness of the mould using Eurochemo and Cast-C POP as a function of water content. It was found that core hardness was in the range of 35 to 55 and it was slightly reduced with water content. The significant reduction was observed in the formulation of 37% water. Similar to the strength properties, the main causes of hardness reduction were porosity and the numbers of gypsum's crystal interlocking, where a higher degree of porosity and reduced interlocking number was leading to smaller resistance to abrasive force and finally smaller core hardness.

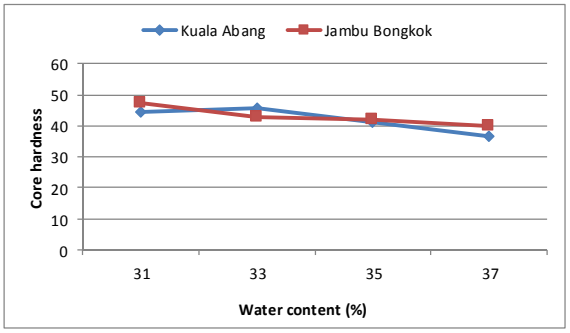

Fig. 9. Core Hardness against Water Content (Eurochemo POP).

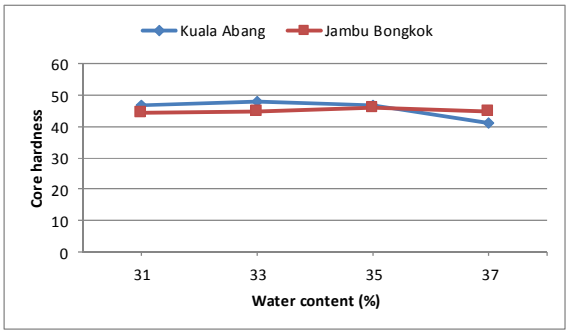

Fig. 10. Core Hardness against Water Content (Cast-C POP).

3.5. Mould hardness

The hardness number is an indication of the degree of compaction and provides some information on the ability of a mould to produce dimensionally accurate castings. From the scale B hardness test as shown in Figs. 11 and 12, the hardness of the mould was found in the range of 92-94 for the Eurochemo plaster while Cast-C was in the range of 88-90. Rao [12] had written that for copper alloy casting, mould hardness should be higher than 70. As expected, the water content did not give any significant influence on the hardness. Although the increment in water content had led to higher porosity, yet it did not affect the hardness because the porosity only occurred on the inner surface of the mould.

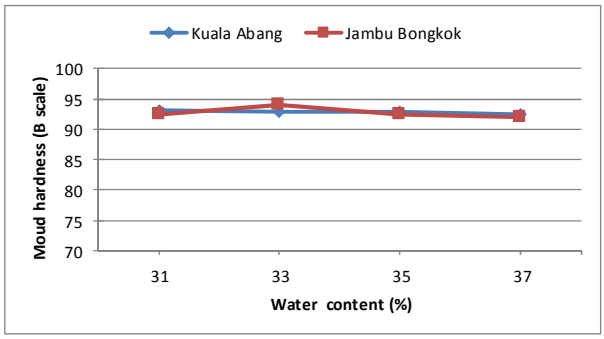

Fig. 11. Mould Hardness as a Function of Water Content (Eurochemo POP).

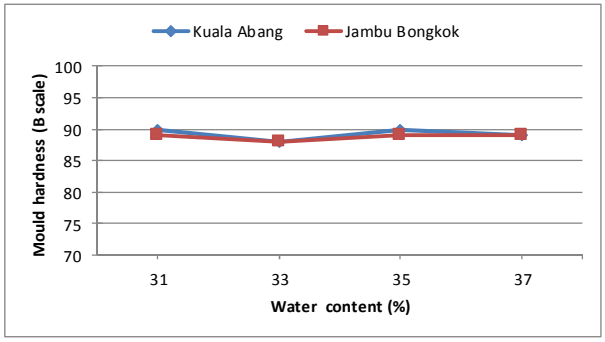

Fig. 12. Mould Hardness against Water Content (Cast-C POP).

3.6. Casting process

Figure 13 shows the mould of Kuala Abang's silica with the formulation of KA3 which contained 75% silica, 25% POP and 35% water before and after pouring process of brass molten metal. No leakage of molten metal was observed and this condition was consistent for all formulations tested. Therefore, it can be confirmed that all the formulations developed in this study had produced appropriate mould's strength and were suitable for casting process of copper alloy.

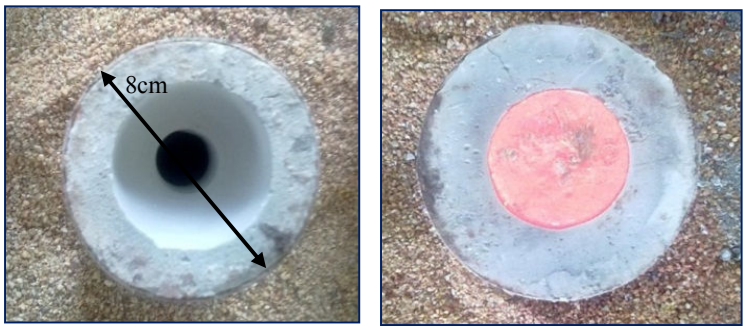

Fig. 13. Mould with Formulation of KA3 Before and After Pouring Process of Brass Molten Metal.

3.7. Cost reduction for local industry

The average market price of the commercial GBI in Malaysia is about RM 4.20/kg. With the use of local silica and the developed mould, the price can be lowered down to RM 0.67/kg, which makes a reduction of 83%. Therefore, it can be said that the development of moulding formulations using local silica will help the growth of small and medium enterprises in the field of casting hence, local casting industry.

4. Conclusions

Referring to the properties of strength, the best GBI formulation was 75% silica, 25% POP and 31% water. However, the percentage of water was found not to be the critical parameter where all water ratios between 31% - 37% can be used provided that the wax pattern could be fully invested. From the strength analysis, the moulds developed in this work have the compressive strength of 600–1100 kN/m^2 which was sufficient for copper alloy casting. From this study, it can be concluded that both Kuala Abang and Jambu Bongkok local silica sand are suitable to be used as refractory materials in the GBI of copper alloy casting and shall reduce the moulding cost up to 80%.

Acknowledgement

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