

**DEVELOPMENT OF BUBBLE GENERATOR FOR MANUFACTURING
FOAMED PLASTER MOLDS**



**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
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THESIS TITLE	Development of Bubble Generator for Manufacturing Foamed Plaster Molds
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ABSTRACT

Plaster mold has been used for complex shape metal castings due to its advantage of good surface finish and no several mold parts requirement. However, the current plaster mold has low permeability. Therefore, pressure or vacuum has to be used to assist mold filling ability of molten metal. Insufficient permeability of plaster mold for gas to be escaped causes either defects in cast components or limiting the number of components per casting. One method to solve this problem is to make the plaster mold more porous. This research aims to investigate the influence of plaster to water ratio, surfactant and strength enhancing additives, and foaming conditions on foam formation of plaster, develop a bubble generator machine, produce a plaster mold with foam-like structure and produce an automotive prototype using the developed foamed plaster mold.

A bubble generator was developed to generate gas bubbles in plaster slurry. A combination of a conventional stirrer and a bubble generator was found to give foamed plaster with more bubbles and higher permeability than using only the bubble generator. Various additives were added to conventional plaster slurry to form structure of foamed plaster with desired strength and permeability. Plasters with PVA, gypsum and $MgSO_4$ additions showed the best characteristics of high strength, homogenous structure and good flow ability slurry. Effects of water temperature and mixing time of plaster slurry on foamed plaster's properties were investigated. Prolonged mixing time was favorable to enhance uniformity of the plaster as a result of shorter reaction time and attributing to an increase in reaction temperature. Higher water temperature with intermediate mixing time is recommended to enhance permeability of the foamed plaster. Coarser

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plaster crystal structure would be attributed to less resistance to the passage of gases and hence enhancing permeability of the foamed plaster. Increasing mixing time with reasonable low water temperatures seems to enhance strength but deteriorate the permeability of the foamed plaster. Small plaster crystal structure would be attributed to strength enhancement and permeability reduction.

Permeability and compressive strength were found to inversely and directly proportional to the density of foamed plasters, respectively. The permeability and compressive strength of as-cast foamed plasters was about an order of magnitude smaller and larger than that of heat treated foamed plasters, respectively. In addition, the permeability seems to be well related to compressive strength irrespective to production conditions.

Foamed and conventional plaster produced with and without vibration/vacuum slurry treatment were investigated. The best surface quality of the foam-like plaster mold was obtained when plaster slurry was left under vacuum at both after mixing and casting without vibration.

A foam-like plaster mold was used for producing turbocharger wheels. Turbocharger wheels with thin blades were completely cast using the foam-like plaster mold but with incomplete castings at some casting positions. Gating design and pattern assembly location seem to be parameters of great importance for controlling the filling of molten metal and hence determining the completeness of casting. The developed plaster molds with the foam-like structure was expected to reduce the cost of both raw plaster and cast metal materials due to the large amount of pores in plaster structure and the increase of production yield.

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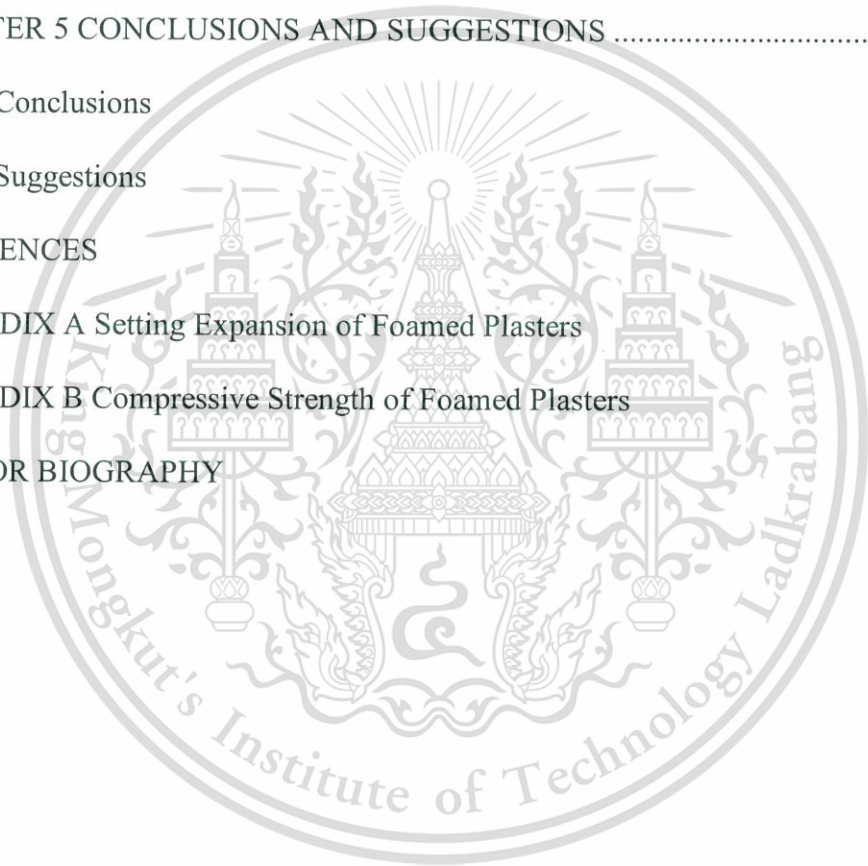
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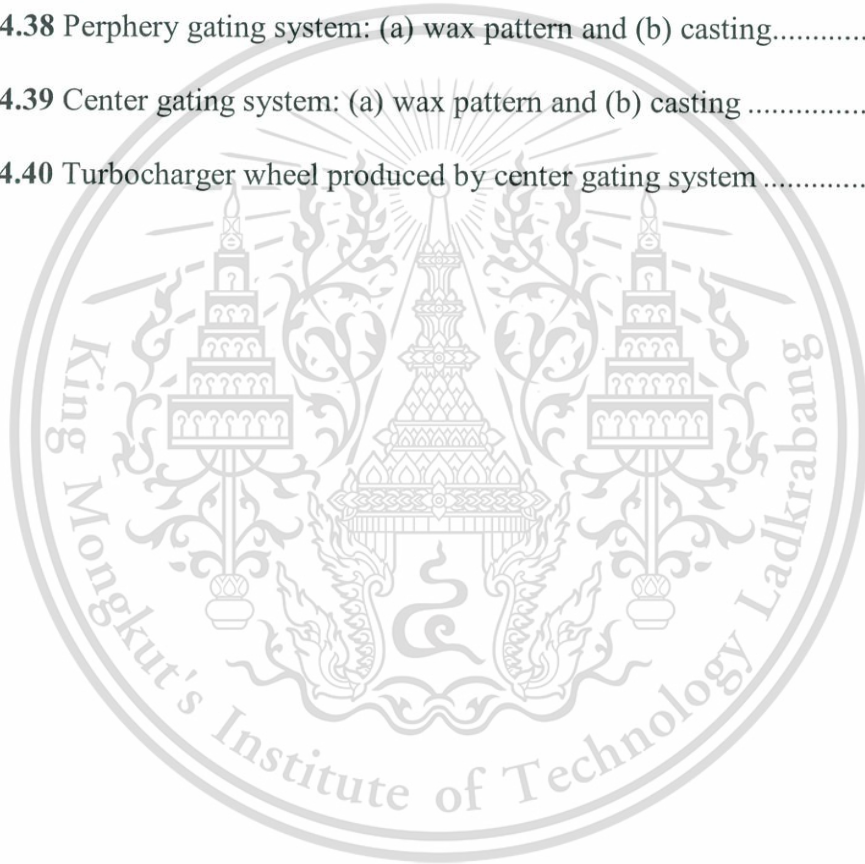
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LIST OF SYMBOLS

SYMBOLS		UNIT
	Celcius	(°C)
	Fahrenheit	(°F)
	Grams	(g)
	Kilonewton	(kN)
	Mega Pascal	(MPa)
	Millilitre	(ml)
	Square meter	(m ²)
<i>A</i>	Cross section area of the specimen perpendicular to the direction of gas flow	(cm ²)
<i>F</i>	Bubbling by the bubble generator	(min)
<i>K</i>	Permeability	(m ²)
<i>K_p</i>	permeability coefficient	(m ²)
<i>L</i>	Length of specimen	(cm)
<i>L</i>	Thickness of the workpiece	(cm)
<i>M</i>	Mixing by the conventional stirrer	(min)
<i>m</i>	Dry weight of the foamed plaster	(g)
<i>P</i>	Permeability number	
<i>P₁</i>	Pressure at outside of the specimen in atmosphere	(Pa)
<i>P₂</i>	Pressure at inside of the specimen in atmosphere	(Pa)
<i>Q</i>	Gas flow rate through material	(cm ³ /sec)
<i>R²</i>	Correlation coefficient	
<i>t</i>	Time	(min)
<i>V</i>	Fluid velocity averaged over the total cross-section of the porous specimen	m/s
<i>V</i>	Volume of the foamed plaster	(mm ³)
<i>v</i>	Volume of gas through workpiece	(ml)

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LIST OF SYMBOLS

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SYMBOLS		UNIT
β	Inertial parameter	
ΔP	Pressure drop over the specimen length	(Pa)
Δl	Expansion after setting	(%)
μ	Viscosity of gas	(kg/m·s)
ρ	Density of the fluid	(kg/m ³)
ρ_f	Bulk density of a foamed plaster	(m ³)
σ_{pl}	Plateau stress	(MPa)



LIST OF TECHNICAL VOCABULARY AND ABBREVIATION

ACRONYMS

ASTM	American Society for Testing and Materials
JPL	Jewelry Plaster Limited
E	Young's modulus
MTEC	National Metal and Materials Technology Center

ABBREVIATIONS

Al	Aluminum
CO ₂	Carbon dioxide
Cu	Copper
Mg	Magnesium
Zn	Zinc
PVA	Polyvinyl alcohol
CMC	Carboxymethyl cellulose
Na ₂ SO ₄	Sodium sulfate
MgSO ₄	Magnesium sulfate
Na ₃ C ₆ H ₅ O ₇	Sodium Citrate
NaC ₆ H ₉ O ₇	Sodium Alginate
Na ₂ SiO ₃	Sodium Silicate
H ₃ PO ₄	Phosphoric acid
Si	Silicon
Fe	Iron
Mn	Manganese
Ti	Titanium

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Plaster mold has been widely used in metal castings, especially jewelries and complicated automobile parts, for example, wheel compressor, turbo charger, blade accessory, static wire condenser, canvas shoes plate, etc. Plaster mold offers benefits in keeping details of filigree [1], less time consumption in mold manufacturing, having a number of non-ferrous metals such as aluminum, copper, magnesium, zinc, silver and gold to be cast with [2,3] and also allowing castings with slender shapes to be made because of its low heat transfer. Moreover, it reduces waste since less finishing is required for castings produced using the plaster mold. All in all, plaster mold can significantly reduce production cost of low to medium volume metal castings. However, plaster mold at present has relatively low permeability [4]. Therefore, pressure or vacuum has to be used to assist mold filling of a molten metal, otherwise trapped air will build up pressure and resist the flow of the molten metal causing either air cavities or incomplete castings. Hence, there is a need to have a new technology for producing a plaster mold with higher permeability.

One method to solve the mentioned problem is to make plaster containing a number of pores in plaster slurry which can be practically generated using a bubble generator. When the plaster slurry sets, set plaster will have a foam-like structure having better permeability property and lightweight. Thus, a mold made by the foam-like structure plaster will have a significant material cost reduction, more complex shape production ability and less defect casting products.

Up to now, a number of small bubble generators have been developed. In 1970s, small gas bubbles with a diameter of ten to over ten micrometers were produced for the first time and used in the military in Russia. Afterwards in 1980s, the United States of America had led this small bubble technology to use as well. In 1990s, Japan had brought this technology to use in commercial [5]. Nowadays, small bubble technology has been widely used in various industries, for example, agriculture, fishery, wastewater treatment, medical, etc. An interested small bubble generator is based on the use of compressed air flowing through narrow channels in liquids [6, 7, 8, 9]. Although this

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small bubble generator has been used in various applications, it has not been used for foamed plaster manufacture. In production of foamed plaster, numerous factors, such as ratio of plaster to water, concentration of surfactants, type or amount of strength enhanced additives significantly affect to mechanical properties of the plaster [10]. The implementation of the small bubble technology to foamed plaster production application is therefore in doubt. This research aims to develop a small bubble generator for manufacturing plaster molds with a foam-like structure for metal casting by the improvement of the current small bubble generator technology.

1.2 Objectives

- To investigate the influence of plaster to water ratio, surfactant and strength enhancing additives, and foaming conditions on foam formation of plaster.
- To develop a bubble generator machine.
- To produce a plaster mold with foam-like structure.
- To produce an automotive prototype using the developed foamed plaster mold.

1.3 Scope of Research

- Select a plaster which is most commonly used in the market to be a model plaster for foam-like structure development.
- Develop a bubble generator for manufacturing plaster molds with foam-like structure that includes.
 - Investigate the flow behavior of plaster slurry within a bubble generator.
 - Control the size and volume of generated gas bubbles.
 - Produce a plaster mold with foam-like structure.
- Test plaster mold properties using ASTM standard test methods for gypsum plaster.
- Test physical and mechanical properties of an automotive prototype produced by the developed foamed plaster mold.

1.4 Thesis Outline

The thesis is arranged in 5 chapters, the contents of which are summarised as follows.

Chapter 1: Introduction

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Chapter 2: Literature review

Chapter 3: Research methodology

Chapter 4: Results and discussion

Chapter 5: Conclusions and suggestions



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CHAPTER 2

LITERATURE REVIEW

2.1 Aluminum Parts in Vehicle

2.1.1 Aluminum Trends in Cars

In 2015, an average vehicle will have 394 pounds of aluminum parts, up from 350 pounds in 2012. By 2025, the average vehicle will have an estimation of 547 pounds of aluminum [11]. Automakers are accelerating the shift to use aluminum because they have gained manufacturing experience with it over the past. Every 1% decrease of the car body weight, the fuel consumption decreases by 0.6% – 1% [12]. Benefits of using aluminum for the car body are lightweight, corrosion resistance, good thermal properties, reachable material cost and manufacturing viability [13].

Figure 0.1 shows the usage of aluminum in automotive industry, which has been significant increase over the past four decades and is predicted to further increase over the next decade. Aluminum improves vehicle performance, reduces CO₂ emissions and promotes fuel economy [14]. Automotive parts are manufactured as "net shape" to reduce the cost associating with waste materials and finishing [13]. Automotive products are widely used by automakers, as shown for example in **Figure 0.2**, to reduce vehicle weight.

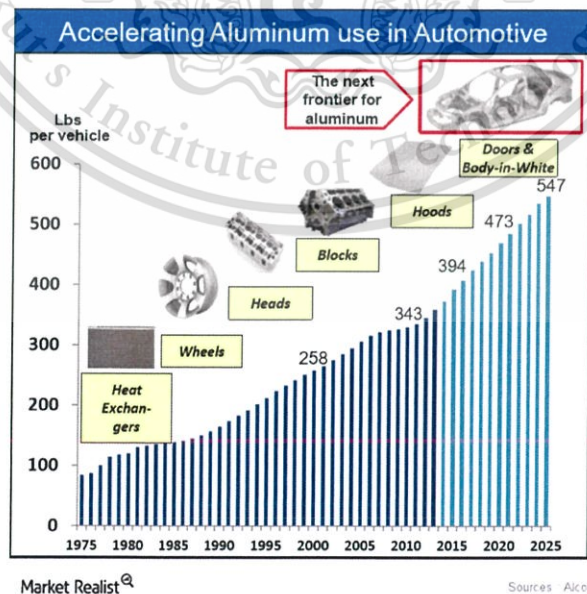


Figure 0.1 Examples of automotive aluminum parts

Source: <http://marketrealist.com/2015/12/auto-industrys-aluminum-usage-increasing/> commercial use.

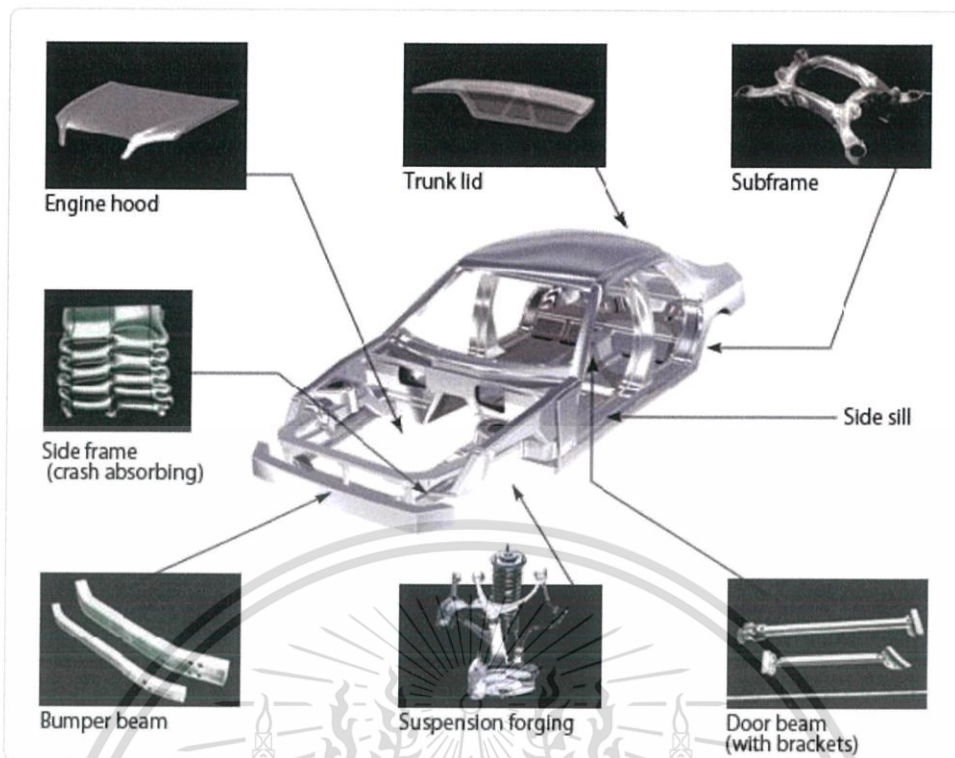


Figure 0.2 Accelerating aluminium use in a car.

Source: <http://www.kobelco.co.jp/english/products/outstanding/lighterautos/>.

2.1.2 Metal Working

Metal working is the process of working with metals to create individual parts or assemblies. Metal working processes can be divided as follows [15].

- Metal Casting processes
- Mechanical working processes
- Machining processes
- Joining processes
- Powder Metallurgy processes

2.1.3 Metal Casting Processes

Casting process is done by pouring molten metal into a mold having a cavity of a desired part. The mold holds this metal in shape as it solidifies to obtain a metal casting. Advantages of this process are flexibility in the size and number of workpieces to be produced and complexity of workpieces that cannot be made by mechanical working processing.

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Types of metal casting processes are as follows [16].

- Sand casting
- Investment casting or lost wax casting
- Permanent mold casting
- Plaster mold casting
- Centrifugal casting
- Shell mold casting
- Die casting

Defects found in casting processes are as follow.

- Porosity in workpiece and surface finish caused by the gas dissolved in the metal released during cooling or porosity of the mold has less.
- Misrun caused by metal water that was too low temperature or terrible of metal gate way.
- Fracture due to heat caused by unstable cooling and workpiece design.
- Gaps caused by shrinkage of metal

2.2 Plaster Mold Casting

2.2.1 Production of Plaster Mold

Plater mold has been used for the manufacture of non-ferrous metal castings[17]. Conventional production of a plaster mold is shown in **Figure 0.3**. A slurry made up of plaster of Paris with water is poured over a wax pattern locating inside a molding box. After setting, the molding box is heated to de-wax leaving a cavity with geometric profile imitation of the wax pattern. A molten metal is then cast into the mold with the assistance of vacuum or pressure to give a complete filling of the mold cavity with the molten metal.

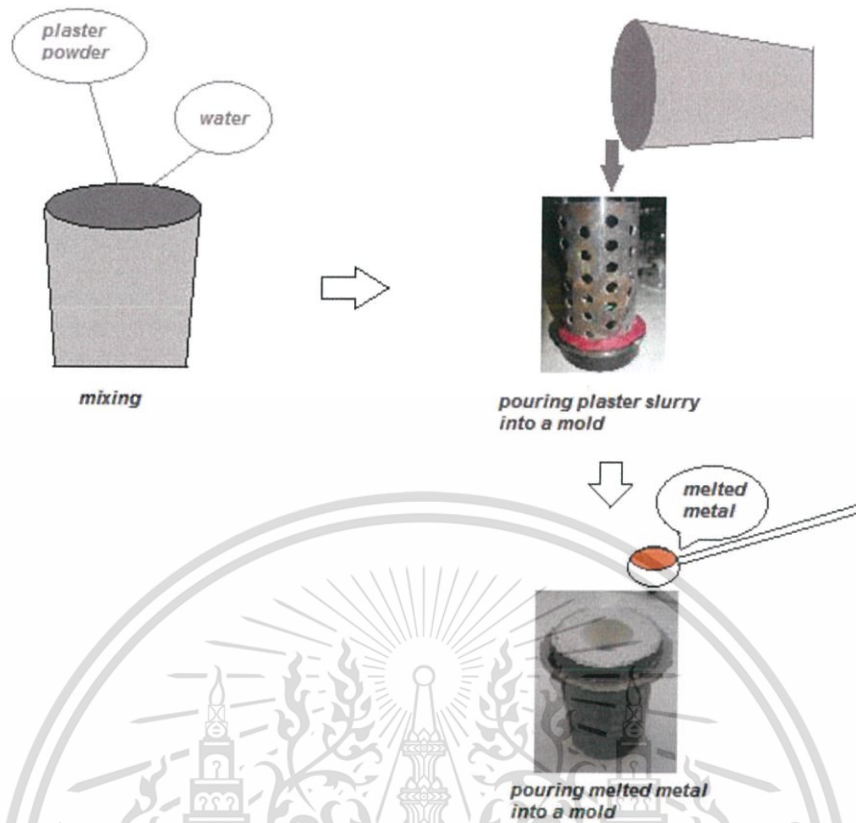


Figure 0.3 Plaster mold casting process

2.2.2 Applications of Plaster Mold Casting

The technology for manufacture of industrial components has become more complicated. Currently, the automotive industry has considerably grown and turbo charger wheels have therefore been designed to be more complex geometries to improve fuel efficiency and engine power for automotive manufacturers [18]. One traditional method for producing complicated products is plaster mold casting which has benefits of keeping details of filigree, reducing time in mold manufacturing, minimizing time for finishing and allowing slender shape to be produced [17].

Non-ferrous metals with low melting temperatures such as aluminum, copper, magnesium and zinc can be cast with plaster mold. Quick prototypes as well as limited production parts of these metals have been produced using the plaster mold casting process, as shown for example in **Figure 0.4**.

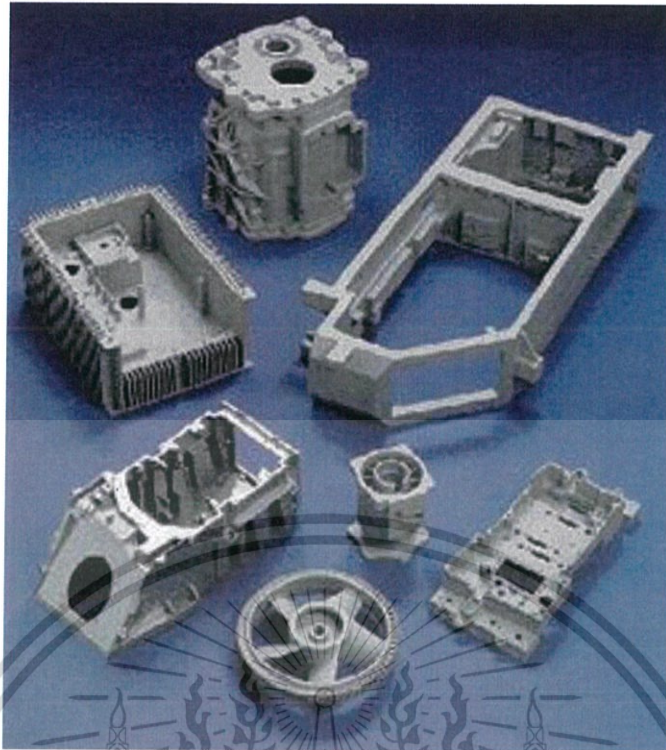


Figure 0.4 Industrial products made by plaster mold casting process

Source: <http://www.metalbot.com/plaster-mold-castings.html>

Advantages of plaster mold casting process are as follows.

- Can produce complex shapes.
- Thin section casting.
- Exact copying of pattern detail.
- Dimensionally accurate castings.
- Good surface finish.
- Minimum residual stresses and distortion in castings.

Limitations of plaster mold casting process are as follows.

- Poor productivity as it has lengthy processing problems.
- Close monitoring of the production process.
- The problems of poor mold permeability.
- Impaired mechanical properties a possibility as a result of slow cooling of the casting.

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2.3 Fundamental of Foamed Plaster

Requirements of more complex geometries casting, such as turbo charger wheels, have raised difficulty in manufacture using the conventional plaster mold casting in that conventional plaster molds have low gas permeability resulting in incomplete casting defects. One method to solve this problem is to make the plaster mold more porous. Basically, permeability of plaster molds can be enhanced by physico-chemical treatment (Antioch process), foaming treatment with foaming agent addition and appropriate mixing technique [1]. Basically, automotive parts which complicate shapes can be cast using foamed plaster molds.

2.3.1 Important Properties of Foamed Plaster

Structure of foamed plaster consists of unit cells with interconnectivity. Each of the unit cells is randomly arranged in different geometries and sizes which depend on production method. Structural parameters of foamed plaster can be described as follows: density, porosity and pore size. Production methods and related parameters of foamed plaster will be described in Sections 2.4 - 2.5.

2.3.2 Applications of Foamed Plaster

The cast products are found in a wide range of applications, including automotive components, aerospace parts, electronics, mechanical devices, and construction supplies. This process can be cast any produce that produced by plaster casting process. The example parts is shown in **Figure 0.5 - Figure 0.6**.



Figure 0.5 Engine housing

Source: https://www.google.co.th/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&sqi=2&ved=0ahUKEwiH5d_czPXUAhXIgI8KHWZ9CH8QFggsMAE&url=http%3A%2F%2Feng.sut.ac.th%2Fme%2Fbox%2F2_55%2F436304%2F6Casting.ppt&usg=AFQjCNFmgbYkH59BwEbm1M2_gdffmRAgCA

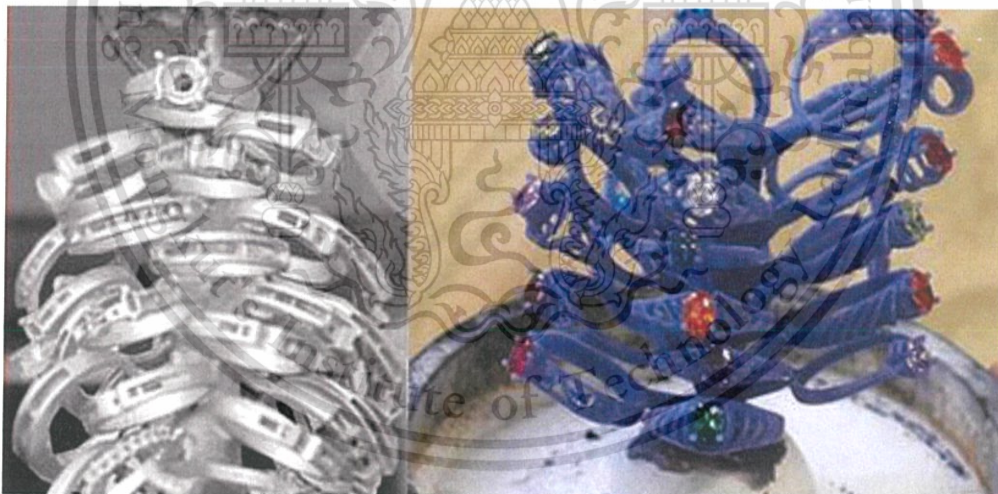


Figure 0.6 A casting tree with numerous ring patterns after removing a plaster mold

Source: <http://www.lapigems.com/blog/post/2015/08/12/Handmade-Jewelry-vs-Casting.aspx>

2.4 Production Methods of Foamed Plaster

Several methods have been used for producing foamed plaster: physico-chemical treatment (Antioch process), foaming treatment with foaming agent addition and appropriate mixing technique, and addition of additives that shrink during drying. This material is reserved for educational use only, not allowed for commercial use.

evaporation of water or thermal decomposition [1]. The simple addition of foaming agents together with the proper mixing of plaster slurry would be a suitable method for making a foam-like plaster mold to realize in technology and machinery in the industry. However, so far, technical feasibility of the foam-like plaster mold has not been proved for manufacture of any complex industry component.

2.5 Production Parameters Influencing on Foam Structure

2.5.1 Permeability

Permeability of a fluid flowing through a mold is characterised based on the type of fluid flow which is described by the Reynolds's number. When the fluid flow is laminar in which the Reynolds's number is in the ranges 1 – 10, permeability of the flowing fluid can be determined by Darcy's law as given in equation (2.1). For higher Reynolds's numbers, the fluid flow is turbulent, and hence the permeability cannot be determined by the linear Darcy's equation. The turbulent flow can be, instead, determined by Forcheimer's equation as given in equation (2.2).

The permeability coefficient of porous materials can be determined by Darcy's equation as shown below.

$$K = \frac{\mu QL}{A(\Delta P)} \quad (0.1)$$

Where K is the permeability, μ is the viscosity of gas, Q is gas flow rate through material in cm^3/sec , L is the length of specimen in cm in the flow direction, A is the cross-sectional area of the specimen perpendicular to the direction of gas flow in cm^2 , ΔP is the pressure drop over the specimen length ($P_2 - P_1$): P_2 and P_1 are the pressure at outside and inside of the specimen in atmospheres, respectively [21].

The permeability coefficient of porous materials with non-linear fluid flow can be determined by Forcheimer's equation as shown below.

$$-\frac{\Delta P}{L} = \frac{\mu}{K}V + \beta\rho V^2 \quad (0.2)$$

Where V is the fluid velocity averaged over the total cross-section of the porous specimen (Q/A), β is the inertial parameter, ρ is the density of the fluid. Density and viscosity of air can be taken from physical properties tables of gases at atmospheric pressure [20].

In practice, the permeability of gas flow rate through a workpiece can be obtained by the standard of American Foundry Association (A.F.S.) which defines as permeability number (P) as shown in Equation (2.3).

$$P = \frac{vL}{\Delta pAt} \quad (0.3)$$

Where v is the volume of gas flowing through the workpiece in cm^3 or ml, L is the thickness of the workpiece in cm, Δp is the pressure drop across the specimen length ($P_2 - P_1$), A is the cross section area in perpendicular to the gas flow of the workpiece in cm^2 and t is the time in min.

2.5.2 Mixing Time

Permeability of a conventional plaster mold rapidly decreases with increasing mixing time. Its decrease is highest comparing with other parameters, such as while the setting time decreases to 50% of its maximum, the permeability decreases to nearly 30% of its maximum as shown in **Figure 0.7** [22]. The reduction of permeability of the plaster mold is not favorable for metal casting particularly when the mold strength is low.

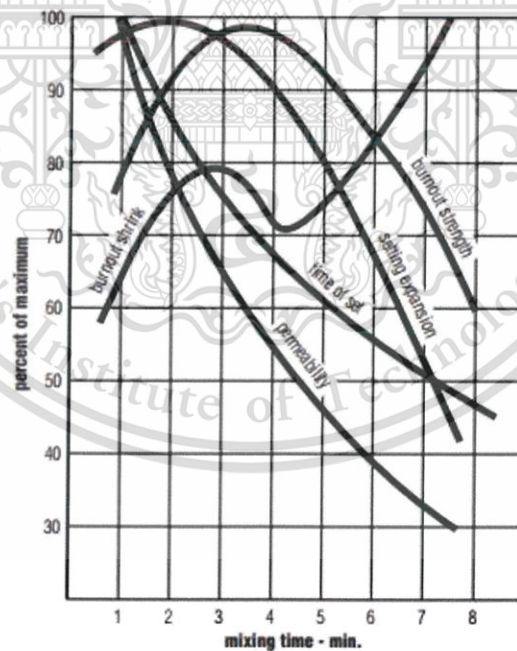


Figure 0.7 Effect of mixing time on set time, permeability, setting expansion, burnout shrink and burnout strength of a conventional plaster

Source: https://www.usg.com/content/dam/USG_Marketing_Communications/united_states/product_promotional_materials/finished_assets/hydrocal-gypsum-cements-application-en-IG538.pdf

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2.5.3 Mixing Temperature

Plaster slurry temperature has an important influence on setting expansion, setting time, permeability and burnout shrink of a conventional plaster. Using a plaster slurry with temperatures higher than 100°F increases the permeability of the plaster as shown in **Figure 0.8** [22].

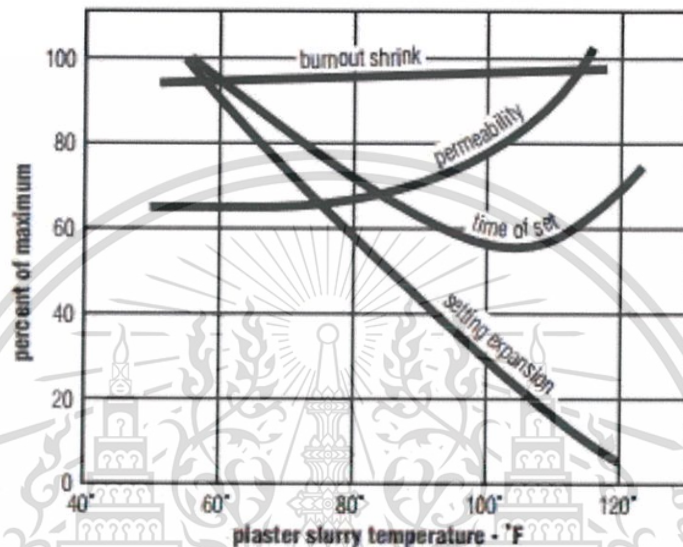


Figure 0.8 Effect of plaster slurry temperature on setting expansion, setting time, permeability and burnout shrink of a conventional plaster

Source: https://www.usg.com/content/dam/USG_Marketing_Communications/united_states/product_promotional_materials/finished_assets/hydrocal-gypsum-cements-application-en-IG538.pdf

2.6 Foamed Plaster Properties

2.6.1 Plaster Properties

Technical data of plaster type JPL Silk Cast Red by Jewelry Plaster Limited Company are given below [23].

Powder / water ratio	100/38-40
Working time	9-10 min.
Gloss off time	11-12 min.
Thermal expansion at 750	0.80%
Setting expansion after 2 hours	0.55%
Volume yield per kg. of powder	770 ml.

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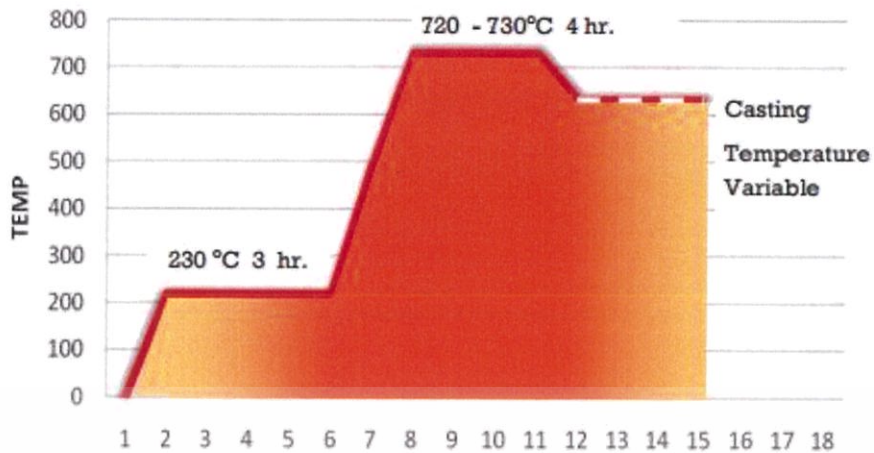


Figure 0.9 Burnout cycle

Figure 0.9 shows a burnout cycle for a most use size of flask. It depends very much on the size of the flask. The larger the flask or the wax content, the longer and more gradual the burnout must be.

2.7 Bubble Generators

Table 0.1 summarises current methods used for production of small bubbles in liquids. Injection of gas through a porous material would be most suitable for the production of small bubbles in plaster slurry because the plaster slurry does not necessary to be circulated in a system and controlled for pressure or temperature. However, when the plaster slurry becomes solid. It cannot dissolve in water, this makes equipment becomes difficult to be cleaned resulting in limitation in device design.

Table 0.1 Current methods used for production of small bubbles in liquids

Methods	Principle
Hydrodynamic type	Most popular method by sucking gas in high speed water swirl to generate microbubbles.
Pressured gas type	Gas dissolves to water by Henry's law. Solubility of gas in a liquid is in proportion to the gas pressure. Dissolved gas at high pressure becomes microbubbles when pressure is released suddenly.
Porous material	Gas injected through a membrane with the size of nanometers to submicrons to give small bubbles in the liquid.
Original hydrodynamic reaction	Combination of pressure, swirl and static-mixer function.
Mechanical agitation	Agitate liquid with a high speed gas.
Sonication	Sonication to the liquid.
Venturi tube	Passing a gas into the center of narrow tube.
Micro-channel method	Flow gas or liquid through micron size of channel.
Gas solubility based on temperature dependence	Bubbles generated by the change of gas solubility in liquid by increasing or decreasing liquid temperature.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Bubble Generator

A bubble generator, as shown in **Figure 0.1**, developed by National Metal and Materials Technology Center (MTEC) was used for bubble generation in plaster slurry. The generation was equipped with impeller and stator, as shown in **Figure 0.2**, for bubble generator, and speed control unit, as shown in **Figure 0.3**, for rotating the impeller at required speeds.

In this work, the performance of the bubble generator was determined with the addition of a perforate disc mixer placing above the impeller, as shown in **Figure 0.4**, and with different rotating speed using a high speed servo motor, as shown in **Figure 0.5**. Details of foamed plaster slurry preparation are given in the next section.



Figure 0.1 A bubble generator developed by National Metal and Materials Technology Center (MTEC).

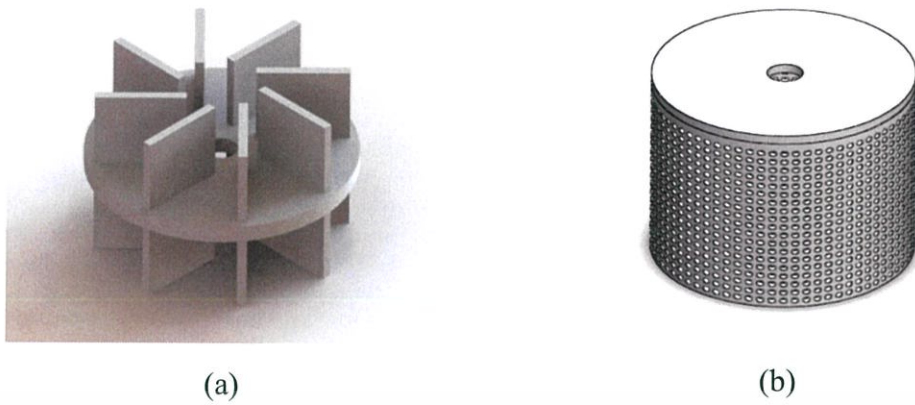


Figure 0.2 Components of bubble generator (a) Impeller and (b) stator of the bubble generator

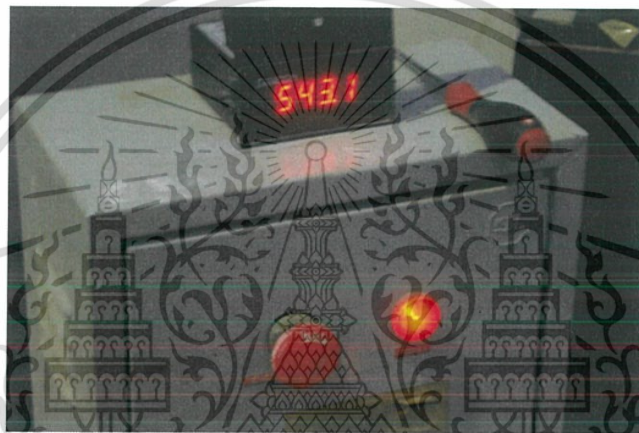


Figure 0.3 A speed control unit of the bubble generator.



Figure 0.4 A perforate disc mixer (indicated by an arrow) of the bubble generator.

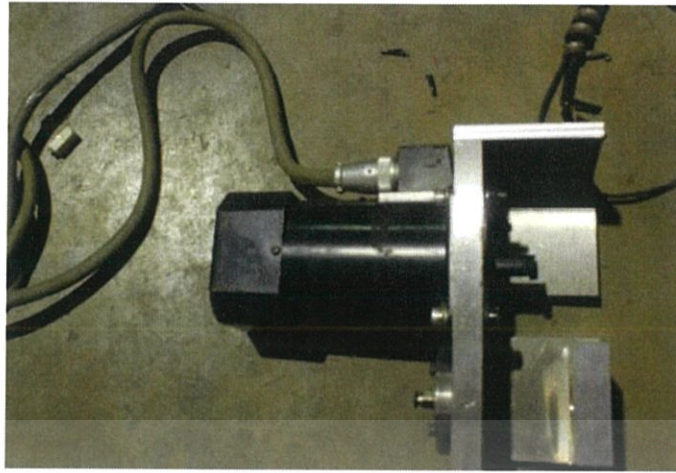


Figure 0.5 A high speed motor of the bubble generator.

Effect of water temperature and mixing time of combination mixing using a conventional stirrer and a bubble generator for the production of foamed plaster is shown in **Table 0.1**. The mixture was firstly mixed using the conventional stirrer (cookery mixer) and subsequently using the bubble generator. Once the mixture was throughout mixed, it was poured into molds for expansion and set time tests as well as specimen production for compressive strength and gas permeability test.

Table 0.1 Conditions of water temperature and mixing time of a combination mixing of a conventional stirrer and a bubble generator for production of foamed plaster with composition of (97%Plaster + 3%Gypsum) + (67%DI + 33%PVA) + 0.4% Sodium lauryl sulfate (overall weight) + 0.25% MgSO₄ (overall weight)

Temperature of water (°C)	A conventional stirrer (min.)	A bubble generator (min.)
20	1	5
	3	3
	5	1
28	1	5
	3	3
	5	1
40	1	5
	3	3
	5	1

3.2 Foamed Plaster Production

3.2.1 Plaster Composition Development

Composition of plaster was developed to obtain slurry with good flow ability, and foamed plaster with enough strength and gas permeability. Raw materials used for the production of foamed plasters are shown in **Table 0.2**. Plaster slurries were prepared using different compositions of the raw materials and using the bubble generator as shown in details in the previous section. Properties of SILK CAST (red) plaster, which is a conventional plaster used as a base plaster in this work, are shown in

Table 0.3.

Table 0.2 Raw materials used for production of foamed plaster

Plaster powder	Liquid	Surfactant	Additive
Plaster type JPL Silk Cast Red by Jewelry Plaster Limited company	Deionized water	Sodium lauryl sulfate	Polyvinyl alcohol (PVA) Agar CMC Na ₂ SO ₄ MgSO ₄ Sodium Citrate Sodium Alginate Sodium Silicate Xanthan Gum Propylene Glycol Phosphoric acid (H ₃ PO ₄) Carrageenan Gypsum

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Table 0.3 Properties of SILK CAST (red) conventional plaster

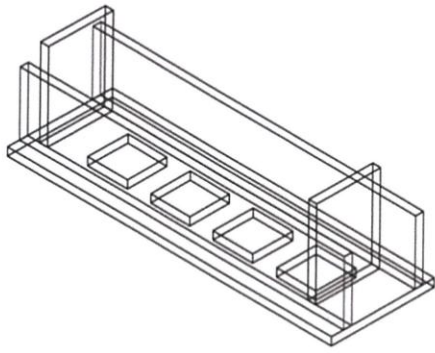
Parameters	Properties
Powder/water ratio	100/38
Working time @25°C slurry temperature	7-8 min.
Gloss off time @25°C slurry temperature	12-14 min.
Thermal expansion at 750°C	0.82%
Setting expansion after 2 hours	0.57%
Volume yield per kg. of powder	770 ml.

3.2.2 Foamed Plaster Surface Quality

Two types of surface were investigated: smooth and rough. Details of plaster specimen preparation of both surface types foamed plaster are given below.

3.2.2.1 Mold Preparation

Wax mold was prepared for foamed plaster casting. The mold was composed of an acrylic mold frame and a silicone master pattern. The acrylic mold frame contained four cavities for casting wax each of 5x5x5 cm as shown in **Figure 0.6**. Two types of silicone master pattern, which was flexible in order to be easily removed from cast wax, were used: smooth and rough, as shown in **Figure 0.7**. Example of a mold prepared for wax casting is shown in **Figure 0.8**. The mold was preheated at 50°C for 12 minutes prior to cast molten wax at 135°C. The cast wax was then left to slowly cool in an oven at 50°C. **Figure 0.9** shows for example of a smooth and a rough wax mold taken out from silicone master patterns to be used for foamed plaster casting.

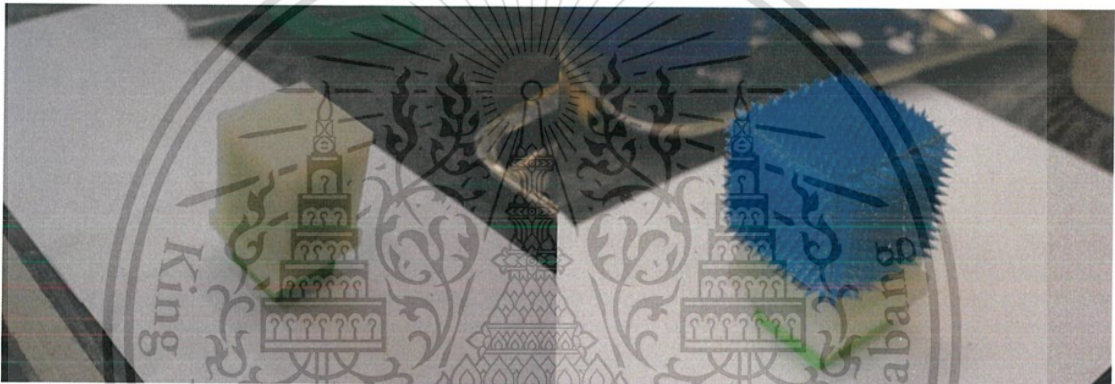


(a)



(b)

Figure 0.6 An acrylic mold frame for wax casting: (a) drawing and (b) actual mold frame



(a)

(b)

Figure 0.7 Silicone master pattern: (a) smooth and (b) rough surface



Figure 0.8 A mold for wax casting

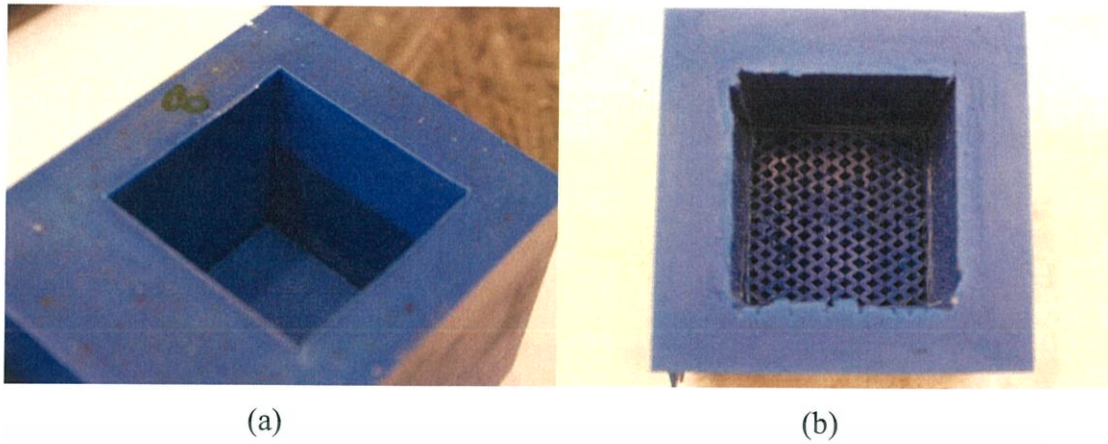


Figure 0.9 Wax mold: (a) smooth and (b) rough surface

Since the surface of a mold made from a foamed plaster always appears tiny pores resulting in metal penetration defect. This work is therefore aiming to eliminate this defect by using either vacuum or vibration to make pore-free at the surface of the foam-like plaster mold. Different sequences of vacuum implementation with and without vibration was performed on plaster slurry during making foamed plaster and conventional plaster molds. Conditions of the foamed and conventional plaster production are given in **Table 0.4**. About 30 to 60 seconds were taken for vacuum. The conventional plaster shown in

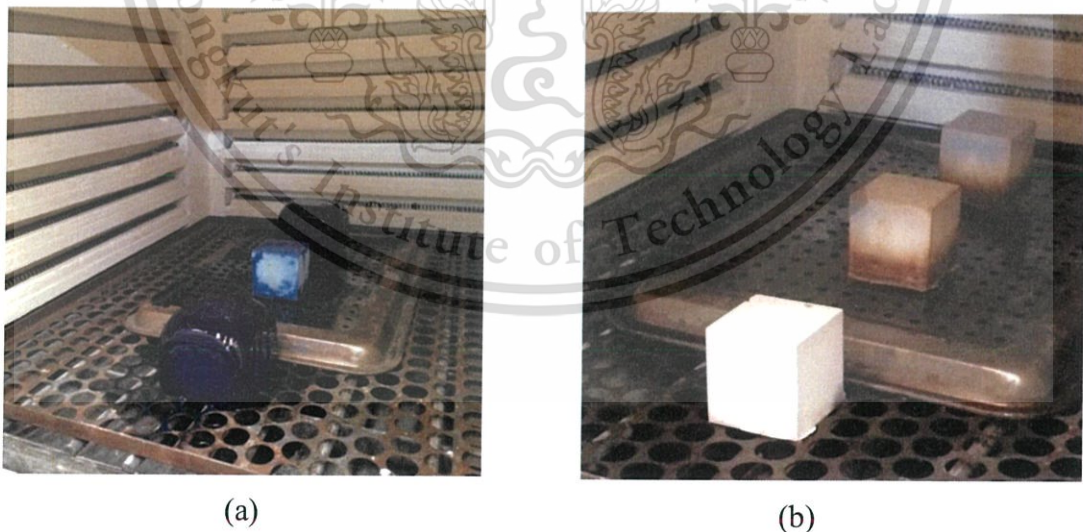


Figure 0.10 Foamed plasters: (a) during and (b) after wax burn-out at 700°C

3.2.2.2 Foamed Plaster Casting

Table 0.3 Properties of SILK CAST (red) conventional plaster was used as a base plaster for foamed plaster production. The weight ratio of plaster powder to water was 100/50. The

plaster powder was firstly hand-mixed for about 1 minute with gypsum, surfactant and MgSO₄, and subsequently mixed with de-ionised water and PVA using a conventional stirrer for 3 minutes to give a foamed slurry with composition of 97% plaster + 3% gypsum + 2/3 of 50% deionized water + 1/3 of 50% PVA+0.4% surfactant (overall weight) + 0.25% MgSO₄ (overall weight). After pouring the plaster slurry into the wax molds shown in **Figure 0.9**, the plaster molds were left to dry at ambient atmosphere and subsequently to de-wax at 700°C as shown in **Figure 0.10**. The surface quality of the molds was then assessed in terms of total area, total number and size of pores.

Table 0.4 Conditions of foamed (a – h) and conventional (y – z) plaster production

Conditions	Vacuum after mixing	Vacuum after molding	Vibration after pouring to mold
a	x	x	x
b	/	/	/
c	x	/	x
d	/	x	/
e	/	x	x
f	x	x	/
g	/	/	x
h	x	/	/
y	x	x	x
z	/	/	x

3.2.3 Gas Permeability Test of Foamed Plasters

Slurry of each composition or test condition was sampled and poured into a ring mold having the sample diameter of 50 mm and height of 10 mm, as shown for example in **Figure 0.11**.

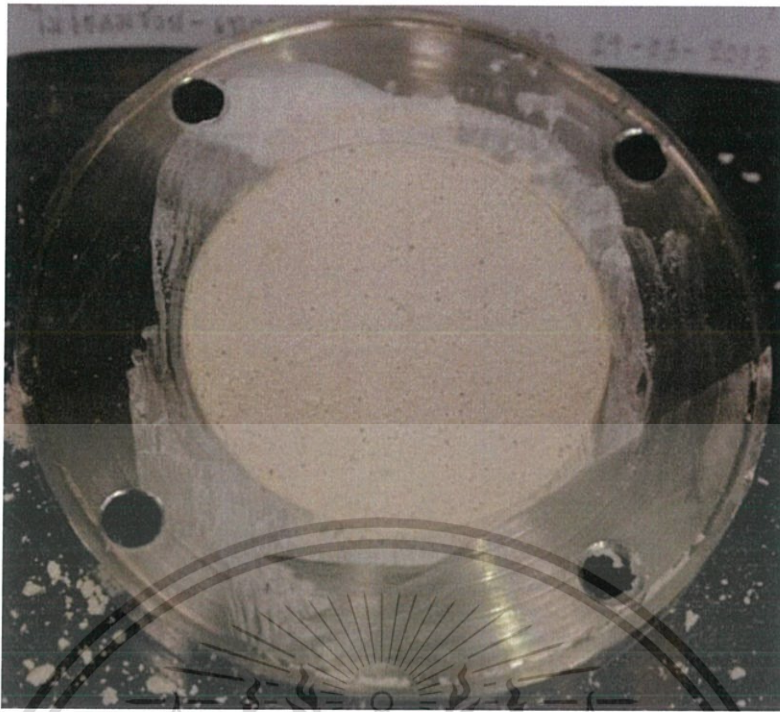


Figure 0.11 Example of a foamed plaster specimen for gas permeability test



Figure 0.12 Permeability test equipment

The plaster specimen was then measured its gas permeability, which is the ability of a porous material to allow fluids to pass through it, using equipment shown in **Figure 0.12**. By bringing the rate of gas flow and pressure drop calculations for the determination of permeability. In measurement of permeability of a porous medium, type of gas flow through the porous medium is a prime determination to permeability.

For laminar flow (Reynolds number is in the range 1 to 10), permeability is a part of the proportionality constant in Darcy's law which relates fluid flow and properties to pressure gradient applied to the porous medium as given by the equation (0.1). In case of the Reynolds number higher than 10, the gas permeability of a porous medium can be determined using Forchheimer's equation (0.2). In practice, the permeability of gas flow rate through a workpiece can be obtained by the standard of American Foundry Association (A.F.S.) which defines as permeability number (P) as shown in Equation (2.3).

3.2.4 Density of Foamed Plasters

Density of foamed plasters was determined using weight-volume measurement given by equation

$$\rho_f = \frac{m}{v} \quad (0.2)$$

Where ρ_f is the bulk density of a foamed plaster, m is the dry weight of the foamed plaster and v is the volume of the foamed plaster. The dry weight of the foamed plaster was measured using a balance with 4 digits of decimal as shown in **Figure 0.13**.



Figure 0.13 Digital balance

3.2.5 Compressive Test of Foamed Plasters

The compressive tests were carried out with as-cast plasters and the plasters with experiencing of 730°C heat treatment using an Instron 8801 universal testing machine having a maximum axial load capacity of 100 kN as shown in **Figure 0.14**. These

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compressive tests were performed at a strain rate of 0.001 s^{-1} until 80% of compressive strain. During compressive tests, deformation of each specimen was recorded using a video camera. Young's modulus (E) and plateau stress (σ_{pl}) of each specimen were determined from stress-strain curves.

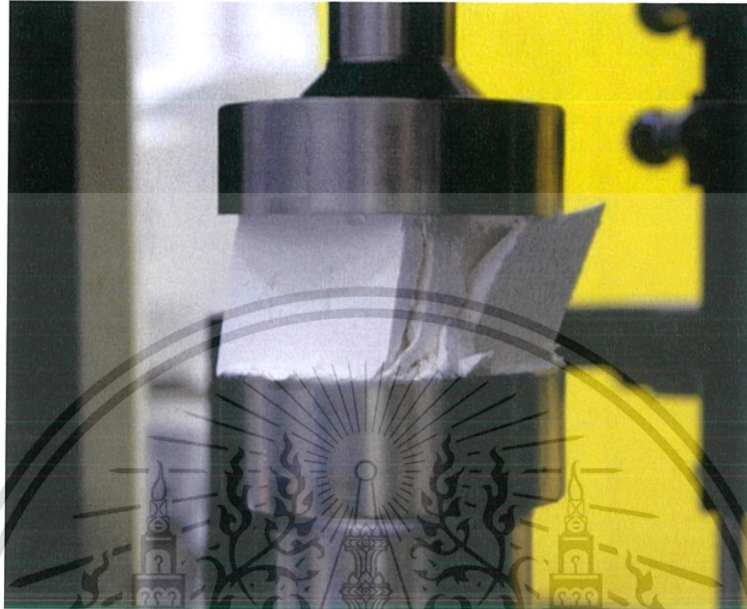


Figure 0.14 Instron 8801 universal testing machine

3.2.6 Setting expansion of foamed plaster

Plaster slurry was poured into a channel of a setting expansion test equipment as shown in **Figure 0.15**. Dimension in the longitudinal direction of the specimen was recorded in mm until the plaster slurry hardened to solid state.

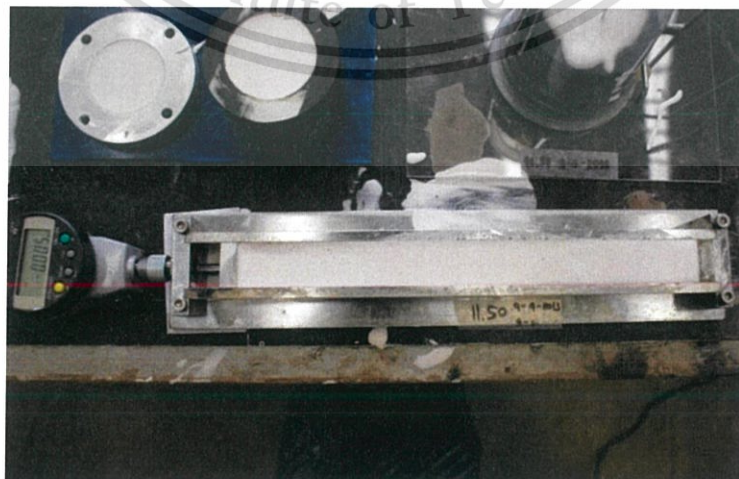


Figure 0.15 Expansion test equipment

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3.2.7 Setting time of foamed plaster

Setting time of plaster slurry was measured using the setting time test equipment shown in **Figure 0.16**. A needle of the setting time test equipment was periodically punched into plaster slurry cast in a rubber mold. The initial time of setting is the time elapsed between the initial contact of plaster powder and water, and the time when the penetration is measured or calculated to be 25 mm. The final time of setting is the elapsed between initial contact of plaster powder and water, and the time when the needle does not leave a complete circular impression on the plaster surface.



Figure 0.16 Setting time test equipment

3.3 Automotive Prototype Production

A turbocharger wheel, as shown in **Figure 0.17**, was used as a master model for determining the feasibility of using a foam-like plaster mold for casting automotive complex components. Processes for manufacturing turbocharger wheels using the foam-like plaster mold include: (i) master model reproduction, (ii) wax pattern making,

(iii) foam-like plaster investing, (iv) wax burn-out and (v) metal casting. Details of manufacturing processes are given below.

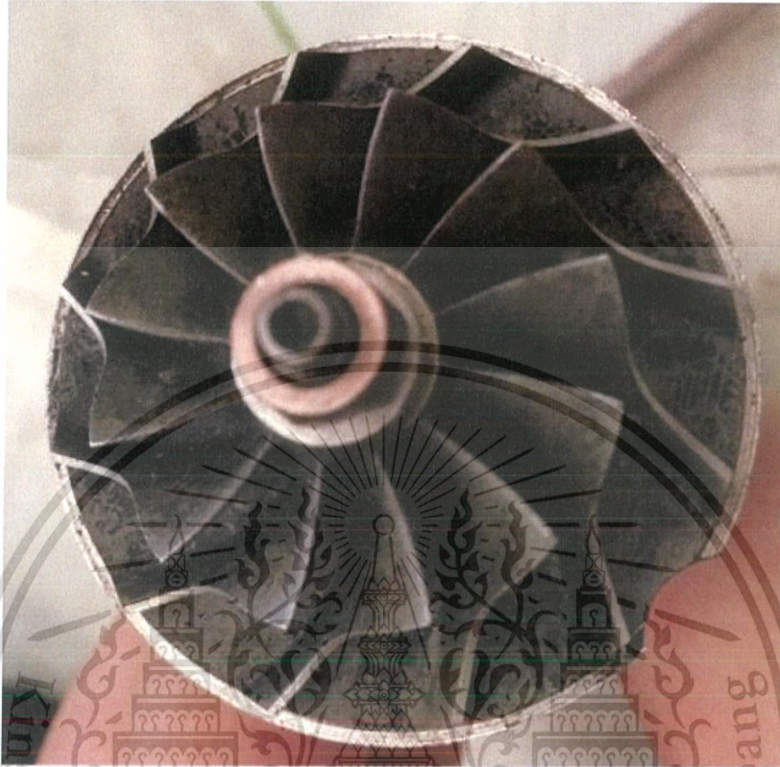


Figure 0.17 Photograph of a turbocharger wheel master model

3.3.1 Master Model Reproduction

Master model of turbocharger wheels, as shown in **Figure 0.18**, was reproduced using a clear liquid silicone with zero shrinkage for accurate model reproduction. Reproduction processes start with securing the master model in a cylindrical and transparent hollow container. Liquid silicone was then poured into the container to completely cover the master model. The container together with the master model and the liquid silicone was then placed in a vacuum chamber to de-bubble the poured liquid silicone, as shown in **Figure 0.19** - **Figure 0.20**. At the end of de-bubbling process, small wires were inserted into the liquid silicone to locate their tip at blade tips to make air vent channels. After the liquid silicone was cured, the container, the master model and the wires were removed giving a silicone mold for casting a wax pattern of turbocharger wheel.

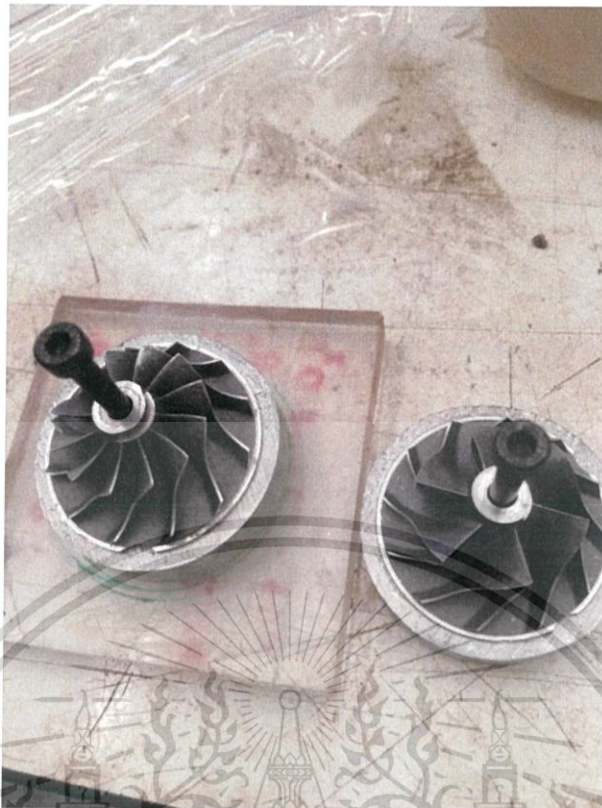


Figure 0.18 Master model of turbocharger wheels

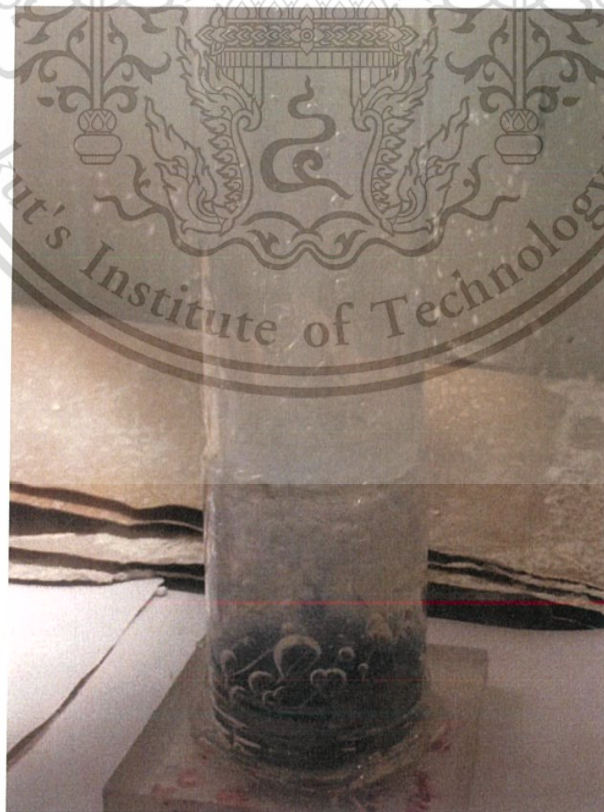


Figure 0.19 Master model reproduction during initial de-bubbling of liquid silicone
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Figure 0.20 Master model reproduction during final de-bubbling of liquid silicone

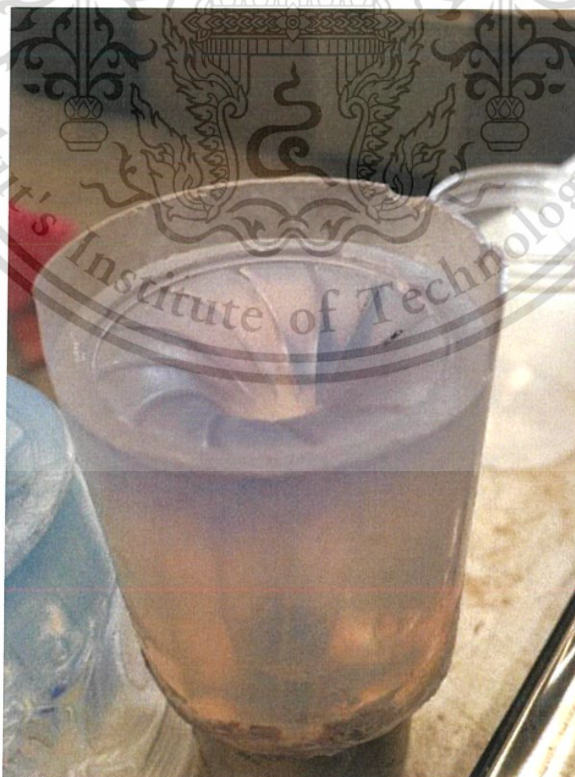


Figure 0.21 Silicone mold for casting a wax pattern of turbocharger wheel

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3.3.2 Wax Pattern Making

Wax pattern of turbocharger wheel was produced using gravitational casting method. The silicone mold, as shown in **Figure 0.21**, was firstly preheated in an oven at 80 - 100°C for at least 30 minutes prior to place 10 g. of wax beads into the mold. The infiltration of wax into the mold cavity occurred soon after the wax beads melted as shown in **Figure 0.22**. The mold whose cavity was completely filled with molten wax was subsequently removed from the oven and was allowed to cool to room temperature by rapid quench in water. Wax pattern of turbocharger wheel was then de-molded from the mold resulting in a wax pattern which completely reproduced its master model, as shown for example in **Figure 0.23**. Several wax patterns were produced and were then assembled to make wax pattern trees having different individual wax pattern placement to give different filling characteristic of molten metal.

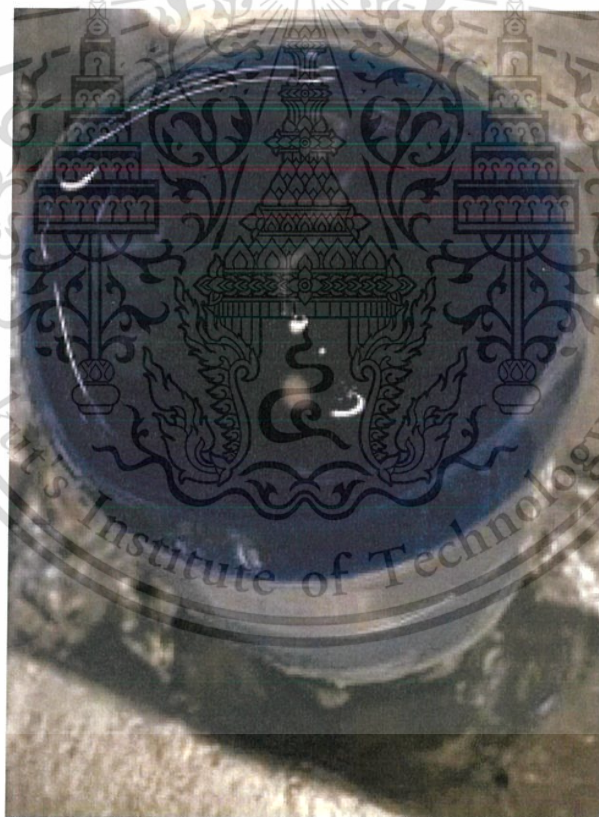


Figure 0.22 Infiltration of molten wax in silicone pattern mold

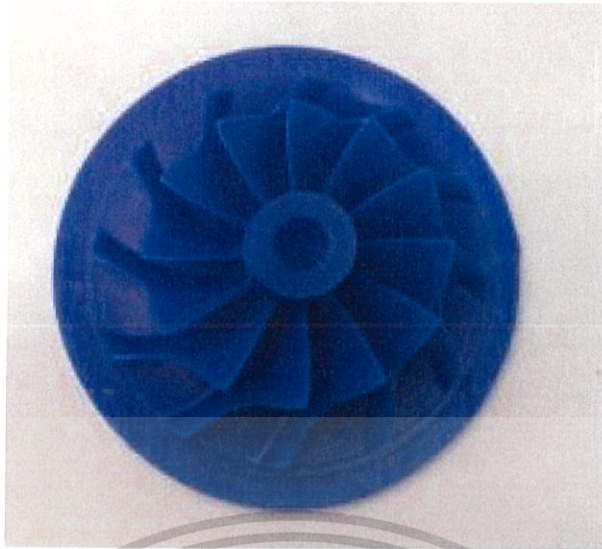


Figure 0.23 Wax pattern

3.3.3 Foamed Plaster Investing

The foamed plaster slurry was prepared using two processing steps: (i) mixing and (ii) bubbling. The mixture was firstly mixed by hand for less than 1 minute prior to mix with a cookery mixer. Once the mixture was throughout mixed, it was foamed using a bubble generator, as illustrated in **Figure 0.1**. In order to prevent metal penetration defect due to porous appearance at mold cavity surface, all wax pattern trees were coated with plaster slurry by dipping into the plaster slurry with powder/water ratio of 100/50, as shown in **Figure 0.24**, resulting in wax pattern trees with thin coat of plaster, as shown for example in **Figure 0.25**. The foamed plaster slurry was then invested into molds each having a wax pattern tree of turbocharger wheels located inside, as shown in **Figure 0.26**. When the foamed plaster slurry set, its structure contained a number of small pores (Mean pore size of $67.9\ \mu\text{m}$ and foamed plaster porosity of 47.7%), as shown for example in **Figure 0.27**, which would be expected to enhance the mold's permeability significantly.

Foamed plaster slurry consists of the mixture of substances whose contents are given below.

- Powder/Liquid = 100/50
- Powder = 97% Plaster + 3% Gypsum
- Liquid = 2/3 Deionized water + 1/3 PVA
- Additives: 0.4% surfactant + 0.25% MgSO_4

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Figure 0.24 A wax pattern tree during coating with plaster slurry

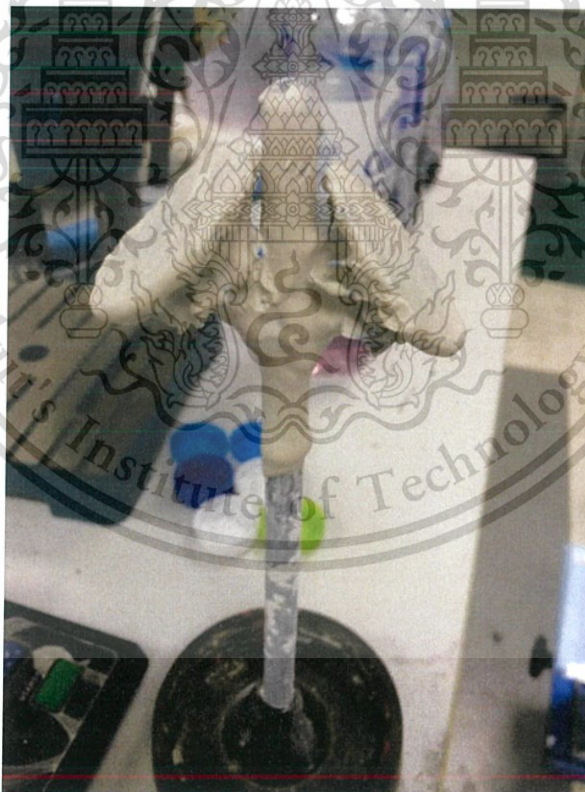


Figure 0.25 A wax pattern tree after coating with plaster slurry

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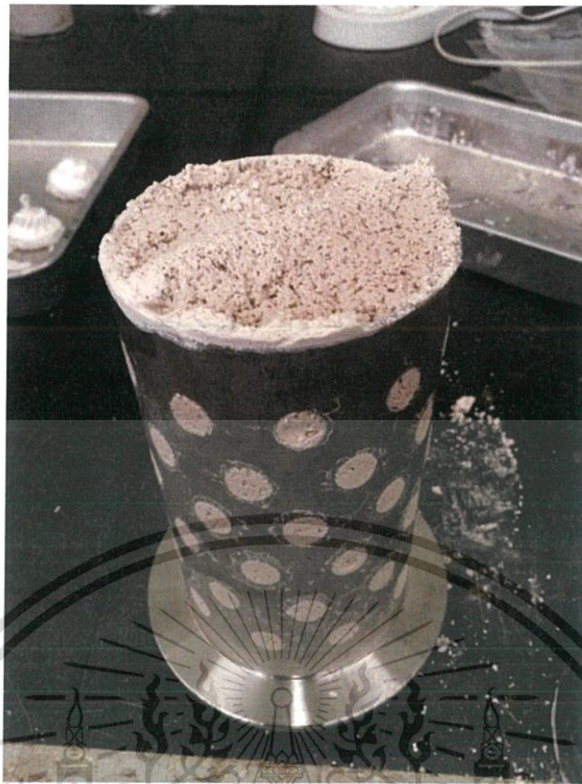


Figure 0.26 A wax pattern tree after investing with foamed plaster



Figure 0.27 Foamed plaster structure

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3.3.4 Wax Burn-out

Wax patterns which were surrounded with foamed plaster were removed by melting out (Burn-out) at the maximum temperature of 730°C using a wax burn-out furnace, as shown in **Figure 0.28**, to leave molds each with a channel for entry of molten metal, as shown in **Figure 0.29**.



Figure 0.28 A wax burn-out furnace

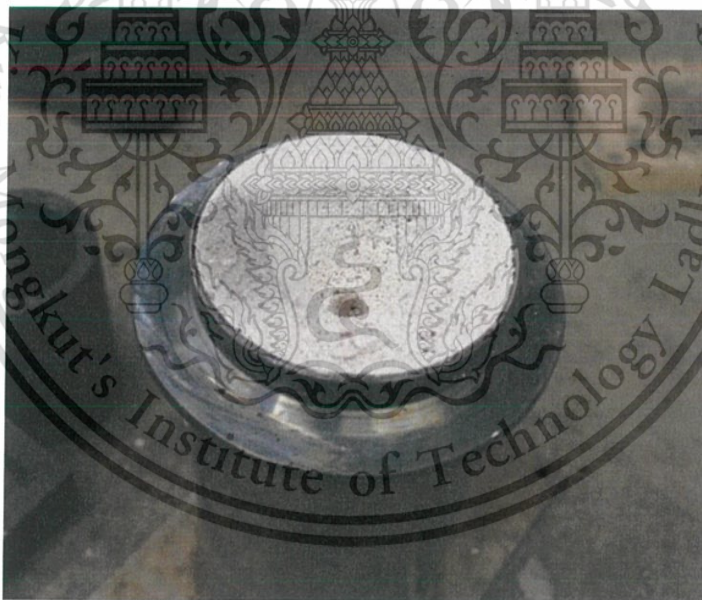


Figure 0.29 A foamed plaster mold after wax burn-out

3.3.5 Metal Casting

Molten AC2A aluminium alloy, whose chemical composition is given in **Table 0.5**, was poured at the temperature of 800°C into molds preheated at the temperature of 500°C, as shown in **Figure 0.30** with the assistance of vacuum pressure of about -99 kPa. After solidification of molten metal, castings were taken out from the molds.

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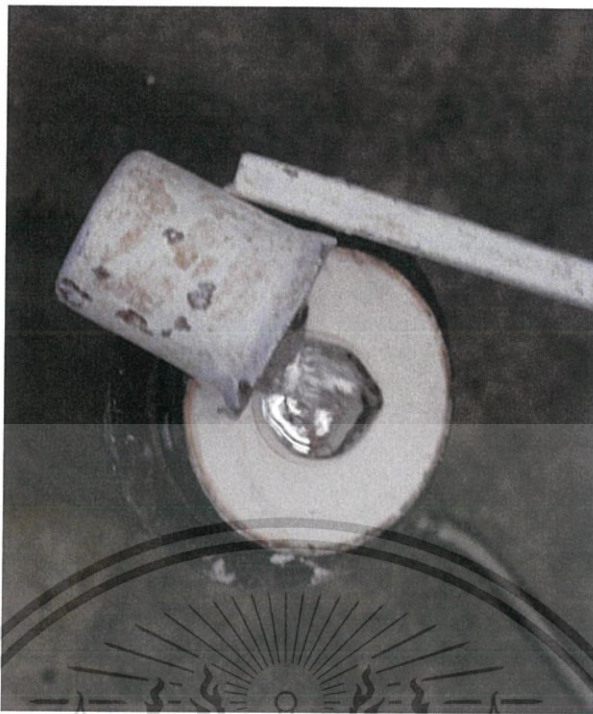


Figure 0.30 A foamed plaster mold during casting of molten aluminium alloy

Table 0.5 Chemical composition of AC2A (A319) aluminium alloy used for producing turbocharger wheel prototypes in this work.

Element	Si	Cu	Mg	Fe	Mn	Zn	Ti	Al
% wt	4.67	4.13	0.22	0.18	0.02	0.01	0.01	Balance

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Development of Mixture and Production Method of Foamed Plaster

4.1.1 Bubble Generator

This research started with further development of a bubble generator developed by National Metal and Materials Technology Center (MTEC) to be used to produce small bubbles in plaster slurry. Initial trial experiments showed that when using a conventional stirrer for mixing plaster together with the bubble generator, as shown in **Figure 0.1**, causes more bubbles than using only the bubble generator, as shown in **Figure 0.2**, depending on the time and the water ratio. The amount of surfactant also influences the amount of bubble and the density of plaster after setting. Therefore, the bubble generator together with the conventional stirrer can be used to produce plaster with foam-like structure.



Figure 0.1 (a) A conventional stirrer and (b) the bubble generator during mixing a foamed plaster slurry

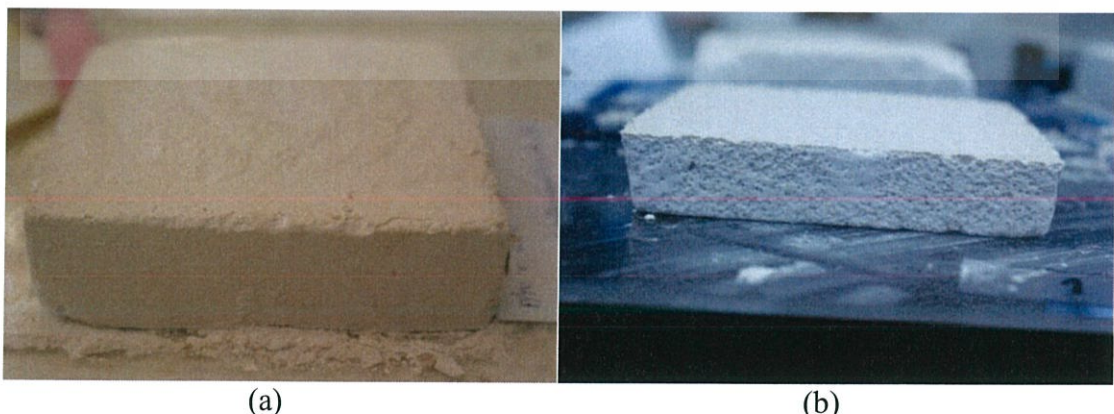


Figure 0.2 Foamed plaster produced (a) without and (b) with a conventional stirrer prior to foaming with the bubble generator

4.1.2 Plaster Composition Development

By adding the plaster slurry with different additives, it was found that the obtained plasters had different density, as shown in **Table 0.1**. The plaster with propylene glycol + MgSO₄ had the lowest density, followed by the plasters with PVA + MgSO₄, carrageenan + MgSO₄, sodium alginate, xanthan gum and carrageenan, respectively. In terms of structure, only the plasters with propylene glycol + MgSO₄ and PVA + MgSO₄ had homogenous structure with small pore size.

Table 0.1 Density of plaster with 66.7% Plaster + 33.3% Liquid (33.3% Additives + 66.7% DI water) + 0.4% Surfactant

Additives	Density of foamed plaster (g/cm ³)
¹ Carrageenan	0.74
¹ Carrageenan + MgSO ₄	0.57
¹ Xanthan Gum	0.65
¹ Sodium Alginate	0.61
¹ Propylene Glycol + MgSO ₄	0.29
¹ PVA + MgSO ₄	0.55
² PVA + MgSO ₄	0.49

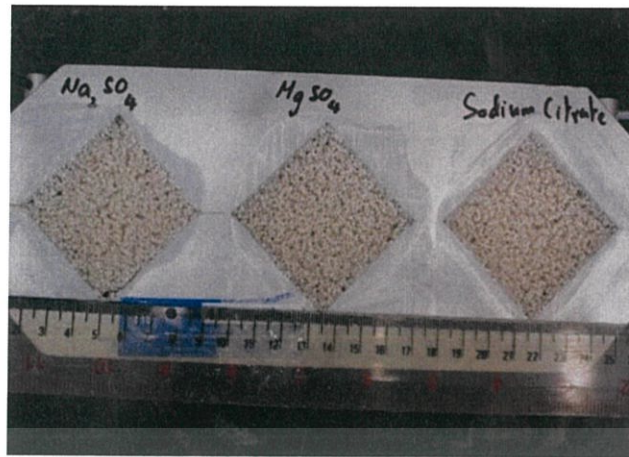
¹ Mixing with a conventional stirrer.

² Mixing with a conventional stirrer and a bubble generator.

Results of foamed plasters having different additives are shown in **Figure 0.3 - Figure 0.5** and are summarised in **Table 0.2**.

Table 0.2 Effect of additives on foamed-like plaster properties

Additives	Advantages	Disadvantage
PVA (1%)	Increase strength Do not collapse	-
Agar (1%)	Increase strength	Plaster collapsed after plaster setting.
CMC (0.2%)	Increase strength	Plaster setting so fast because an obstacle to pouring plaster slurry into the model. Swelling after dry in a furnace at temperature 50°C.
Na ₂ SO ₄ (1%)	Faster setting	Plaster collapsed after plaster setting.
MgSO ₄ (1%)	Faster setting Increase strength	Plaster collapsed after plaster setting.
Sodium Citrate (1%)	Faster setting	Plaster collapsed after plaster setting.
Sodium Alginate (0.27%)	Increase strength	Plaster collapsed after plaster setting.
Sodium Silicate (1%)	Increase strength	Plaster collapsed after plaster setting.
Xanthan Gum (0.48%)	Increase strength	Plaster collapsed after plaster setting.
Alkanol (0.06%)	Increase strength	Plaster collapsed after plaster setting.
H ₃ PO ₄	-	The specimen is expanded and cracks after plaster slurry setting.
Carrageenan	Increase strength Do not collapse	The mixture is very viscous and hardens slowly.
Gypsum	Increase strength	-



(a)



(b)

Figure 0.3 Plaster with Na_2SO_4 , MgSO_4 and Sodium citrate in a 50 x 50 x 50 mm mold that was produced by a conventional stirrer: (a) after suddenly pouring plaster slurry into the mold and (b) after leaving the plaster slurry setting

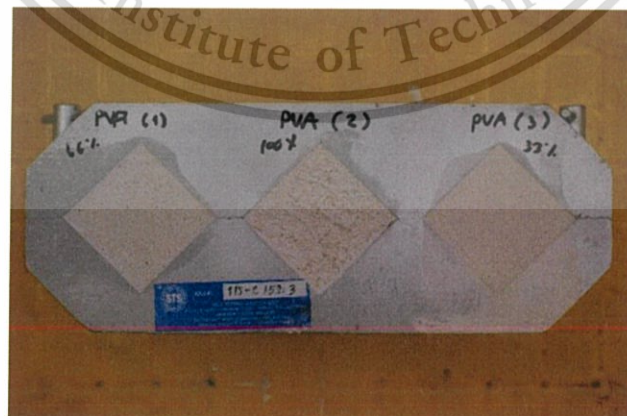
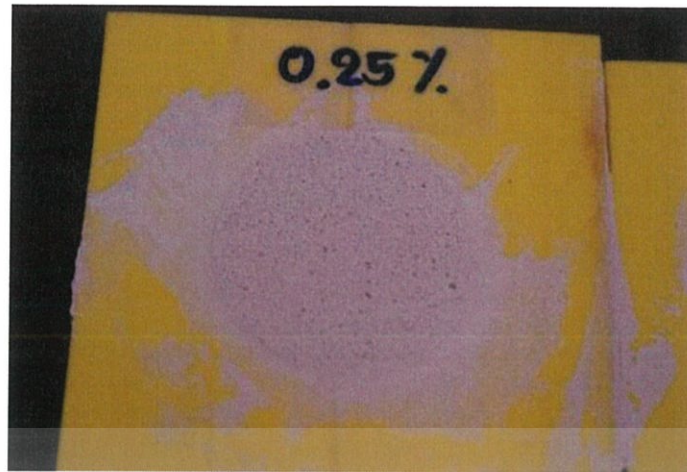
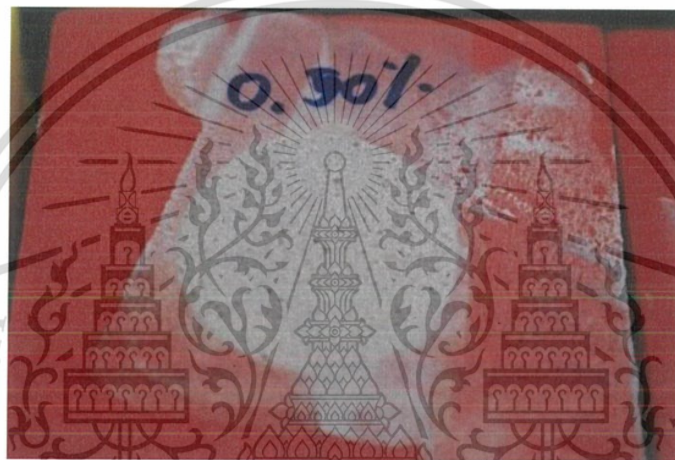


Figure 0.4 Plaster with the various quantity of PVA by 66.7% plaster powder + 33.3% liquid (33.3% PVA + 66.7% DI water (right), 66.7% PVA + 33.3% DI water (left) and 100% PVA (middle)) + 0.4% surfactant that was produced by a conventional stirrer.

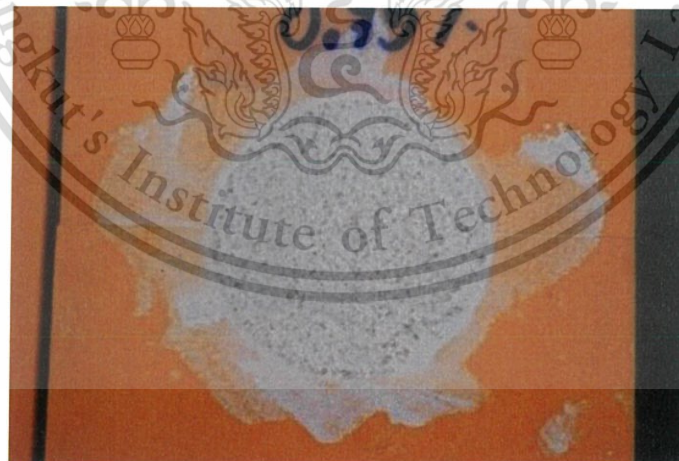
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(a)



(b)



(c)

Figure 0.5 Plaster with the various quantity of surfactant by 66.7% plaster powder + 33.3% liquid (33.3% PVA + 66.7% DI water) + 0.4% surfactant $MgSO_4$: (a) 0.25%, (b) 0.50% and (c) 0.75% that was produced by a conventional stirrer.

Table 0.3 Compressive strength of plaster specimens of 66.7% Plaster + 33.3% Liquid (Liquid = 66.7% PVA + 33.3% DI water) + 0.4% Surfactant + 0.25% MgSO₄

Production method	Avg. compressive strength (MPa)	
	As cast	Heat treated
A conventional stirrer	0.58	0.05
A conventional stirrer together with a bubble generator	0.34	0.04

Plasters made with a conventional stirrer together with a bubble generator had lower average compressive strength than plasters produced with only the conventional stirrers, as shown in **Table 0.3**. The strength of all plasters was relatively low especially the plasters which were heat treated. Plaster slurry made by the conventional stirrer together with the bubble generator resulted in plaster having higher gas permeability than that produced with only the conventional stirrer as shown in **Figure 0.6** and **Table 0.4**.

In summary, the plasters with PVA, gypsum and MgSO₄ additions showed the best characteristics of high strength, homogenous structure and good flow ability slurry. Additives of these plasters were also available in the market with reasonable prices.

The best composition of foamed plaster is given below.

Plaster : Water
 100 : 50
 (97%Plaster + 3%Gypsum) : (67%DI + 33%PVA)
 0.4% Sodium lauryl sulfate (overall weight) + 0.25% MgSO₄ (overall weight)

From this work, the foamed plaster is suggested to produce using the conventional stirrer together with the bubble generator to make small bubbles in slurry.

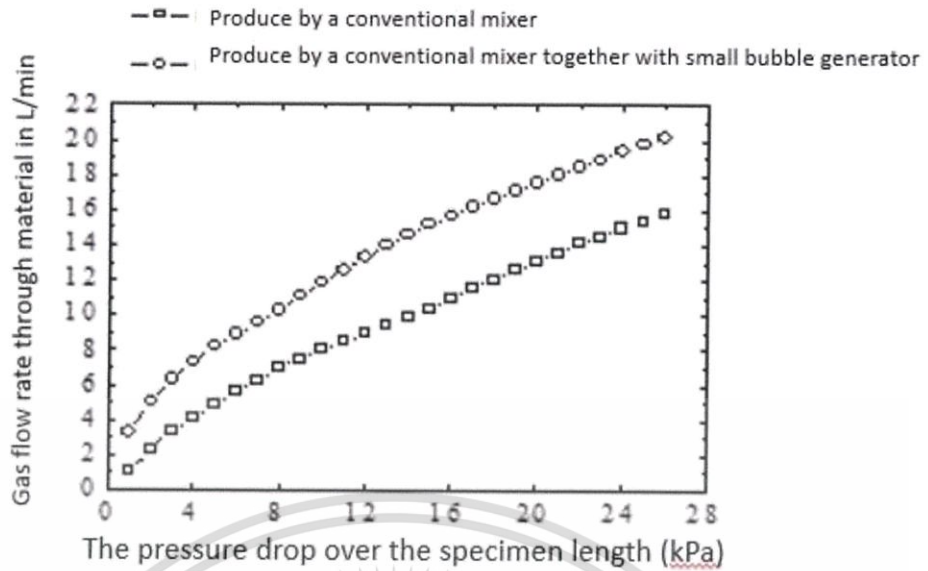


Figure 0.6 Gas permeability of plaster specimens (as-cast) with 66.7% Plaster + 33.3% Liquid + 0.4% Surfactant + 0.25% MgSO₄ mixed with a conventional stirrer (Liquid = 66.7% PVA + 33.3% DI water) and with a conventional stirrer together with a bubble generator (Liquid = 33.3% PVA + 66.7% DI water)

Table 0.4 Coefficient of gas permeability through plaster specimens of 66.7% Plaster + 33.3% Liquid + 0.4% Surfactant + 0.25% MgSO₄

	As-cast	Heat treated
A conventional stirrer (Liquid = 66.7% PVA + 33.3% DI water)	$8.13 \times 10^{-13} \text{ m}^2$	$6.88 \times 10^{-13} \text{ m}^2$
A conventional stirrer together with a bubble generator (Liquid = 33.3% PVA + 66.7% DI water)	$8.95 \times 10^{-13} \text{ m}^2$	$1.08 \times 10^{-12} \text{ m}^2$

4.2 Influence of Water Temperature and Mixing Time of Plaster Slurry on Foamed Plaster's Properties

Results of water temperature and mixing time of plaster slurry on setting expansion (See **Appendix A**), reaction temperature (at peak), reaction time (at peak), as-cast density, heat treated density (See **Appendix B**), as-cast compressive strength (See **Appendix B**), heat treated compressive strength and permeability of foamed plasters are summarised in **Table 0.5 - Table 0.7** and **Figure 0.7**. It can be seen from these tables that water temperature and mixing time of plaster slurry, to some extent, had an effect on foamed plaster's properties. The effect of these parameters on foamed plaster's properties can be generalised as shown in **Figure 0.8 - Figure 0.11**.

Reaction time (at peak) decreases with increasing mixing time of bubble generator when water temperatures are 20 and 40°C, except for the water temperature of 28°C at which the reaction time changes from decrease to increase at the middle period of mixing time in the ranges 1 – 5 min. The minimum reaction time takes place at the mixing time of 3 min. The prolonged mixing time is favorable when water temperatures of 20 and 40°C are used to be beneficial to enhance uniformity of the plaster as a result of shorter reaction time.

Reaction temperature (at peak) trends to slightly increase with increasing mixing time of bubble generator for all water temperatures. Higher reaction temperatures may be attributable to the uniformity of structure which results in simultaneously exothermic reaction throughout the plaster.

The setting expansion seems to be well below its maximum when the mixing time of 3 min is used. At this mixing time, the permeability is also maximum suggesting that the plaster structure would become less close and hence resulting in less resistance to the passage of gases. Further increasing mixing time, not only decreases the permeability but also increases density and compressive strength for both as-cast and heat treated conditions. Higher water temperature is also recommended to enhance permeability of the foamed plaster. The high water temperatures may cause coarser plaster crystal structure resulting less resistance to the passage of gases.

Increasing mixing time with reasonable low water temperatures seems to enhance strength but deteriorate the permeability of the foamed plaster. Small plaster crystal structure would be attributed to the strength enhancement and the permeability reduction.

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Table 0.5 Setting expansion, reaction temperature (at peak) and reaction time (at peak) of the foamed plasters produced by the conditions shown in **Table 0.1**

Conditions of water temperature and mixing time	$\Delta l_{@ 24hr}$ (%)	t_{set} (min)	$T_{react @ peak}$ (°C)	$t_{react @ peak}$ (min)
20-M1-F5	0.009	-	36.51	15.65
20-M3-F3	0.014	-	33.71	19.02
20-M5-F1	0.002	-	31.33	26.45
28-M1-F5	0.019	-	36.53	15.4
28-M3-F3	0.013	-	34.97	8.87
28-M5-F1	0.016	-	34.53	18.63
40-M1-F5	0.008	-	38.68	13.1
40-M3-F3	0.007	-	35.04	16.15
40-M5-F1	0.013	-	37	17.02

The denoted symbol of conditions represents for water temperature (°C)-mixing time of the conventional stirrer (min)-mixing time of the bubble generator (min).

Table 0.6 As-cast and heat treated density and compressive strength of the foamed plasters with dimensions of 50 x 50 x 50 mm produced by the conditions shown in **Table 0.1**

Conditions of water temperature and mixing time	$\rho_{@ Ascast}$ (g/cm ³)	$\rho_{@ 730^\circ C}$ (g/cm ³)	$\sigma_{@ Ascast}$ (MPa)	$\sigma_{@ 730^\circ C}$ (MPa)
20-M1-F5	0.6(0.04)	0.56(0.03)	0.7(0.19)	0.04(0.01)
20-M3-F3	0.47(0.02)	0.46(0.02)	0.4(0.02)	0.02(0.01)
20-M5-F1	0.44(0.01)	0.41(0.01)	0.45(0.05)	0.02(0.01)
28-M1-F5	0.64(0.03)	0.59(0.03)	0.82(0.16)	0.07(0.01)
28-M3-F3	0.45(0.04)	0.42(0.04)	0.35(0.04)	0.02(0.01)
28-M5-F1	0.47(0.03)	0.44(0.03)	0.31(0.12)	0.03(0.01)
40-M1-F5	0.7(0.03)	0.65(0.02)	0.33(0.09)	0.03(0.01)
40-M3-F3	0.49(0.02)	0.45(0.01)	0.29(0.09)	0.02(0.00)
40-M5-F1	0.47(0.02)	0.44(0.02)	0.34(0.07)	0.02(0.00)

The denoted symbol of conditions represents for water temperature (°C)-mixing time of the conventional stirrer (min)-mixing time of the bubble generator (min).

Table 0.7 Gas permeability of the foamed plasters with dimensions of 50 mm in diameter and 10 mm in height produced by the conditions shown in **Table 0.1**

Conditions of water temperature and mixing time	As cast				
	Darcy's law		Forchheimen's eq.		P
	k_p (m ²)	R^2	k_p (m ²)	R^2	
20-M1-F5	2.72E-12	98	3.13E-12	99.8	9.85
20-M3-F3	3.53E-12	95.3	4.60E-12	99.8	11.86
20-M5-F1	3.69E-12	94.9	5.16E-12	99.8	11.64
28-M1-F5	2.72E-12	98.2	2.69E-12	99.8	8.55
28-M3-F3	4.03E-12	94	5.95E-12	99.9	12.64
28-M5-F1	3.20E-12	95.3	5.05E-12	99.9	10.02
40-M1-F5	8.09E-13	99.9	8.05E-13	99.8	2.59
40-M3-F3	4.18E-12	95.9	5.76E-13	99.3	13.11
40-M5-F1	3.72E-12	95.7	6.03E-12	99.9	13.04
Conditions of water temperature and mixing time	Heat treated				
	Darcy's law		Forchheimen's eq.		P
	k_p (m ²)	R^2	k_p (m ²)	R^2	
20-M1-F5	3.18E-12	99.1	4.42E-12	99.7	10.05
20-M3-F3	3.88E-12	96.9	6.43E-12	99.8	12.7
20-M5-F1	5.30E-12	95.7	2.28E-11	95.7	15.12
28-M1-F5	-	-	-	-	-
28-M3-F3	5.17E-12	96.9	2.45E-11	99.9	17.7
28-M5-F1	4.11E-12	95.9	3.62E-12	99.5	12
40-M1-F5	1.41E-12	99.8	1.88E-12	99.7	4.25
40-M3-F3	4.42E-12	96.6	4.39E-12	99.5	12.27
40-M5-F1	4.94E-12	97.1	1.18E-11	99.8	14.56

The denoted symbol of conditions represents for water temperature (°C)-mixing time of the conventional stirrer (min)-mixing time of the bubble generator (min).

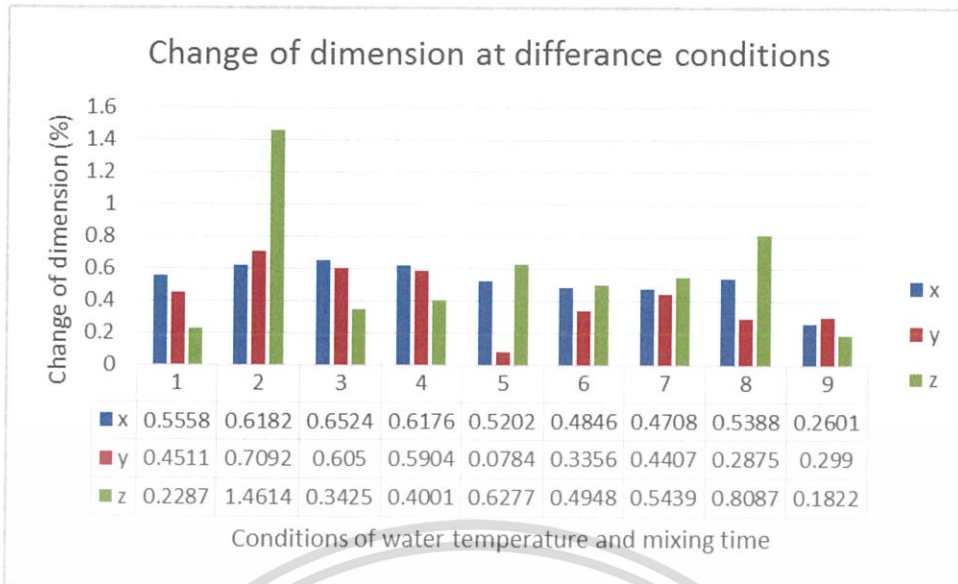
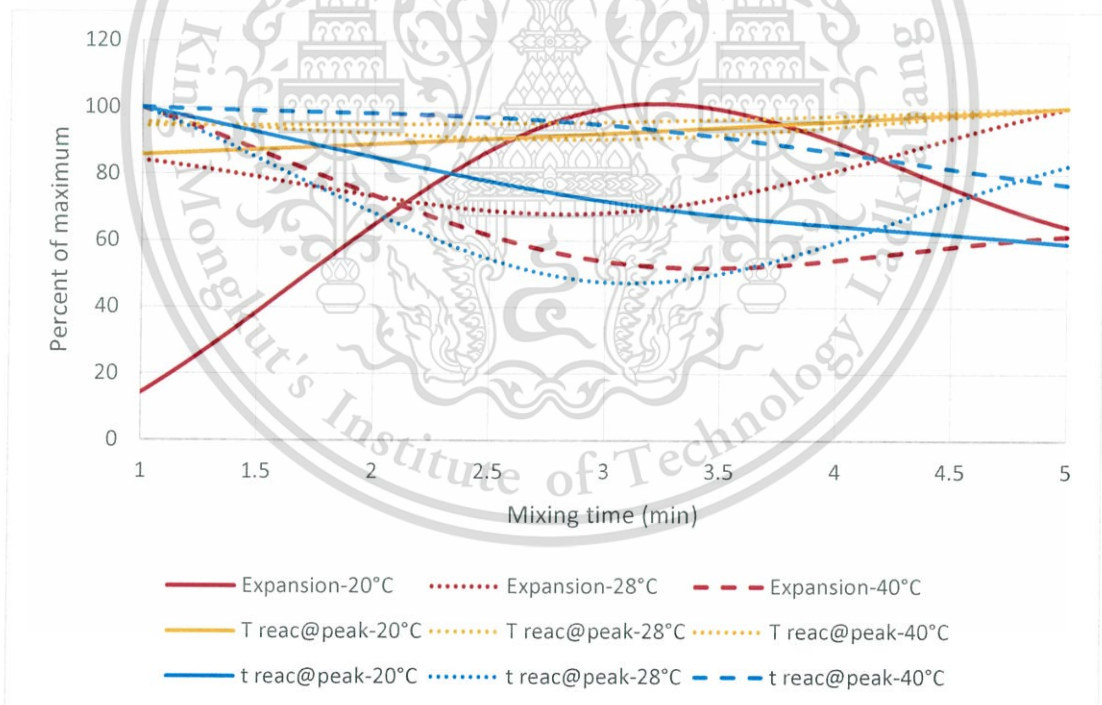
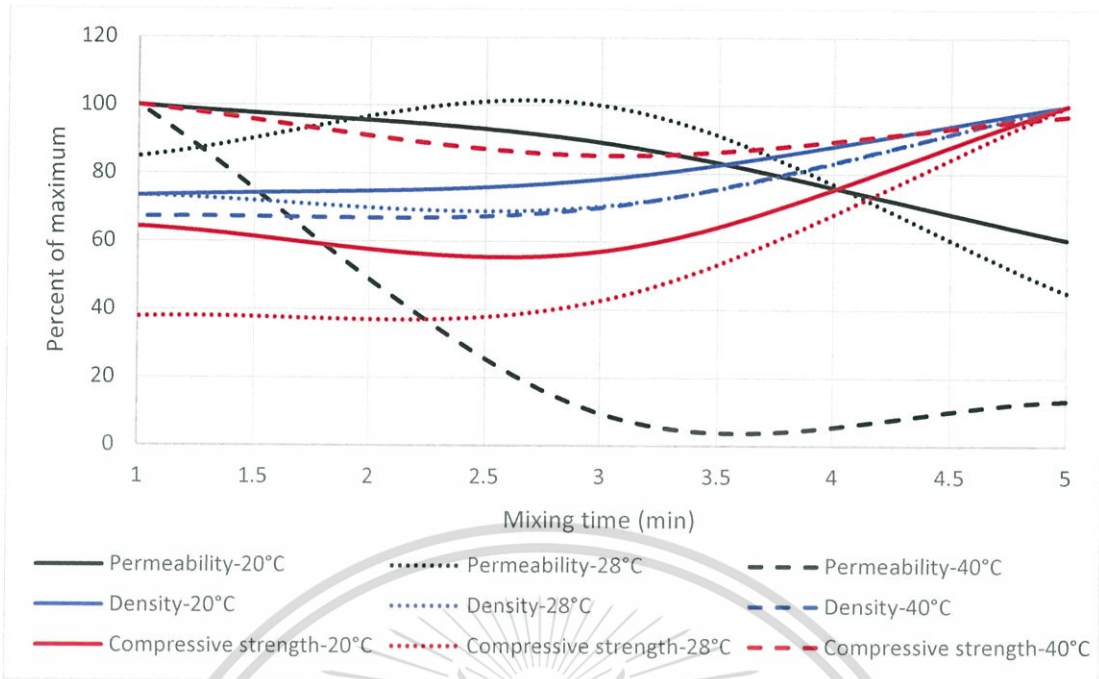


Figure 0.7 Dimension change in x, y and z directions of 50 mm x 50 mm x 50 mm foamed plaster specimens produced with different conditions: 1=20-M1-F5, 2=20-M3-F3, 3=20-M5-F1, 4=28-M1-F5, 5=28-M3-F3, 6=28-M5-F1, 7=40-M1-F5, 8=40-M3-F3, 9=40-M5-F1



(a)



(b)
Figure 0.8 Effect of mixing time on: (a) setting expansion, reaction temperature (at peak) and reaction time (at peak) and (b) permeability, density and compressive strength of as-cast foamed plasters

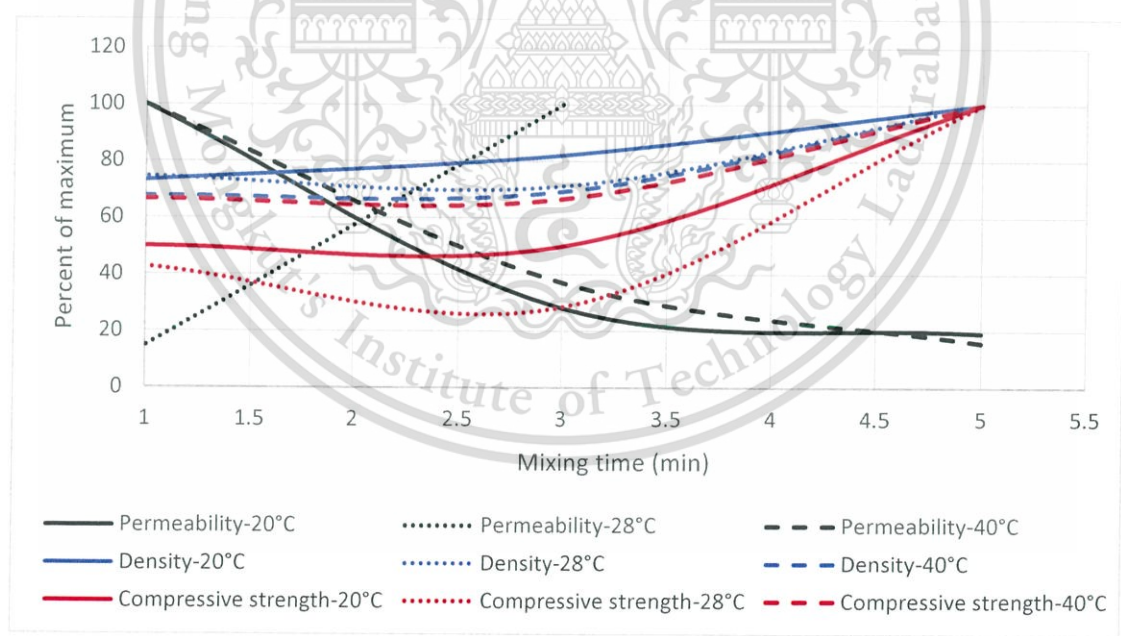
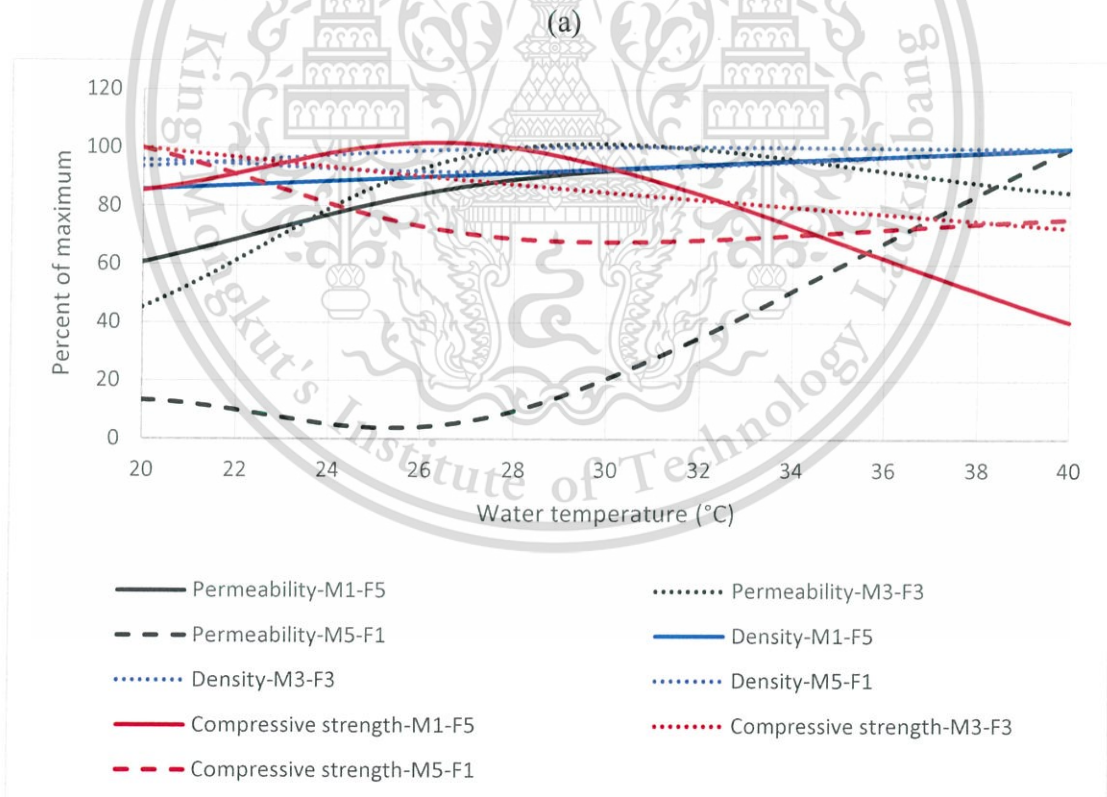
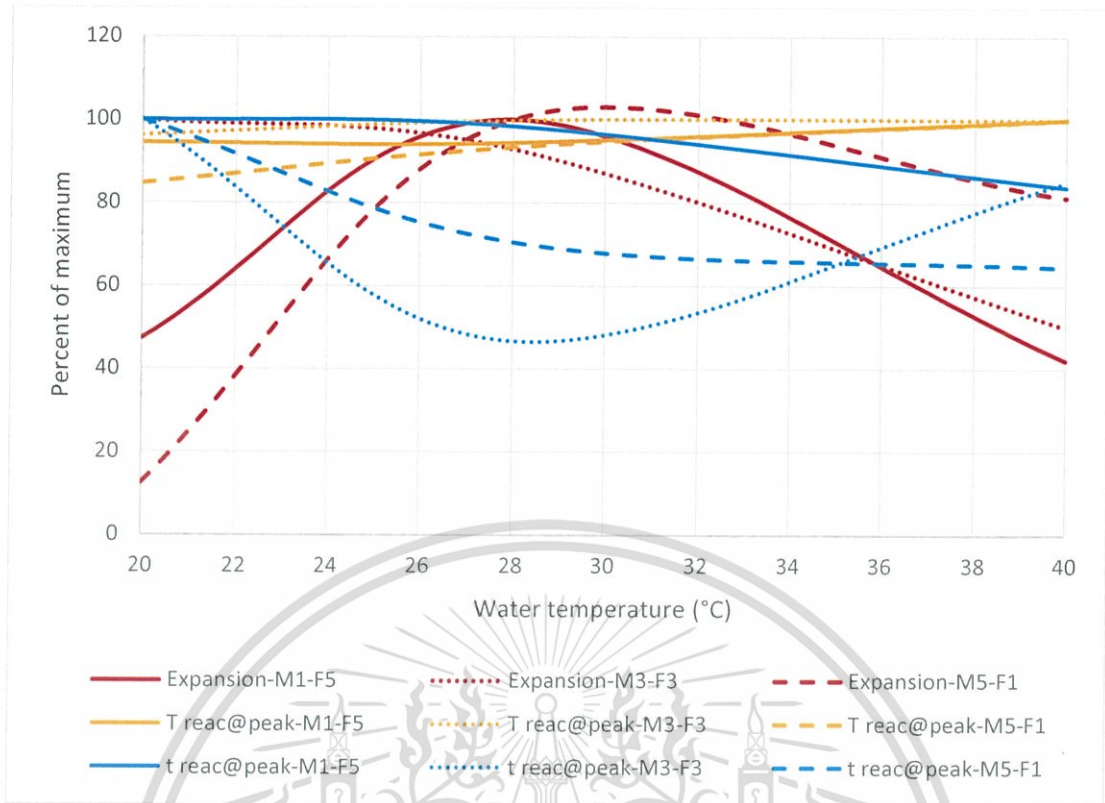


Figure 0.9 Effect of mixing time on permeability, density and compressive strength of heat treated foamed plasters



(b)

Figure 0.10 Effect of water temperature on: (a) setting expansion, reaction temperature (at peak) and reaction time (at peak) and (b) permeability, density and compressive strength of as-cast foamed plasters

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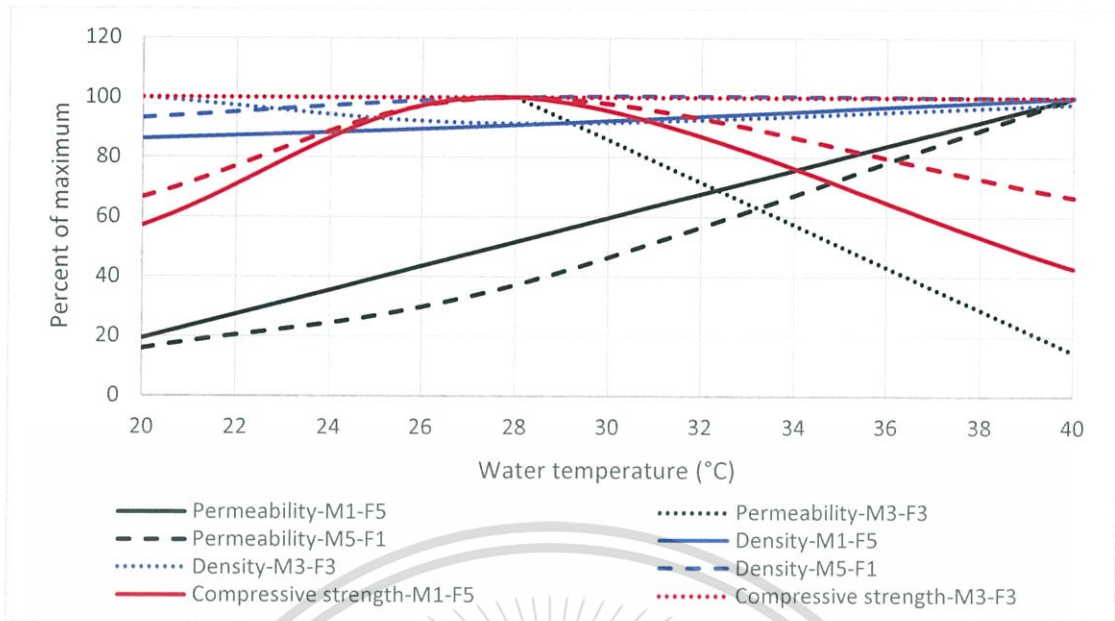


Figure 0.11 Effect of water temperature on permeability, density and compressive strength of heat treated foamed plasters

4.3 Influence of Density on Permeability and Compressive Strength of Foamed Plaster

Permeability and compressive strength are obviously related to the density of foamed plasters as shown in **Figure 0.12** and **Figure 0.13**, respectively. Permeability was found to inversely proportional to the density of foamed plasters, while compressive strength was directly proportional to the density of foamed plasters. Permeability of as-cast foamed plasters was about an order of magnitude smaller than that of heat treated foamed plasters, while compressive strength of as-cast foamed plasters was about an order of magnitude larger than that of heat treated foamed plasters. Permeability seems to be well related to compressive strength irrespective to production conditions as shown in **Figure 0.14**. This suggests that the denser structure is responsible for the higher compressive strength and lower permeability, and vice versa, of the foamed plaster.

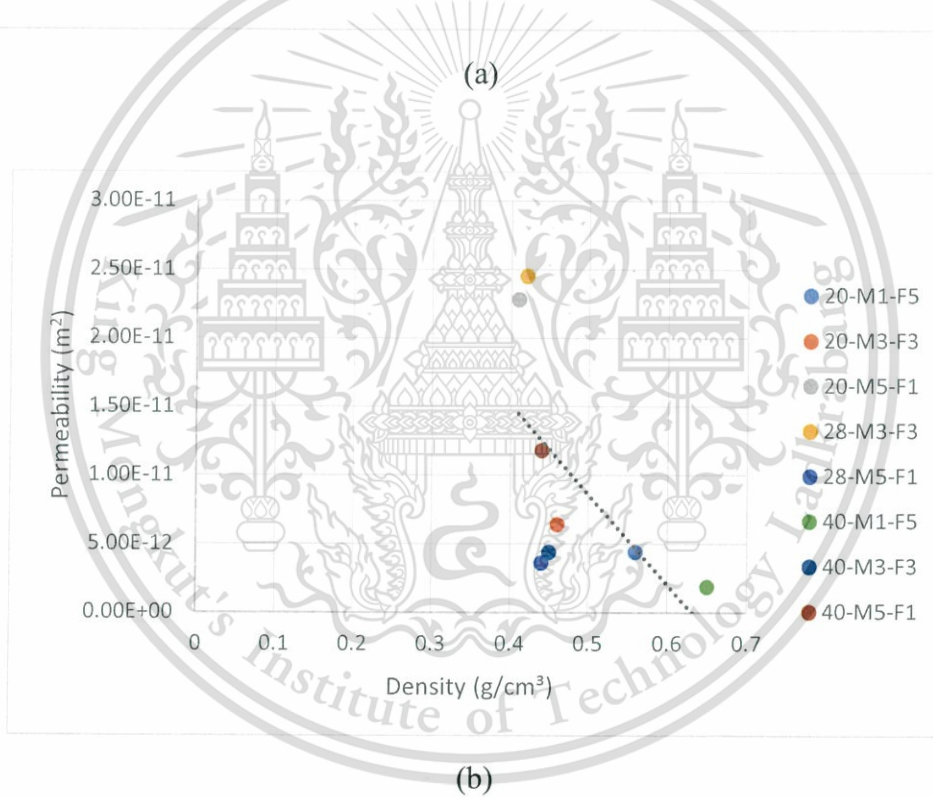
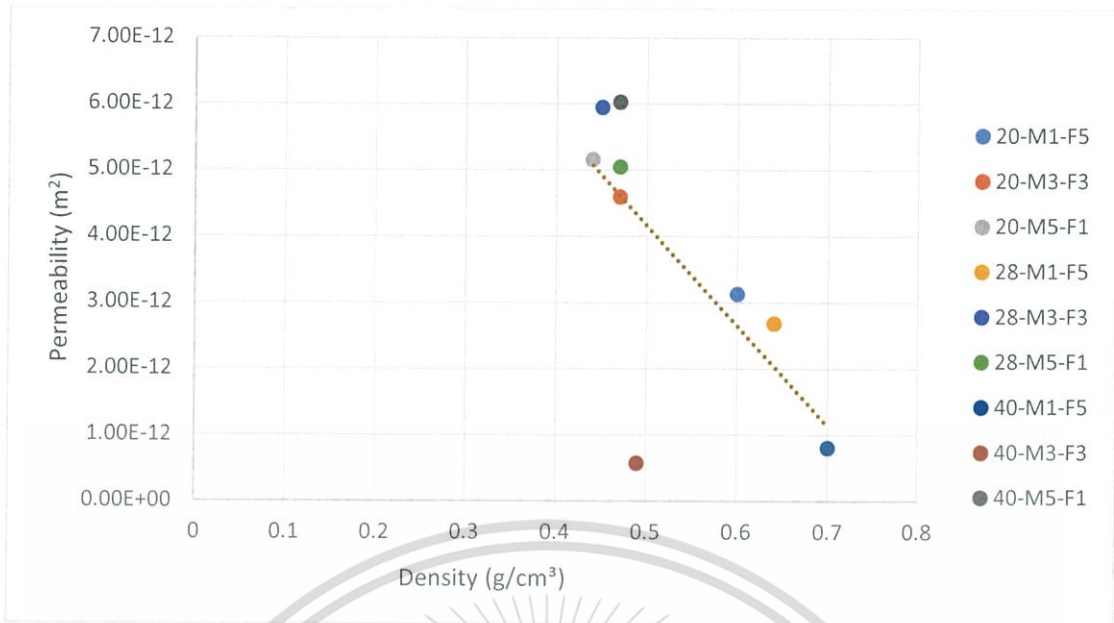
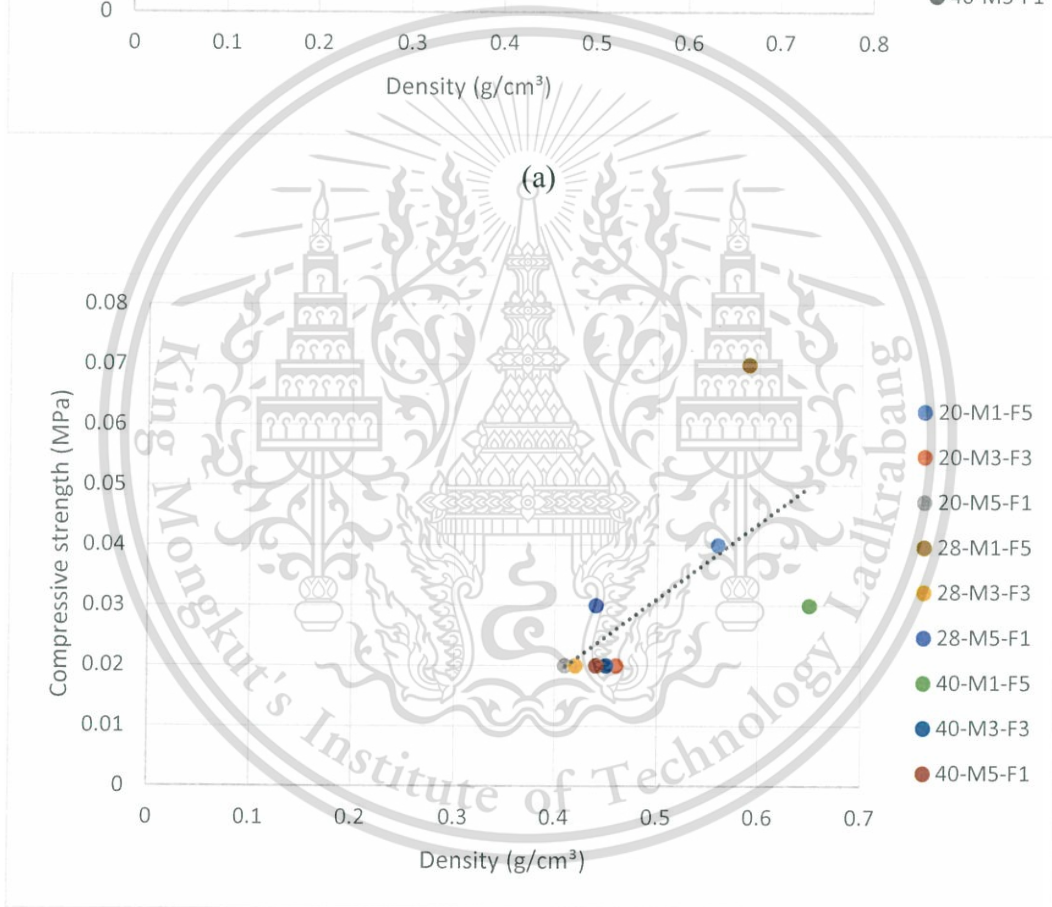
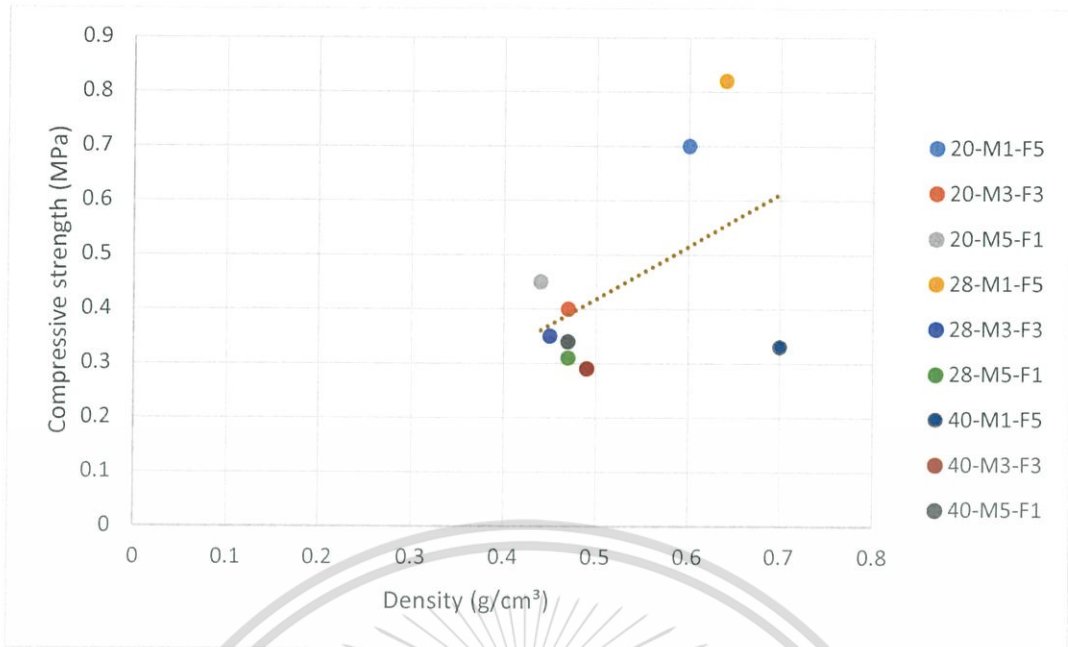


Figure 0.12 Effect of density on permeability of: (a) as-cast and (b) heat-treated foamed plasters



(b)

Figure 0.13 Effect of density on compressive strength of: (a) as-cast and (b) heat-treated foamed plasters

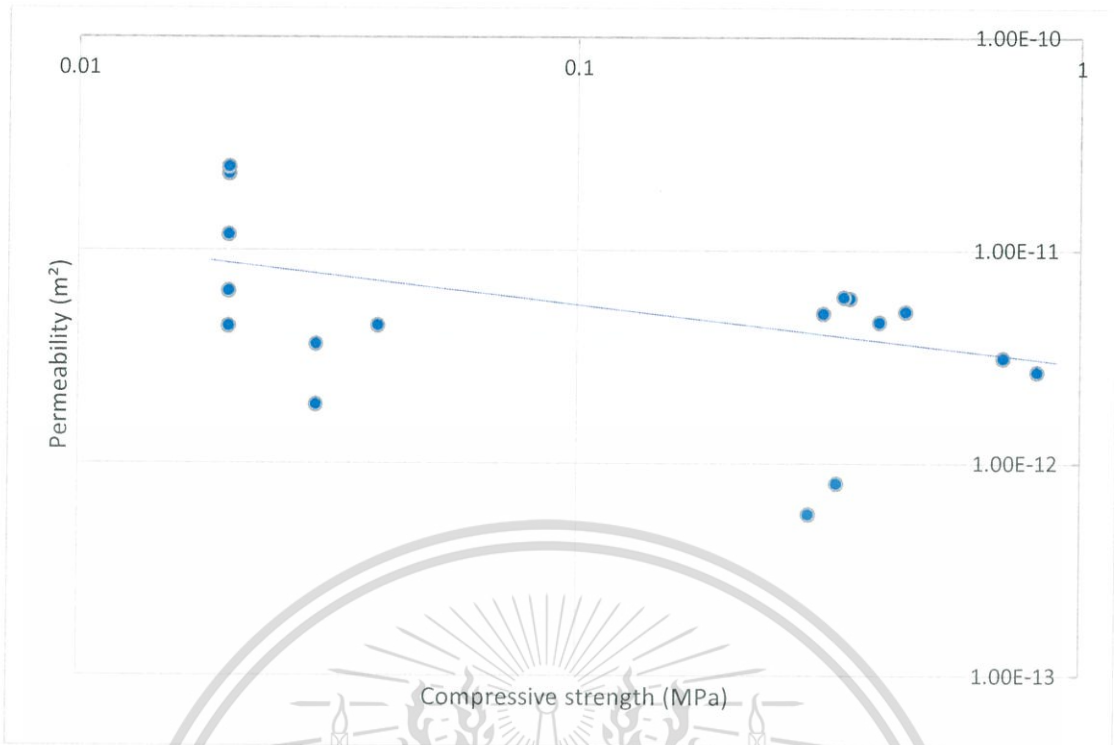
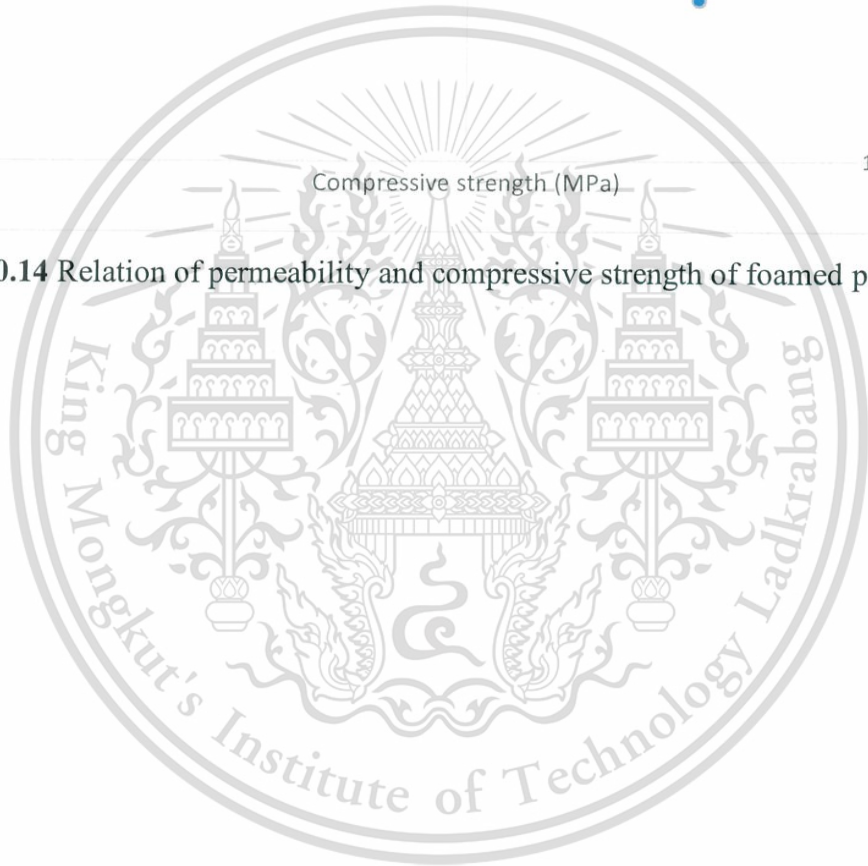


Figure 0.14 Relation of permeability and compressive strength of foamed plasters



4.4 Foamed Plaster Surface Quality

Foamed and conventional plaster produced with and without vibration after slurry casting under various conditions: both after mixing and casting without vacuum (XX), after mixing without vacuum but after casting with vacuum (X/), after mixing with vacuum but after casting without vacuum (/X), and both after mixing and casting with vacuum (//), showed different surface quality as shown in **Figure 0.15 - Figure 0.32**. The best surface quality of the foam-like plaster mold was obtained when plaster slurry was left under vacuum at both after mixing and casting without vibration. Physical properties of these plasters are summarised in **Table 0.8**. The change of physical properties of the foamed plaster comparing with those of conventional plasters was illustrated in **Figure 0.33 - Figure 0.37**.

Vibration was found to increase porosity and plaster density, but decrease pore size.

Vacuum after mixing was found to increase porosity and pore size, but decrease plaster density.

Vacuum after casting was found to increase porosity but decrease plaster density.

Vibration and vacuum after casting gave some influence on bubbles which appeared at corners of workpieces. It was found that the use of vibration caused the size of the bubbles smaller. Vacuum after mixing, on the other hand, resulted in larger bubbles.

Vacuum after pouring (Vacuum after molding) was found to enlarge the bubbles.

Bubbles at specimen corners were found to decrease with vibration, and decrease with vacuum for after both mixing and casting.

Size of pores trended to decrease with the implementation of vibration, but invariant relation was found for the number of pores. Vibration was only advantageous for surface improvement when no vacuum was performed on plaster slurry for both before and after casting. Two types of pores, which are entrained and entrapped pores, were found.

When considering the quality of plaster surface and its structure, it was found that the use of only vibration may not significantly help to improve the quality of the plaster surface. It has been found that the use of vacuum after casting markedly reduced porosity. The ideal foamed plaster mold should have smooth surface but porous inside structure. The use of vacuum after mixing was found to provide foamed plaster with good surface.

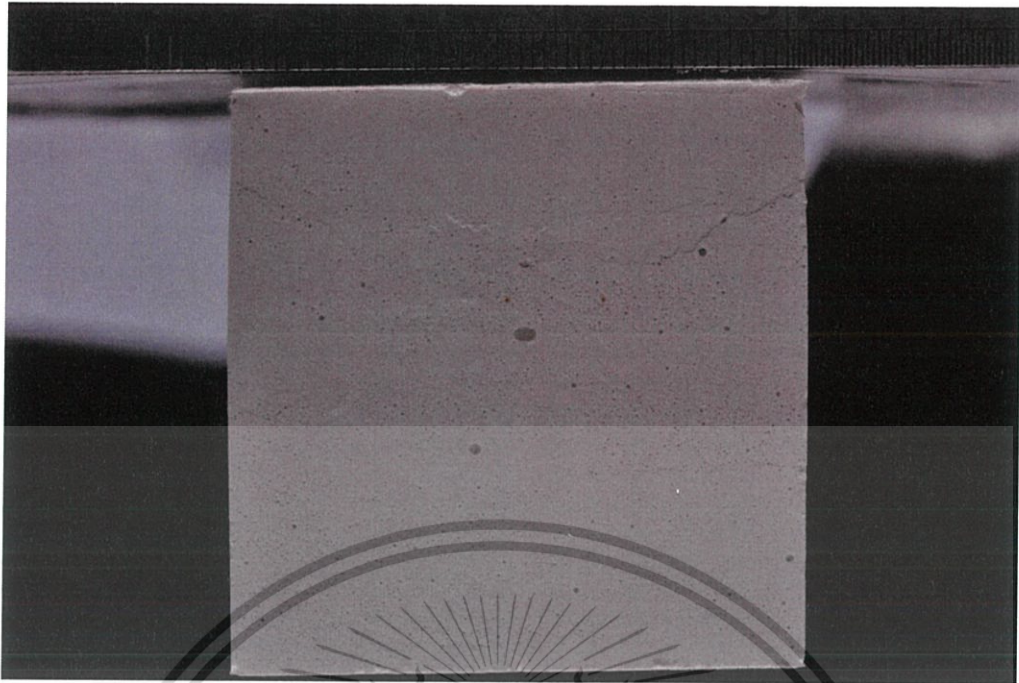


Figure 0.15 Foamed plasters produced using conditions shown in **Table 0.4**: (a) after mixing without vacuum, casting without vacuum and without vibration (XXX)



Figure 0.16 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (a) after mixing, casting without vacuum and without vibration (XXX)

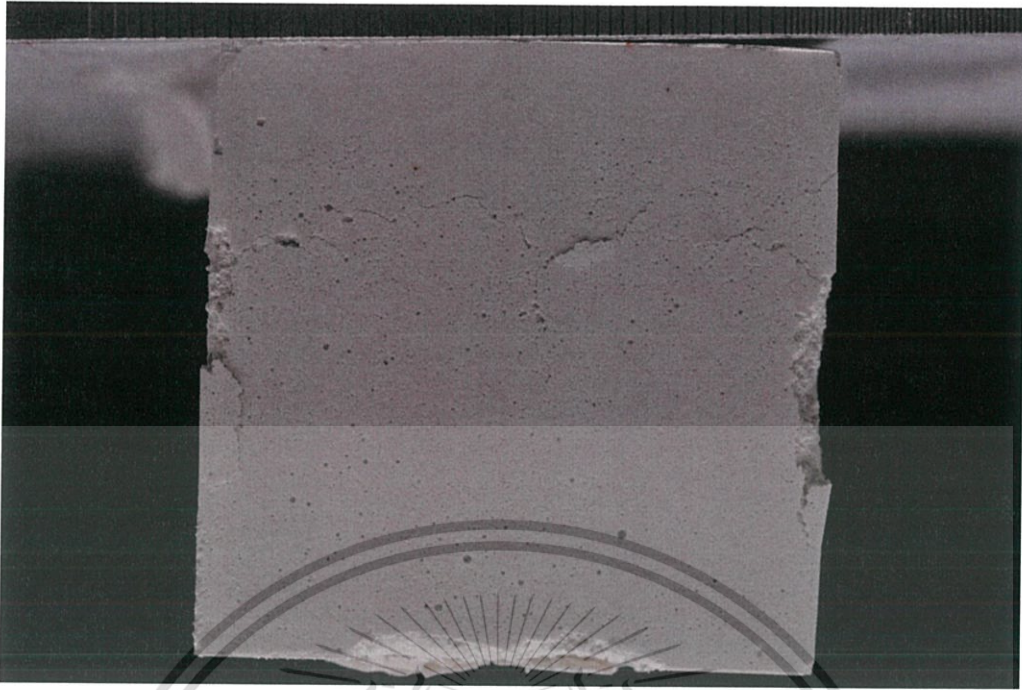


Figure 0.17 Foamed plasters produced using conditions shown in **Table 0.4**: (b) after mixing with vacuum, casting with vacuum and with vibration (///)



Figure 0.18 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (b) after mixing with vacuum, casting with vacuum and vibration (///)

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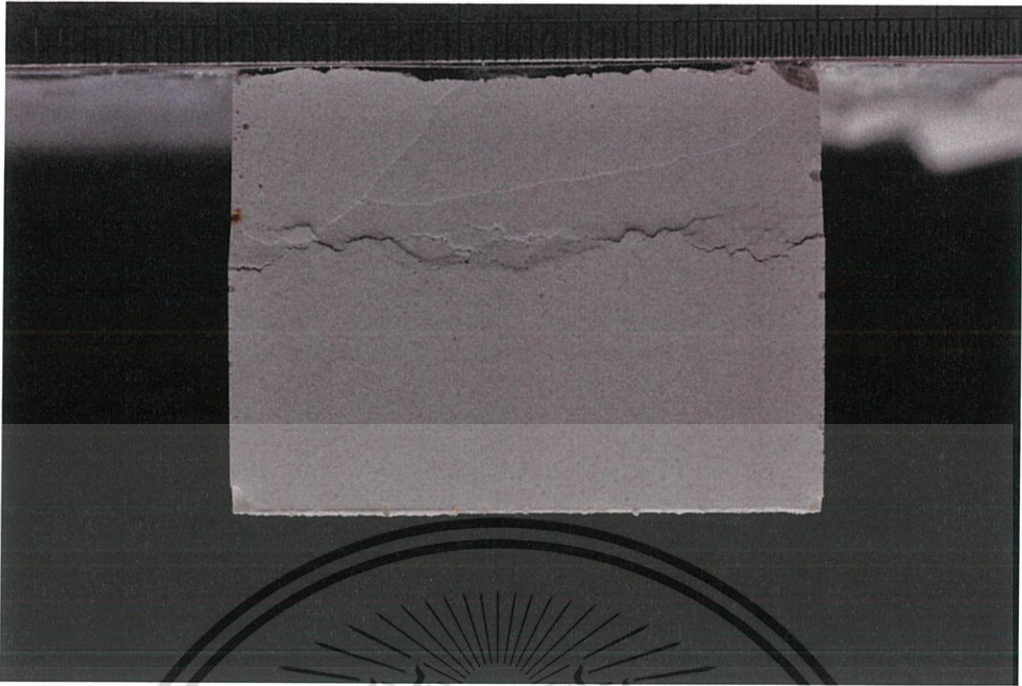


Figure 0.19 Foamed plasters produced using conditions shown in **Table 0.4**: (c) after mixing without vacuum, casting with vacuum and without vibration (X/X)



Figure 0.20 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (c) after mixing without vacuum, casting with vacuum and without vibration (X/X)

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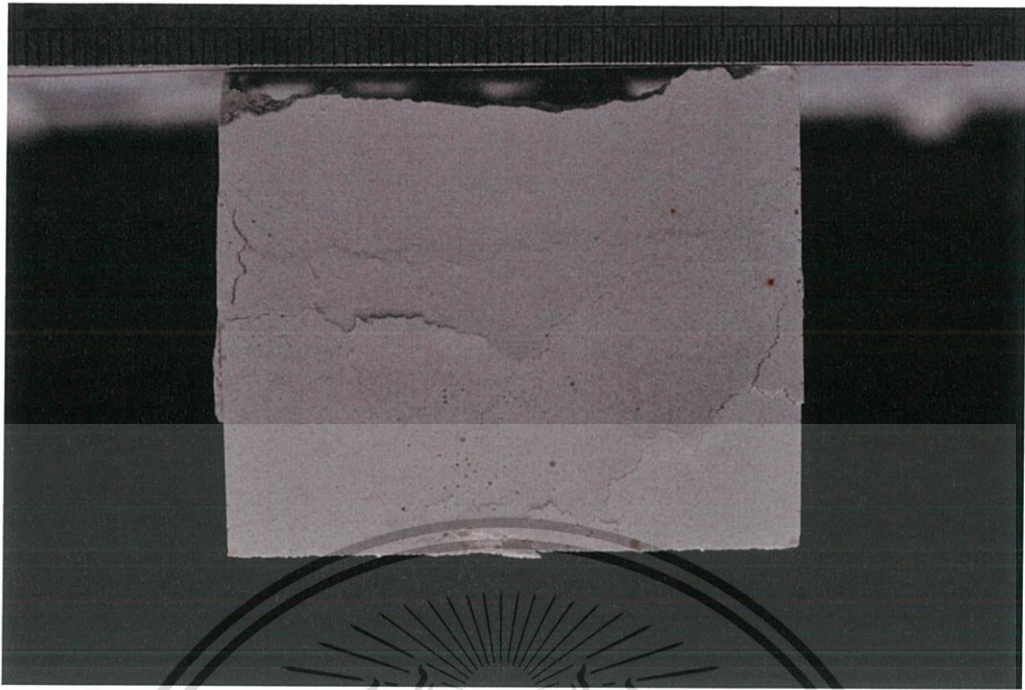


Figure 0.21 Foamed plasters produced using conditions shown in **Table 0.4**: (d) after mixing with vacuum, casting without vacuum and with vibration (/X/)



Figure 0.22 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (d) after mixing with vacuum, casting without vacuum and with vibration (/X/)

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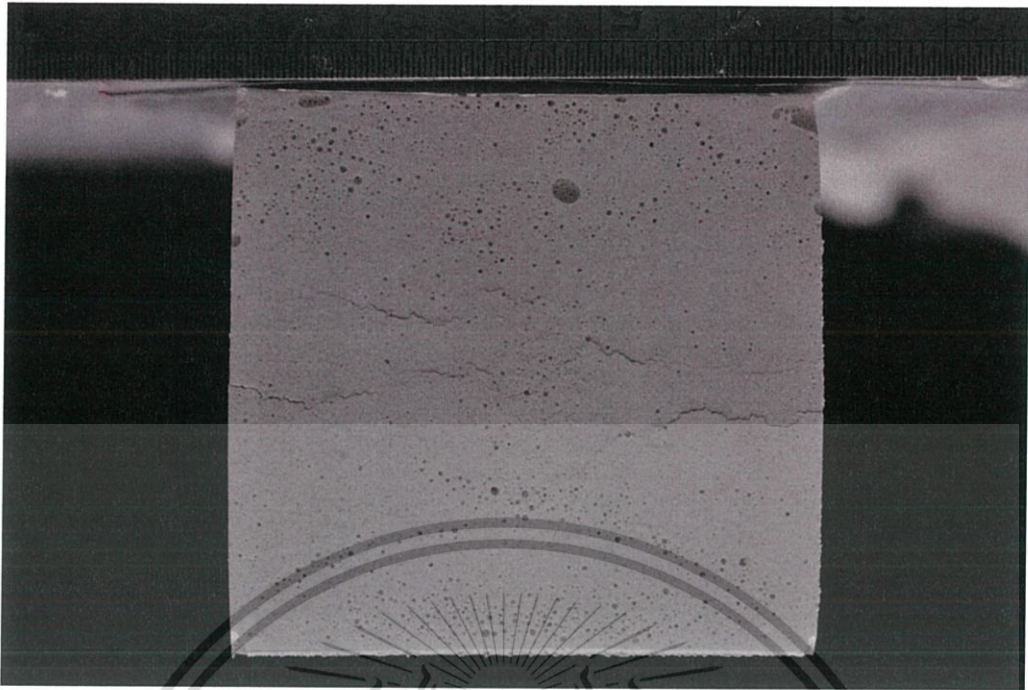


Figure 0.23 Foamed plasters produced using conditions shown in **Table 0.4**: (e) after mixing with vacuum, casting without vacuum and without vibration (/XX)

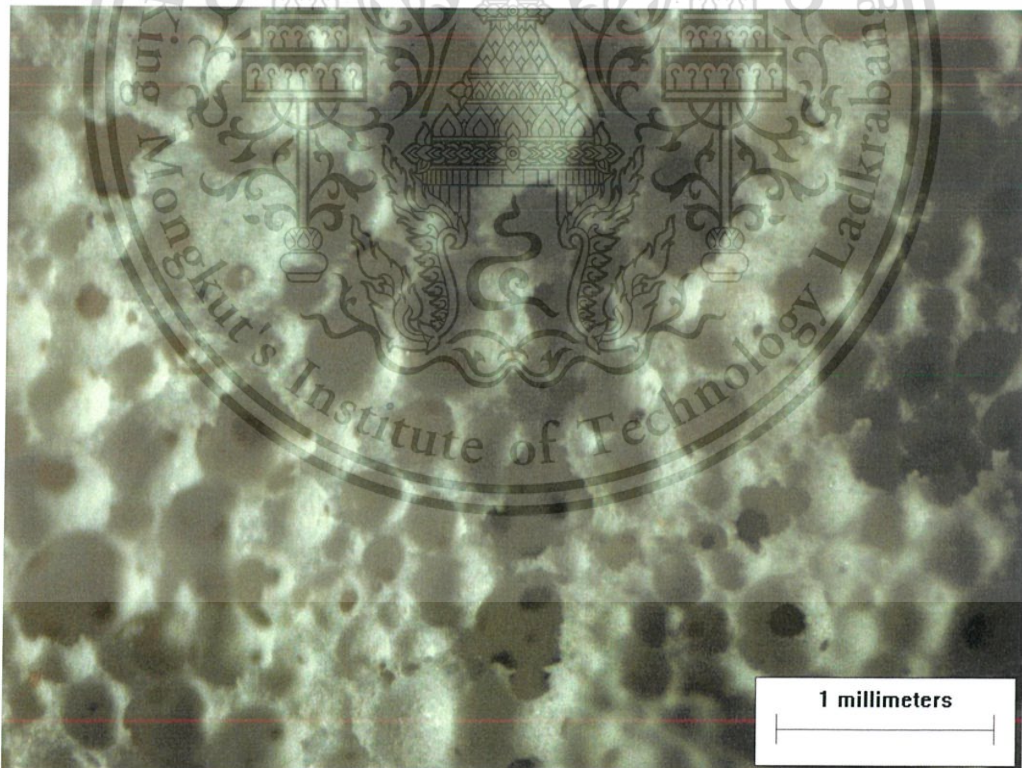


Figure 0.24 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (e) after mixing with vacuum, casting without vacuum and without vibration (/XX)

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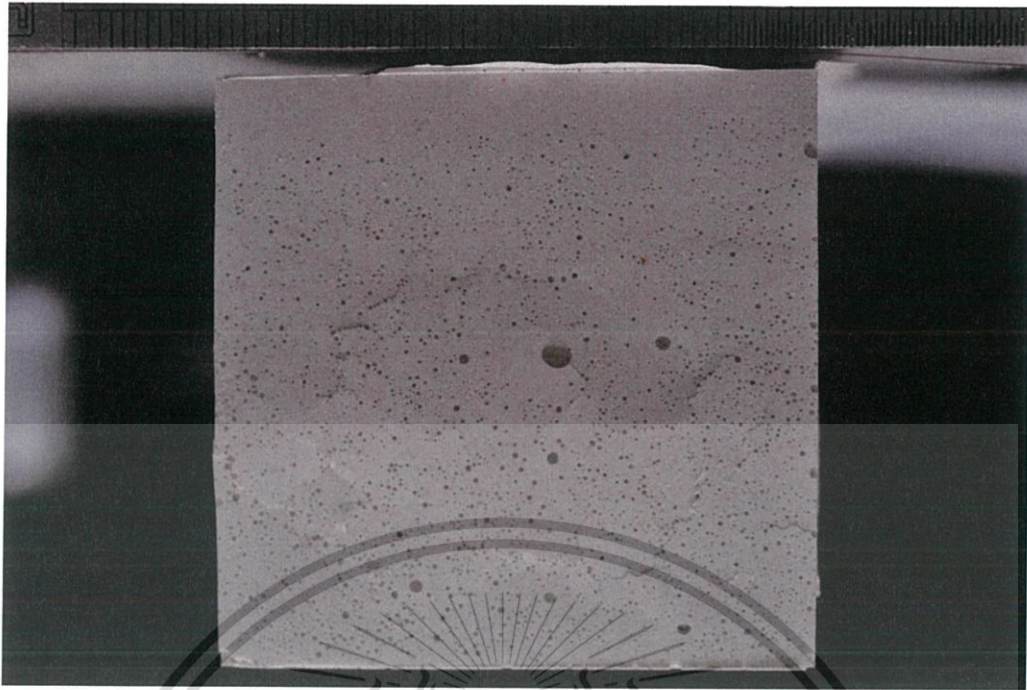


Figure 0.25 Foamed plasters produced using conditions shown in **Table 0.4**: (f) after mixing without vacuum, casting without vacuum and with vibration (XX/)

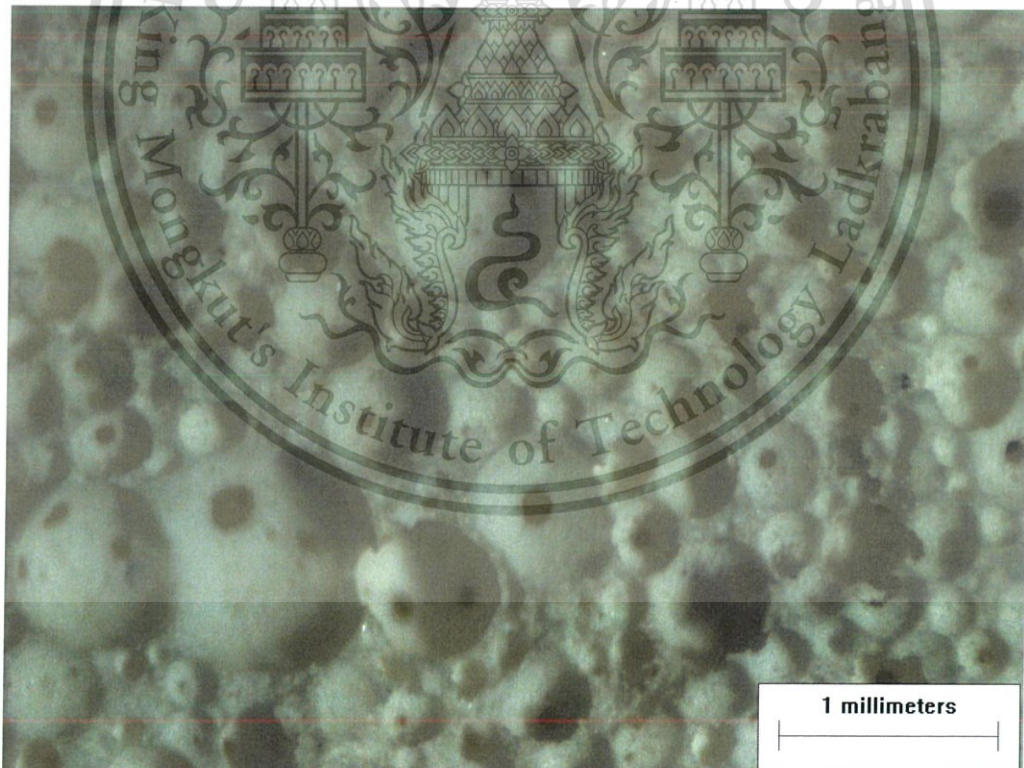


Figure 0.26 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (f) after mixing without vacuum, casting without vacuum and with vibration (XX/)

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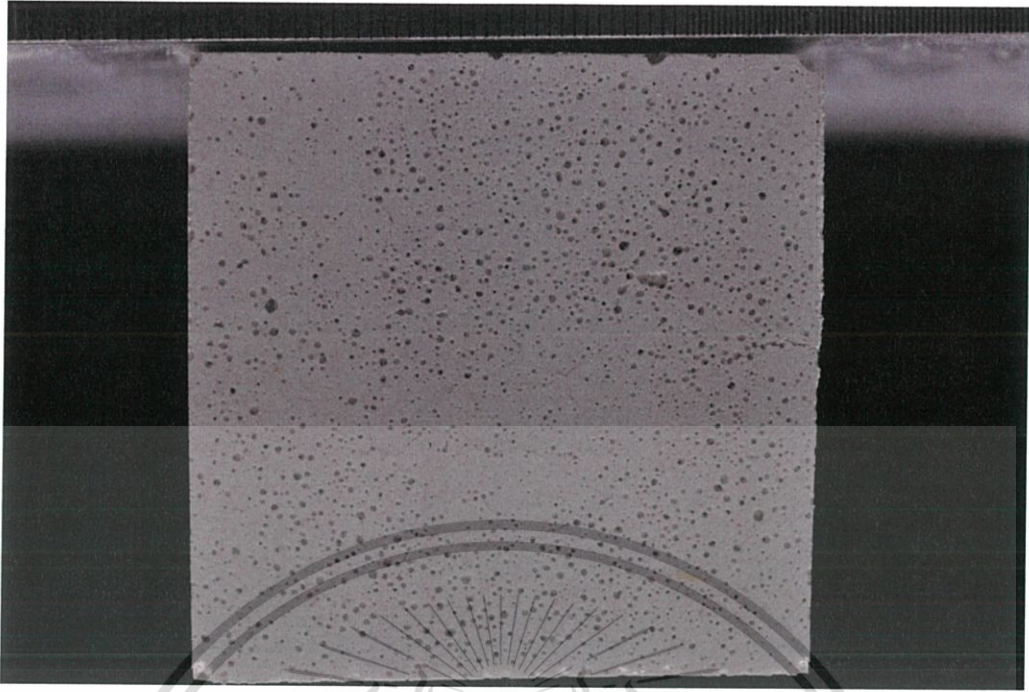


Figure 0.27 Foamed plasters produced using conditions shown in **Table 0.4:** (g) after mixing with vacuum, casting with vacuum and without vibration (//X)



Figure 0.28 High magnification images of foamed plasters produced using conditions shown in **Table 0.4:** (g) after mixing with vacuum, casting with vacuum and without vibration (//X)

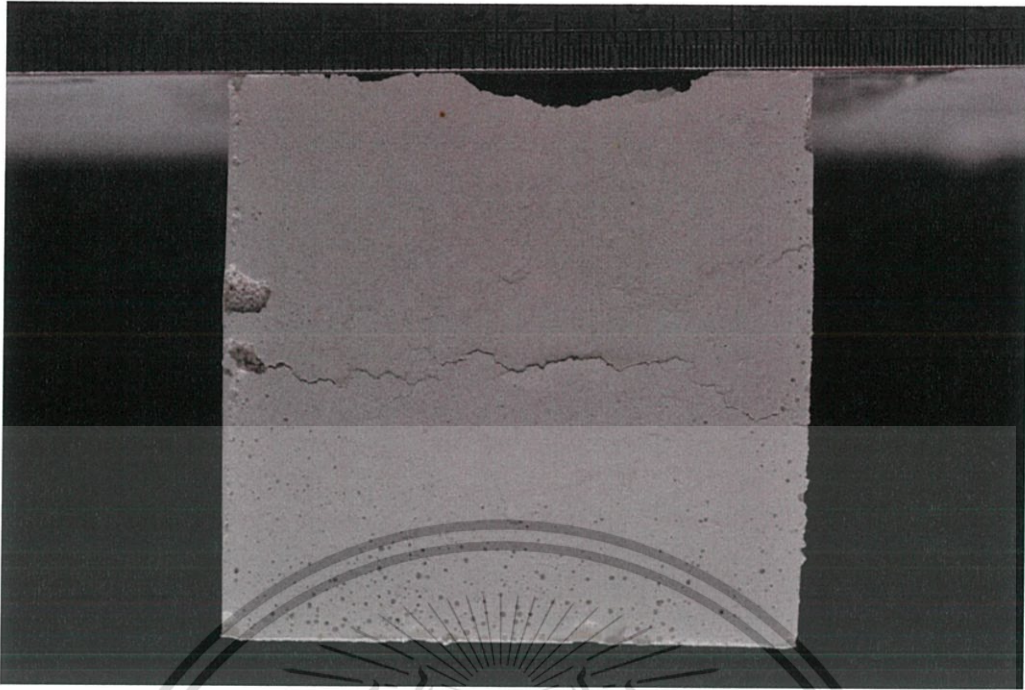


Figure 0.29 Foamed plasters produced using conditions shown in **Table 0.4**: (h) after mixing without vacuum, casting with vacuum and with vibration (X//)

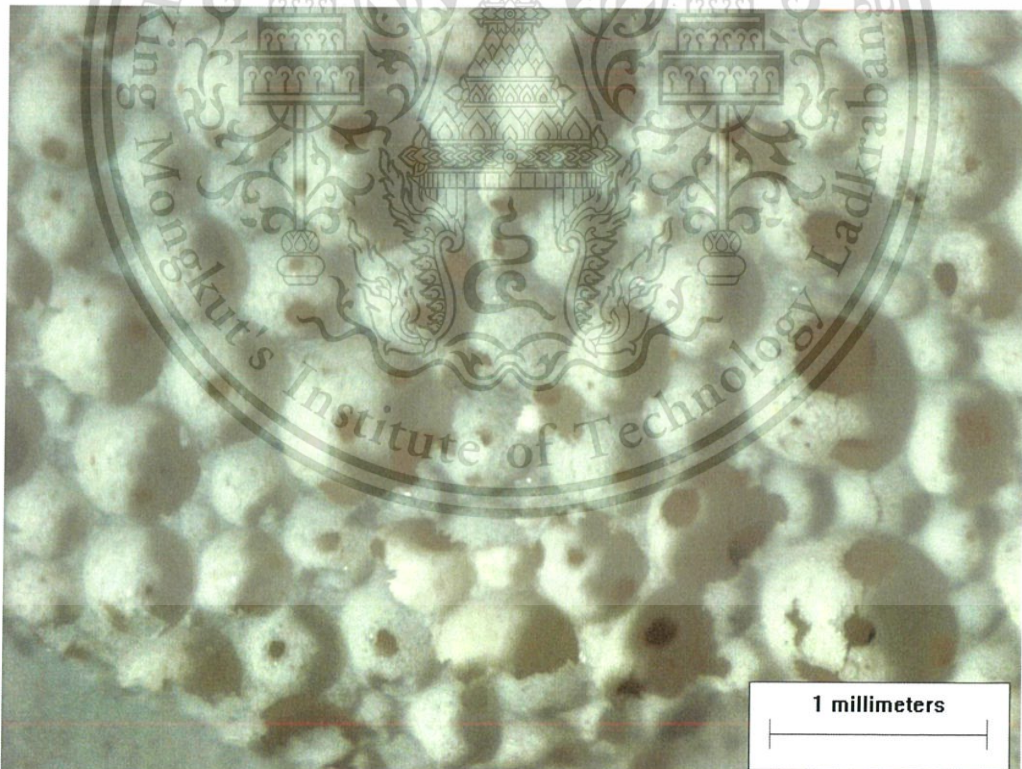


Figure 0.30 High magnification images of foamed plasters produced using conditions shown in **Table 0.4**: (h) after mixing without vacuum, casting with vacuum and with vibration (X//)

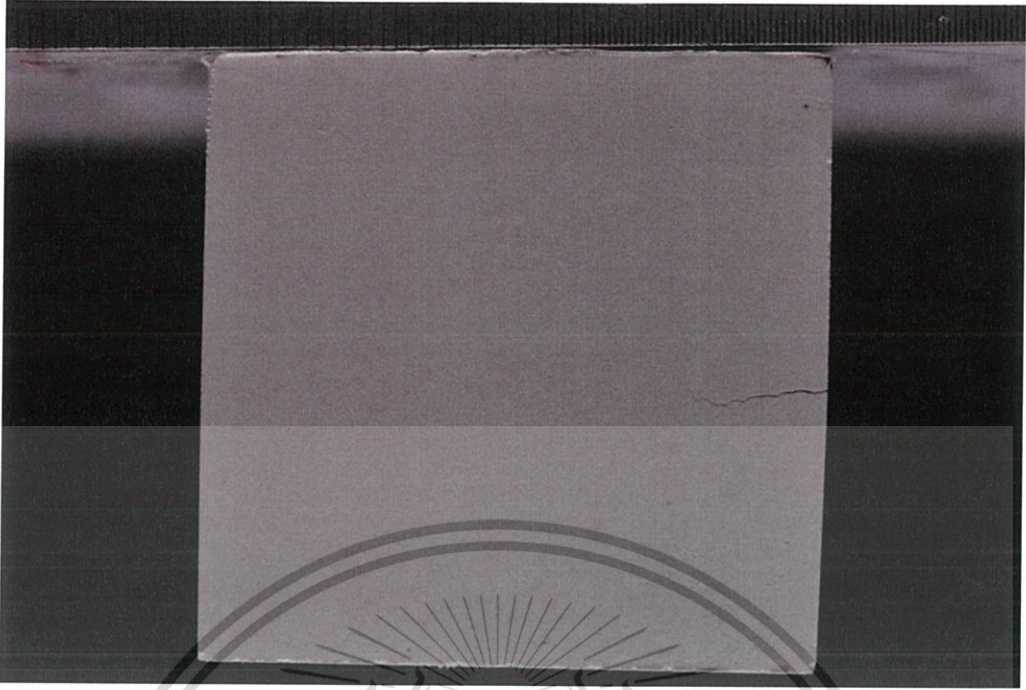


Figure 0.31 Conventional plasters produced using conditions shown in **Table 0.4:** (y) after mixing without vacuum, casting without vacuum and without vibration (XXX)

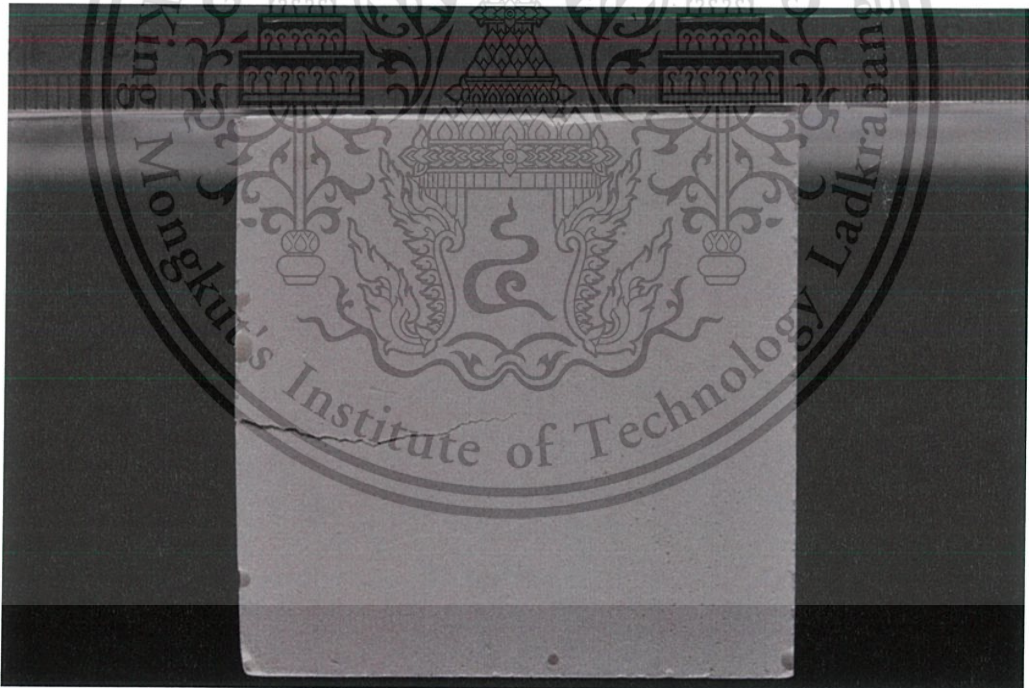


Figure 0.32 Conventional plasters produced using conditions shown in **Table 0.4:** (z) after mixing with vacuum, casting with vacuum and without vibration (//X)

Table 0.8 Properties of foamed and conventional plasters produced using conditions shown in **Table 0.4**

Properties	Unit	Conditions of plaster production				
		a	b	c	d	e
Total pore of side surface	number	8615	9578	32	143	5508
Avg. pore dia. of side surface	mm.	0.068	0.061	0.091	0.074	0.116
Total density	g/cm^3	0.672	0.665	0.516	0.671	0.433
Total weight	g.	82.534	79.061	66.845	66.996	54.052
% Porosity of side surface	%	1.756	1.695	0.021	0.054	3.508
Properties	Unit	Conditions of plaster production				
		f	g	h	y	z
Total pore of side surface	number	5003	1139	672	10	57
Avg. pore dia. of side surface	mm.	0.127	0.097	0.085	0.081	0.075
Total density	g/cm^3	0.592	0.576	0.534	1.284	1.271
Total weight	g.	72.248	69.801	63.798	158.341	158.050
% Porosity of side surface	%	4.114	0.601	0.258	0.004	0.020

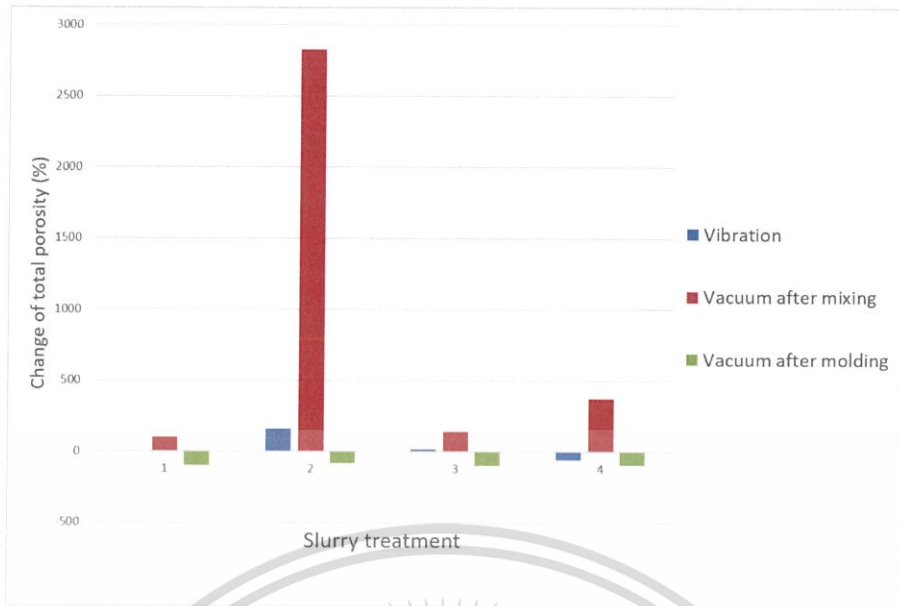


Figure 0.33 Change of porosity of foamed plasters produced using conditions shown in **Table 0.4**: (1) both after mixing and casting without vacuum (XX), (2) after mixing without vacuum but after casting with vacuum (X/), (3) after mixing with vacuum but after casting without vacuum (/X), and (4) both after mixing and casting with vacuum (//)

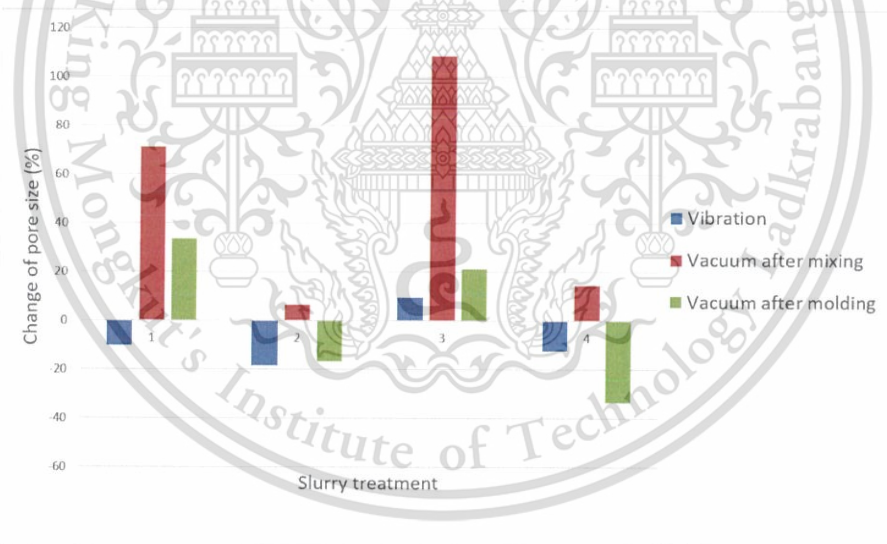


Figure 0.34 Change of pore size of foamed plasters produced using conditions shown in **Table 0.4**: (1) both after mixing and casting without vacuum (XX), (2) after mixing without vacuum but after casting with vacuum (X/), (3) after mixing with vacuum but after casting without vacuum (/X), and (4) both after mixing and casting with vacuum (//)

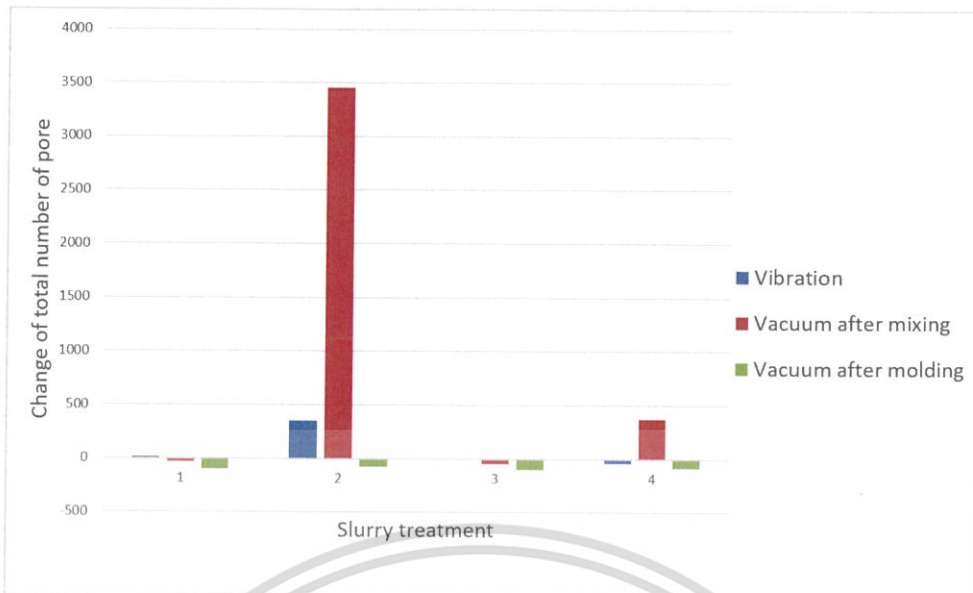


Figure 0.35 Change of total number of pore of foamed plasters produced using conditions shown in **Table 0.4**: (1) both after mixing and casting without vacuum (XX), (2) after mixing without vacuum but after casting with vacuum (X/), (3) after mixing with vacuum but after casting without vacuum (/X), and (4) both after mixing and casting with vacuum (//)

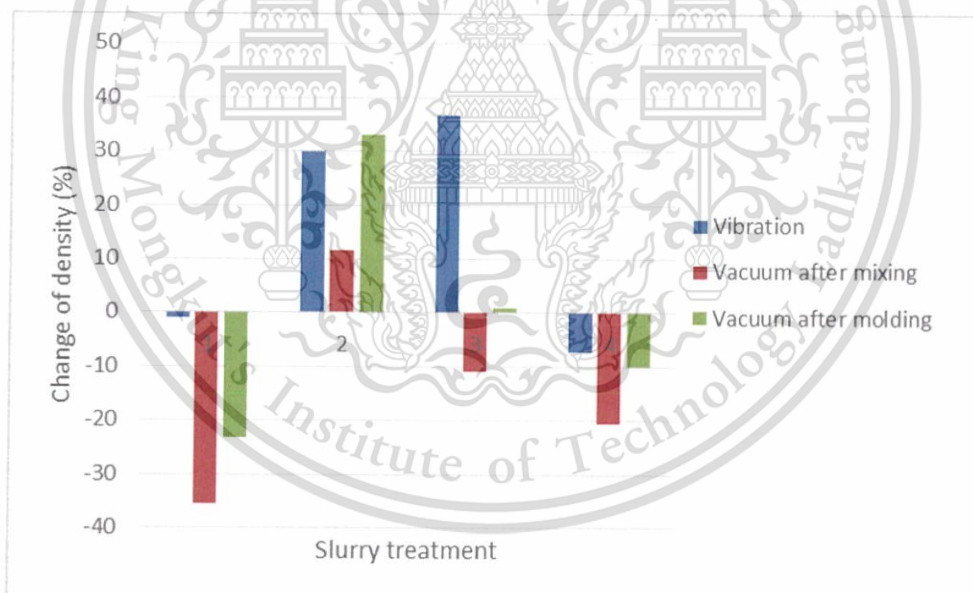


Figure 0.36 Change of density of foamed plasters produced using conditions shown in **Table 0.4**: (1) both after mixing and casting without vacuum (XX), (2) after mixing without vacuum but after casting with vacuum (X/), (3) after mixing with vacuum but after casting without vacuum (/X), and (4) both after mixing and casting with vacuum (//)

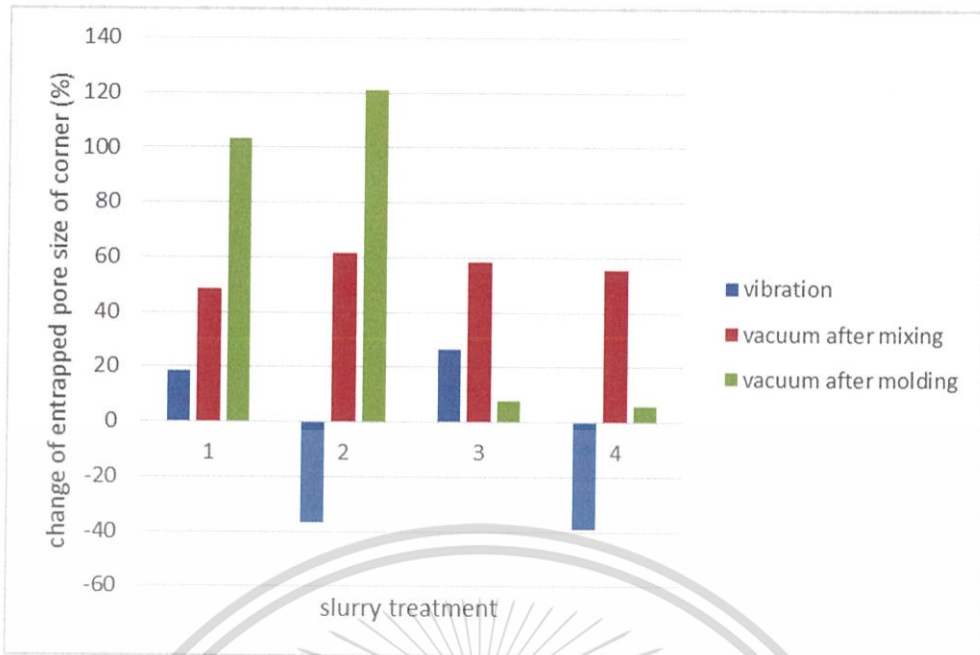


Figure 0.37 Change of entrapped pore size at corner of foamed plasters produced using conditions shown in **Table 0.4**: (1) both after mixing and casting without vacuum (XX), (2) after mixing without vacuum but after casting with vacuum (X/), (3) after mixing with vacuum but after casting without vacuum (/X), and (4) both after mixing and casting with vacuum (//)

4.5 Automotive Prototype Production

Figure 0.38 and **Figure 0.39** show the comparison between wax pattern and casting of turbocharger wheels of the wax pattern trees having different gating design. The casting with the gate at the periphery of turbocharger wheels (**Figure 0.38**) was found to have more defects than that with the gate at the center of turbocharger wheels (**Figure 0.39**). Defects in the casting with the gate at the periphery of turbocharger wheels were misrun, flash and bubble, while only misrun defect was found in the casting with the gate at the center of turbocharger wheels. It should be noted that the incomplete turbocharger wheel castings were those assembled close to the pouring basin for both gating systems. The significant difference in defects found in different gating systems and pattern assembly locations suggests the vital role of gating and pattern assembly design in foam-like plaster mold casting.

Figure 0.40 shows a complete cast turbocharger wheel produced using the center gating system. It can be seen that the casting of different thickness with the thinnest portion of less than 1 mm can be produced using this work foam-like plaster mold. The high gas permeability of the foam-like plaster mold would be the key to successfully produce this complicated shape turbocharger wheel.

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In terms of production cost, based on calculation and experiment, this foam-like plaster was estimated to use raw material cost, plaster volume, heating period and cooling period of 0.53, 0.51, 0.25 and 0.44 time of those of the conventional plaster. The use of this foam-like plaster can therefore reduce raw material cost, energy cost, cycle time and used plaster waste.

It should be noted that the completely cast turbocharger wheel shown in **Figure 0.40** was one of the two castings locating at top of the pattern tree and was among the two complete castings shown in **Figure 0.39**. If the cast turbocharger wheels were machined, they would be look like the master model.

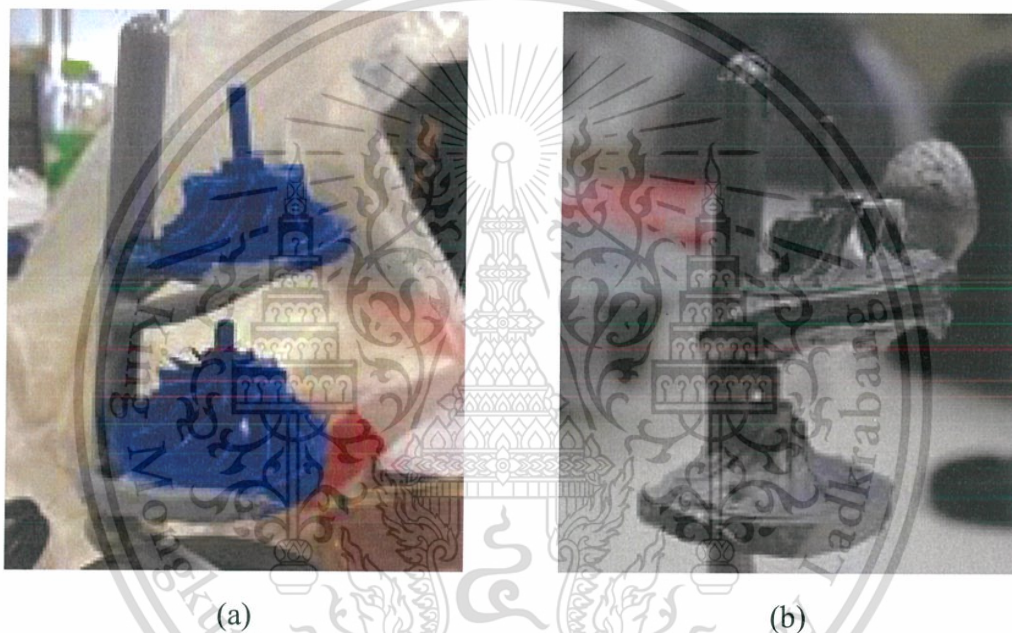


Figure 0.38 Periphery gating system: (a) wax pattern and (b) casting



(a)



(b)

Figure 0.39 Center gating system: (a) wax pattern and (b) casting

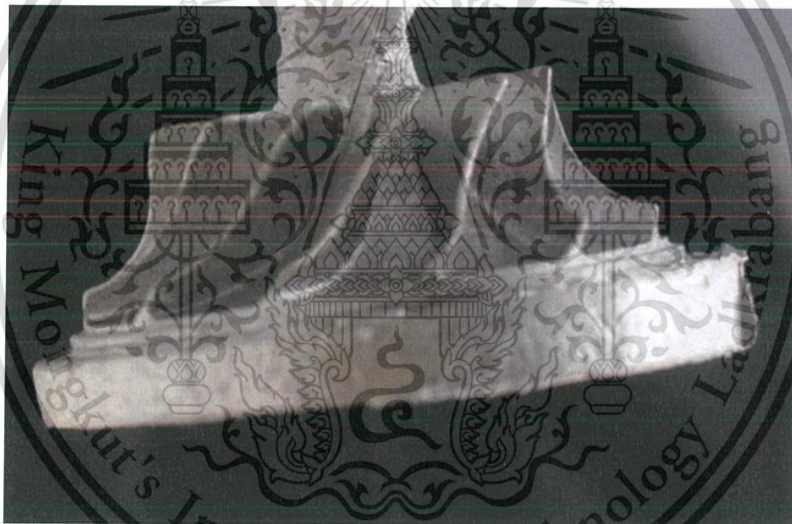


Figure 0.40 Turbocharger wheel produced by center gating system

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

Conventional plaster mold is capable of casting metals with complex shapes. However, it is susceptible to incomplete fill with molten metal due to its low permeability. This work aims to investigate the influence of plaster to water ratio, surfactant and strength enhancing additives, and foaming conditions on foam formation of plaster, develop a bubble generator machine, produce a plaster mold with foam-like structure and produce an automotive prototype using the developed foamed plaster mold.

A bubble generator was developed to generate gas bubbles in plaster slurry. A combination of a conventional stirrer and a bubble generator was found to give foamed plaster with more bubbles and higher permeability than using only the bubble generator. Various additives were added to conventional plaster slurry to form structure of foamed plaster with desired strength and permeability. Plasters with PVA, gypsum and $MgSO_4$ additions showed the best characteristics of high strength, homogenous structure and good flow ability slurry.

Water temperature and mixing time of plaster slurry had an effect on foamed plaster's properties. Based on generalising the effect of these parameters on properties of foamed plasters, some conclusions could be made, as follows.

- The prolonged mixing time is favorable to enhance uniformity of the plaster as a result of shorter reaction time and attributing to an increase in reaction temperature.
- Higher water temperature with intermediate mixing time is recommended to enhance permeability of the foamed plaster. Coarser plaster crystal structure would be attributed to less resistance to the passage of gases and hence enhancing permeability of the foamed plaster.
- Increasing mixing time with reasonable low water temperatures seems to enhance strength but deteriorate the permeability of the foamed plaster. Small plaster crystal structure would be attributed to the strength enhancement and the permeability reduction.

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Permeability and compressive strength were found to inversely and directly proportional to the density of foamed plasters, respectively. The permeability and compressive strength of as-cast foamed plasters was about an order of magnitude smaller and larger than that of heat treated foamed plasters, respectively. In addition, the permeability seems to be well related to compressive strength irrespective to production conditions.

Foamed and conventional plaster produced with and without vibration after slurry casting under various conditions: both after mixing and casting without vacuum, after mixing without vacuum but after casting with vacuum, after mixing with vacuum but after casting without vacuum, and both after mixing and casting with vacuum, showed different surface quality. The best surface quality of the foam-like plaster mold was obtained when plaster slurry was left under vacuum at both after mixing and casting without vibration.

This work also determined the feasibility of using a foam-like plaster mold for manufacture turbocharger wheels. It was found that turbocharger wheels with thin blades can be completely cast using the foam-like plaster mold. However, incomplete castings were found with some castings even though a foam-like plaster mold with good permeability was employed. Gating design and pattern assembly location seem to be parameters of great importance for controlling the filling of molten metal and hence determining the completeness of casting. The developed plaster molds with the foam-like structure was expected to reduce the cost of both raw plaster and cast metal materials due to the large amount of pores in plaster structure and the increase of production yield. This process could be adapted to produce other casting components.

5.2 Suggestions

The strength of the foamed plaster is still required to enhance to allow the foamed plaster to be used as a mold for industrial casting.

More test data of water temperature and mixing temperature are needed to establish a more define trend for the effect of these parameters on properties of foamed plasters.

In-depth investigation of microstructure of foamed plaster produced under a well control of additive addition is needed in order to understand mechanism of structural formation during setting of the foamed plaster.

Bubble stability is recommended to investigate to enhance understanding of the phenomenon of foaming and influence of processing parameters.



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- 23) Jewelry Plaster (JPL) LTD, Copyright © 2013 Jewelry Plaster. Website:
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APPENDIX A Setting Expansion of Foamed Plasters

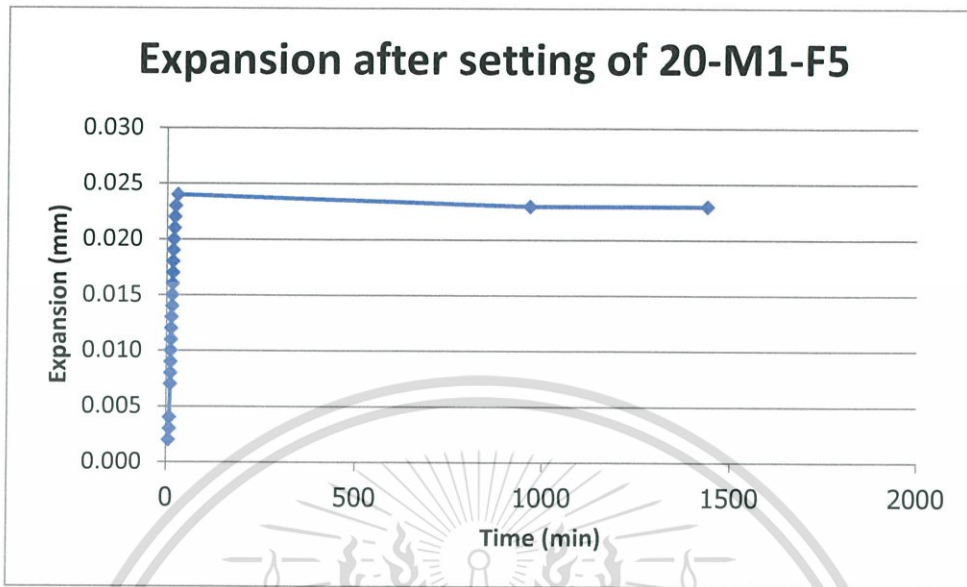


Figure A-1 Setting expansion of 20-M1-F5 foamed plaster

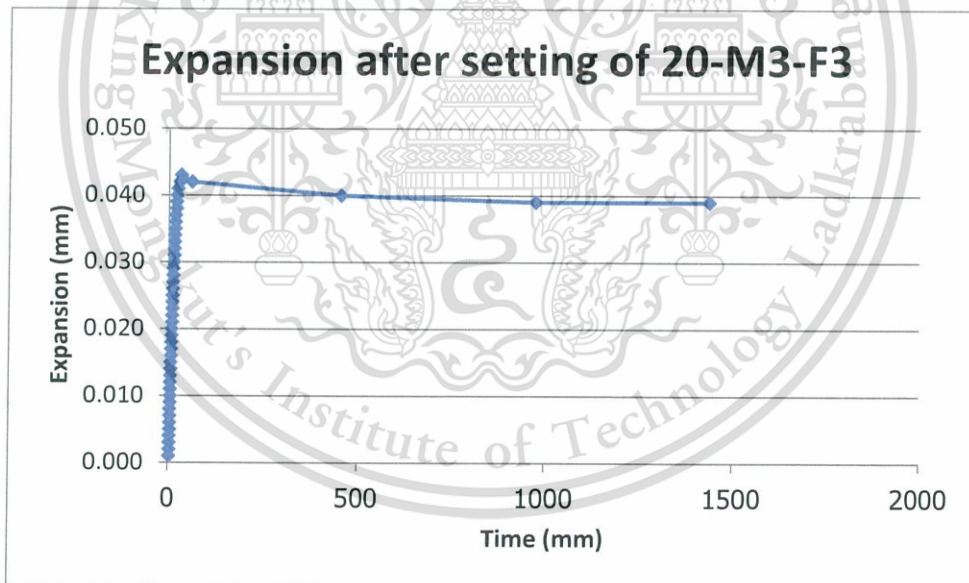


Figure A-2 Setting expansion of 20-M3-F3 foamed plaster

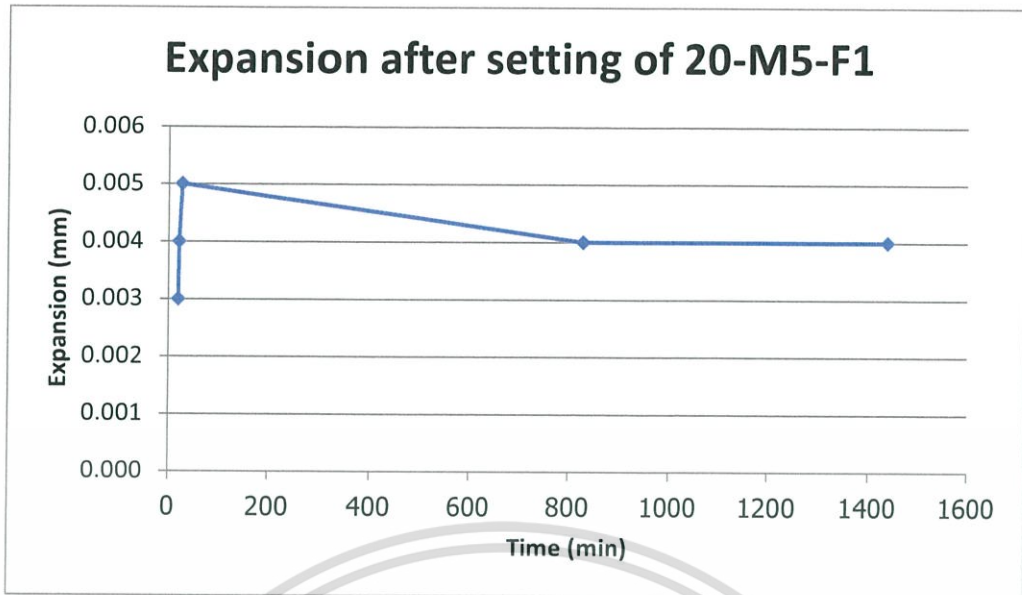


Figure A-3 Setting expansion of 20-M5-F1 foamed plaster

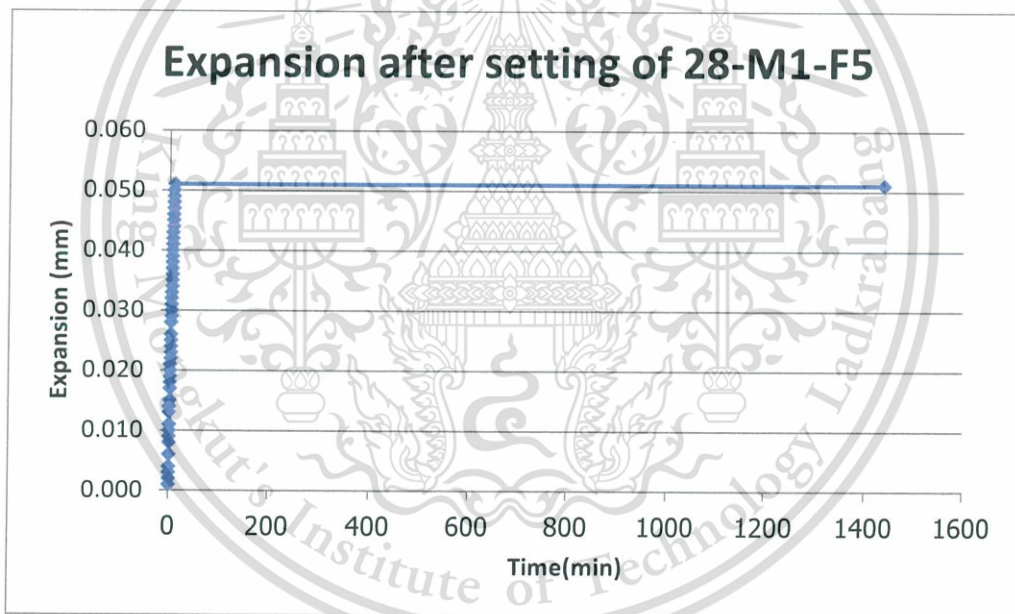


Figure A-4 Setting expansion of 28-M1-F5 foamed plaster

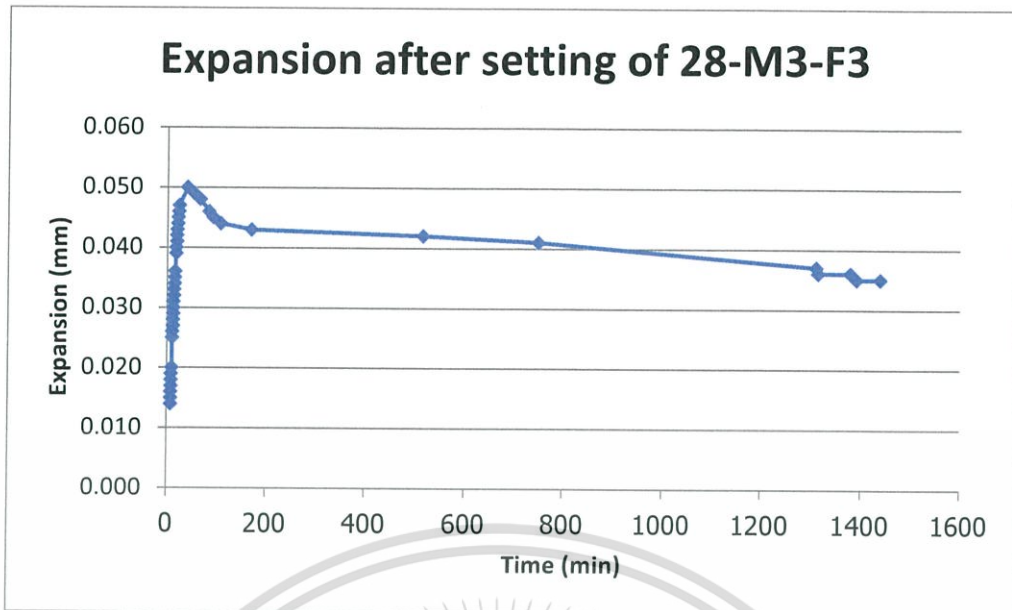


Figure A-5 Setting expansion of 28-M3-F3 foamed plaster

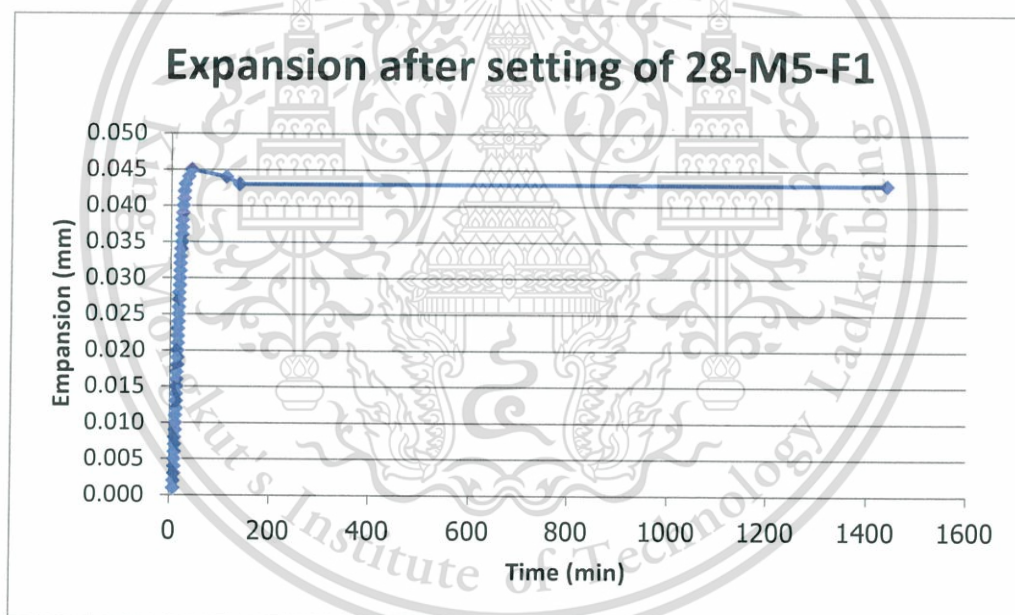


Figure A-6 Setting expansion of 28-M5-F1 foamed plaster

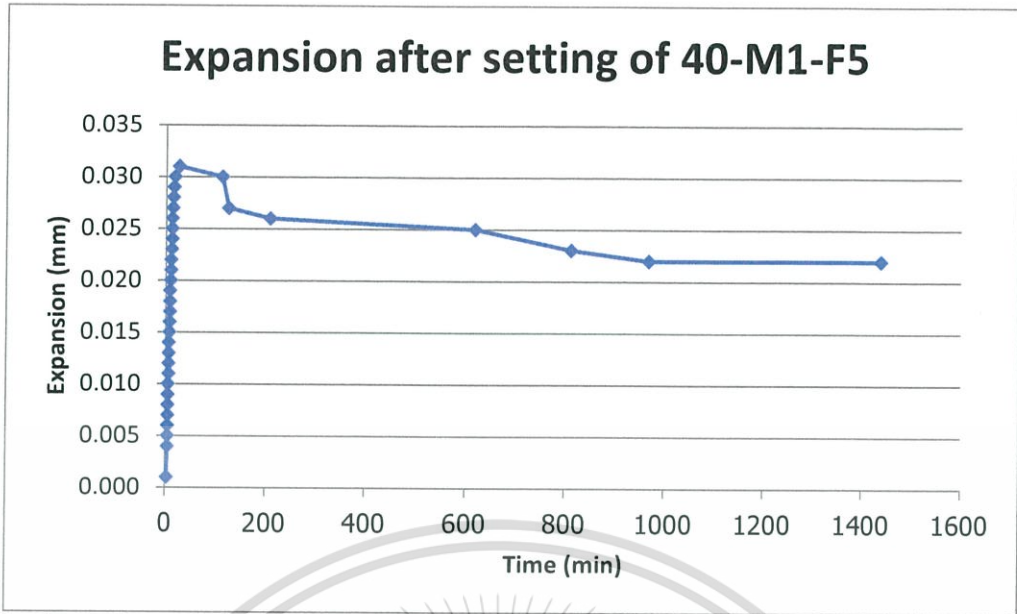


Figure A-7 Setting expansion of 40-M1-F5 foamed plaster

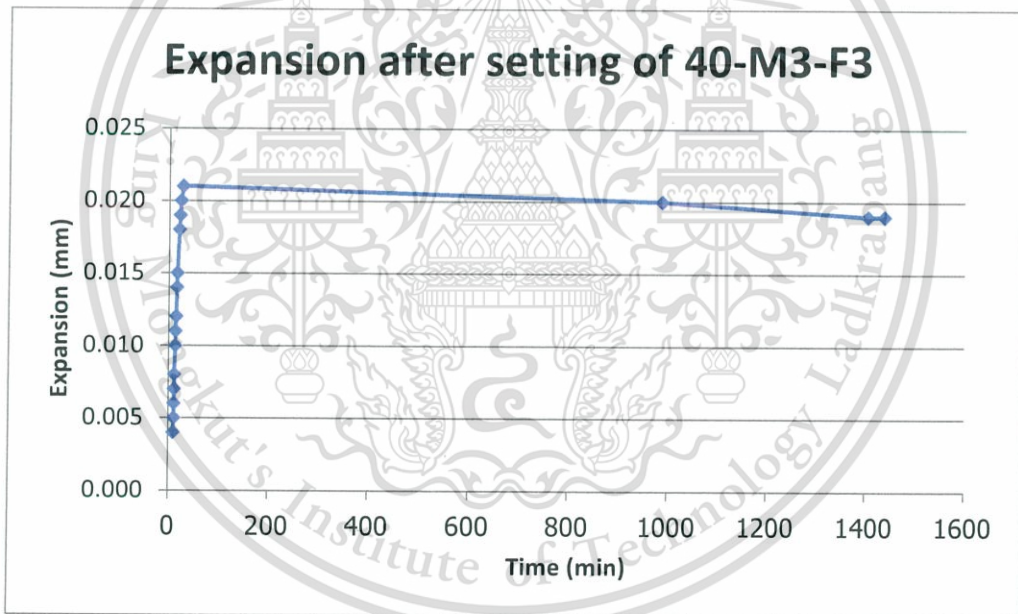


Figure A-8 Setting expansion of 40-M3-F3 foamed plaster

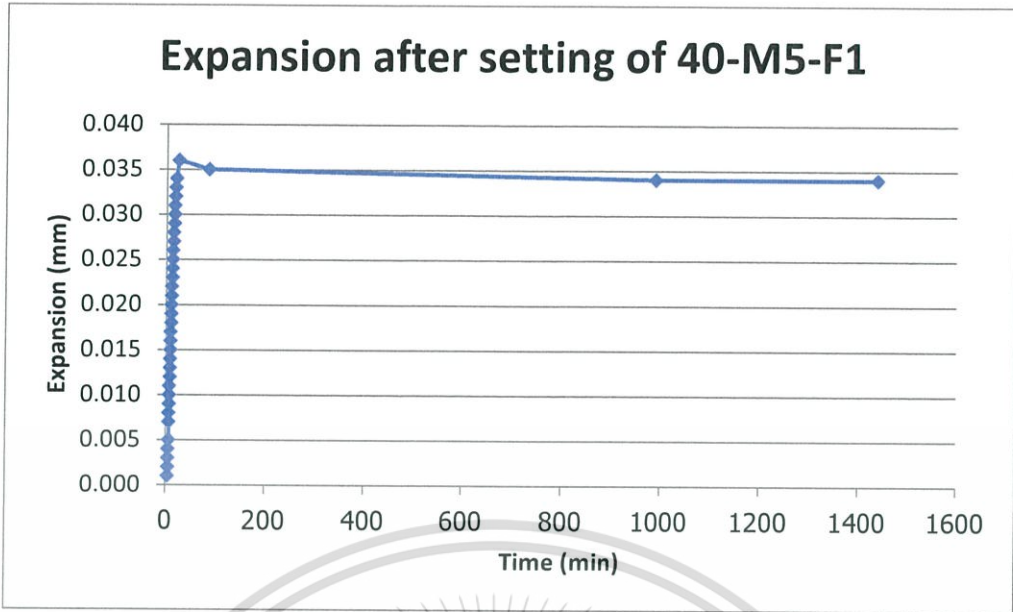
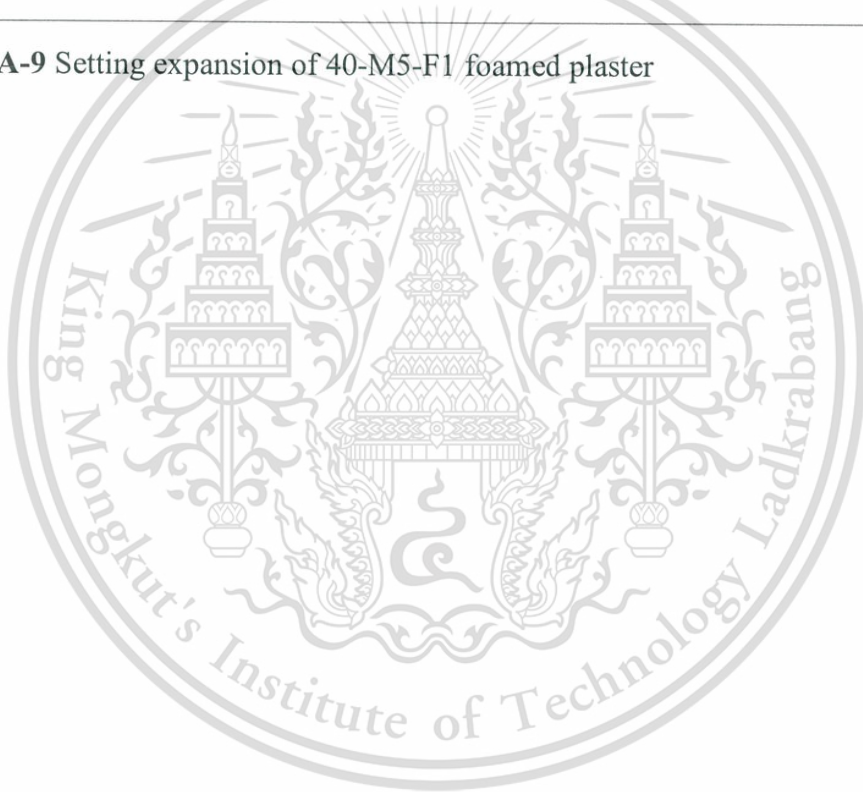


Figure A-9 Setting expansion of 40-M5-F1 foamed plaster



APPENDIX B Compressive Strength of Foamed Plasters

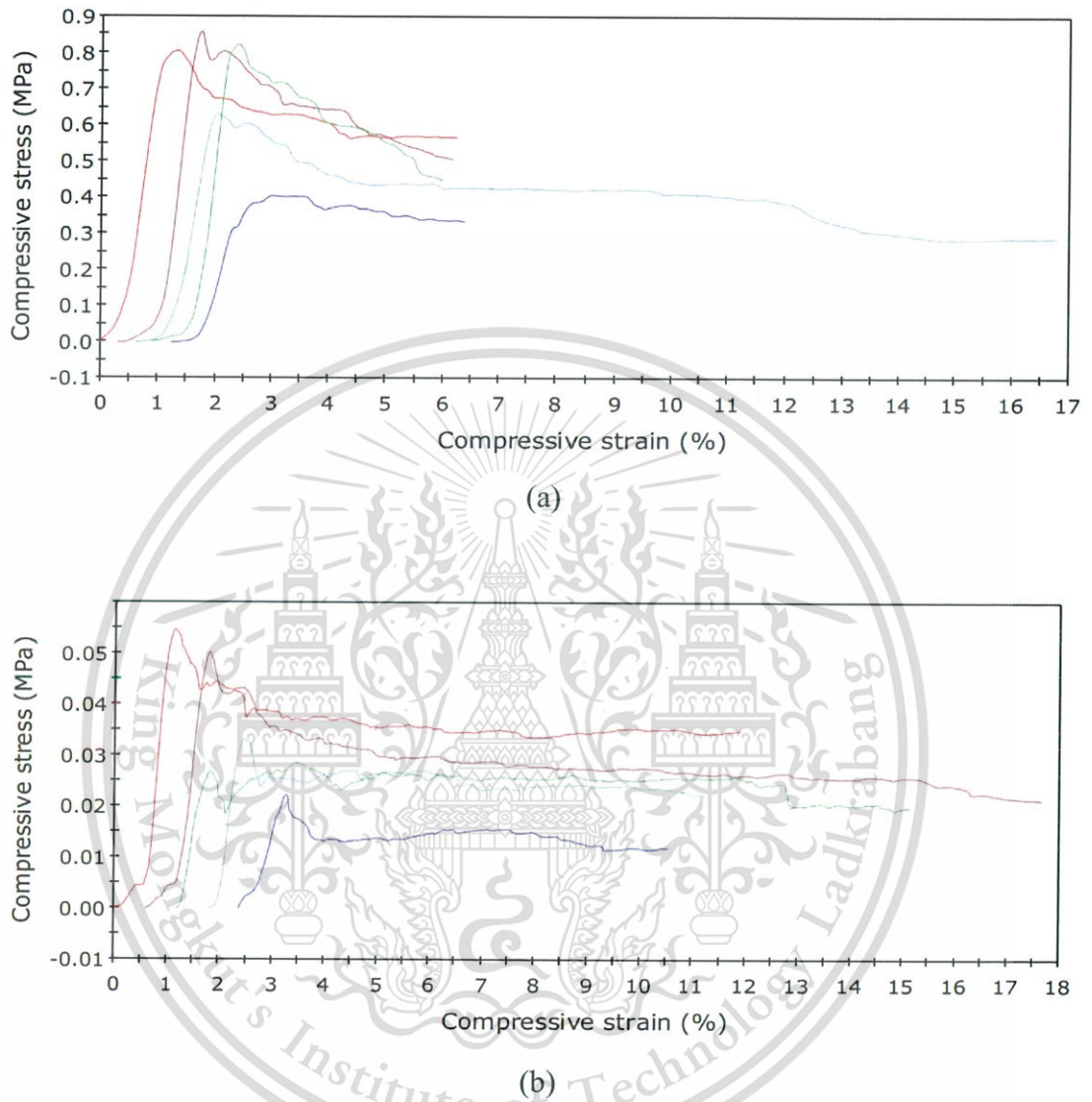


Figure B-1 Compressive strength of 20-M1-F5 foamed plaster: (a) As-cast and (b) heat treated condition

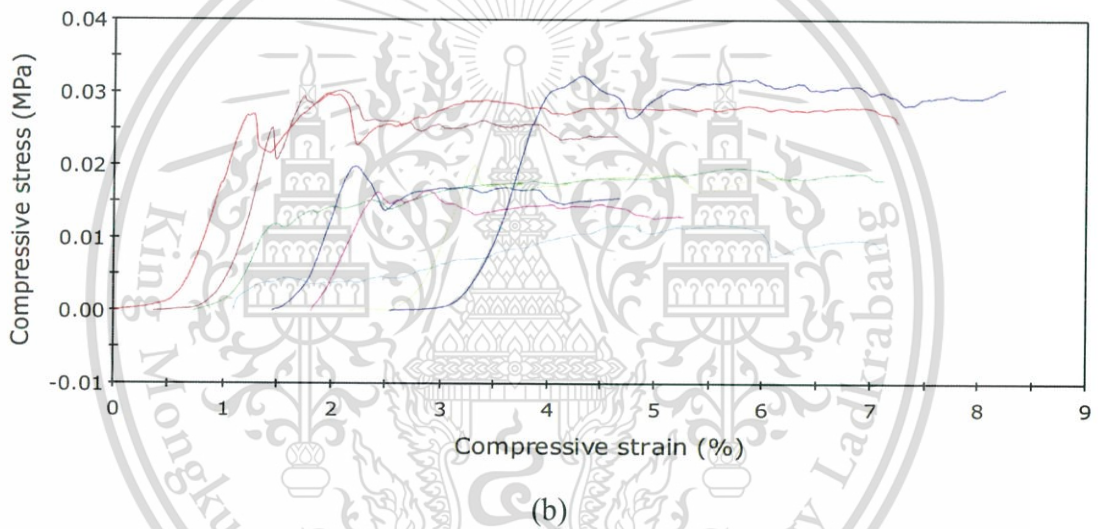
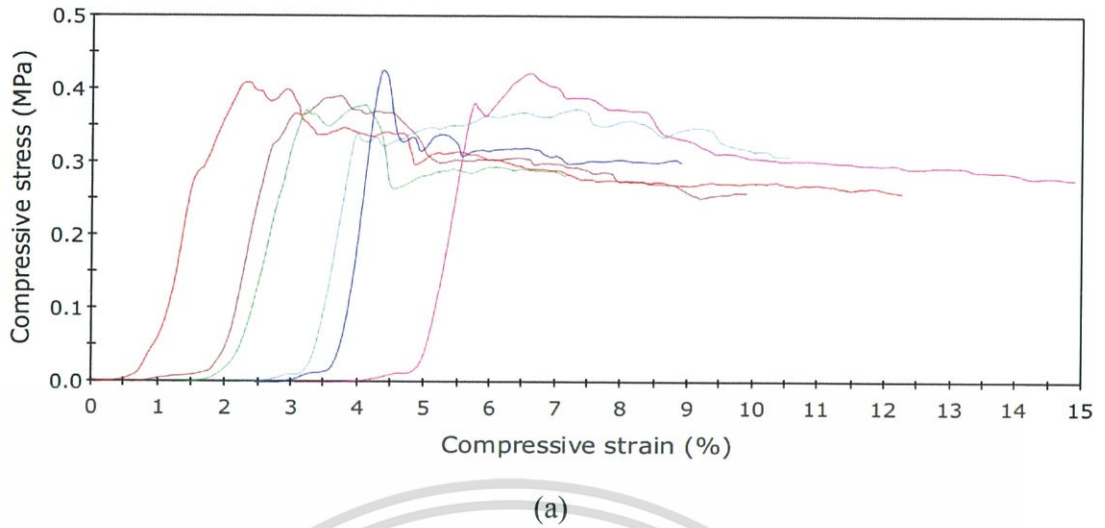
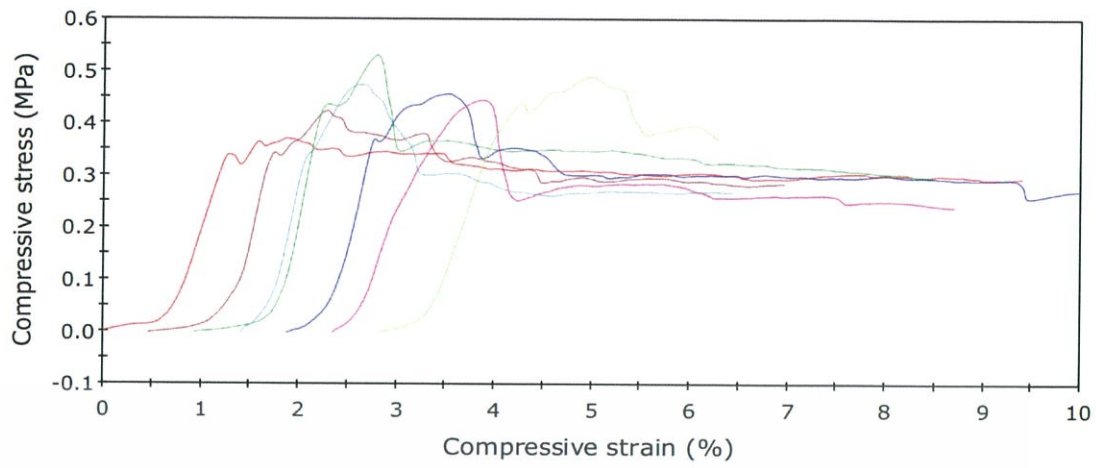
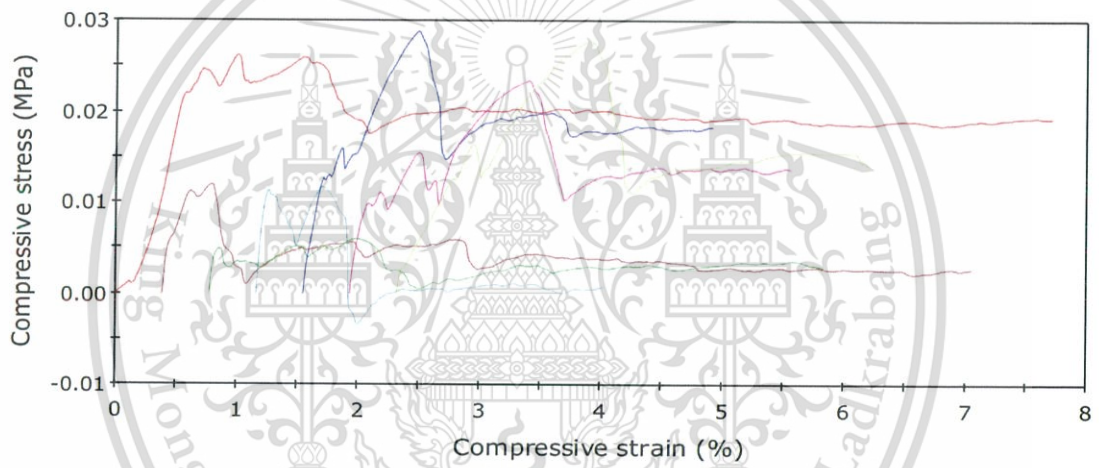


Figure B-2 Compressive strength of 20-M3-F3 foamed plaster: (a) As-cast and (b) heat treated condition

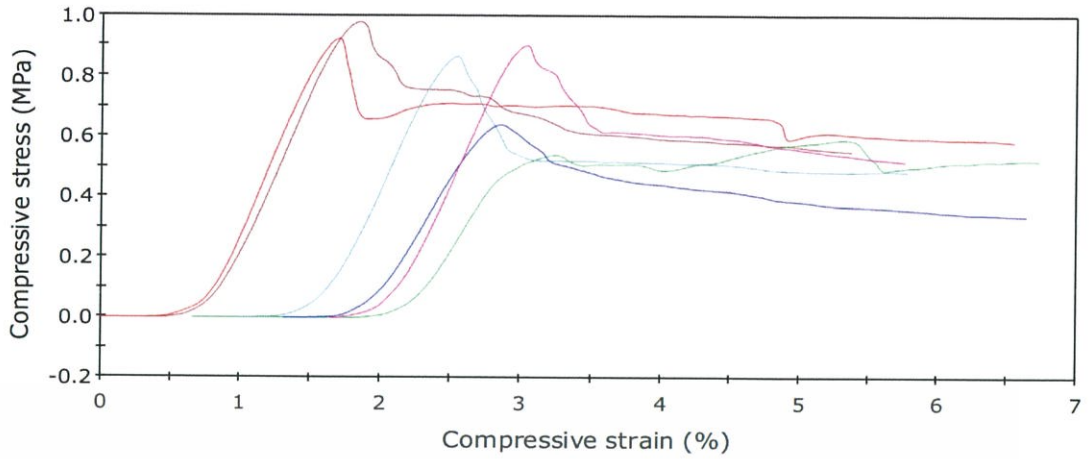


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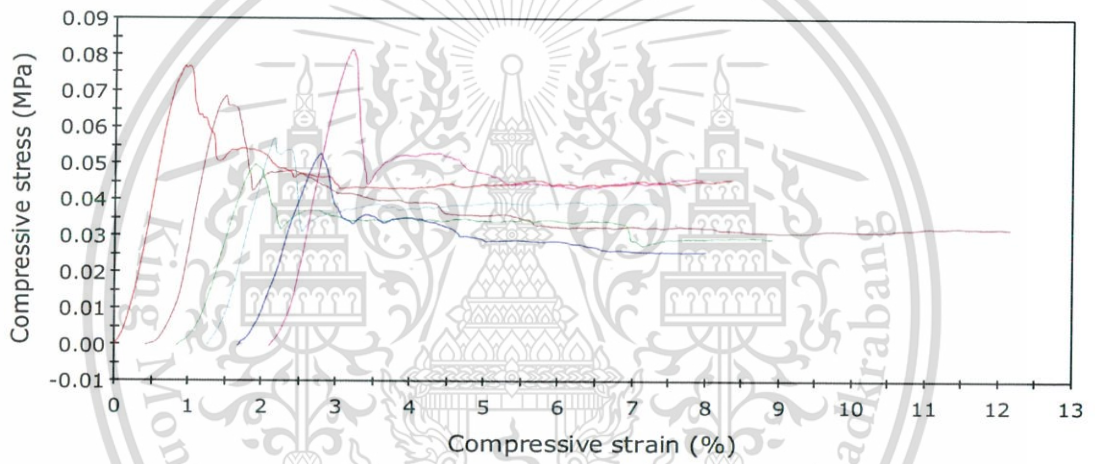


(b)

Figure B-3 Compressive strength of 20-M5-F1 foamed plaster: (a) As-cast and (b) heat treated condition

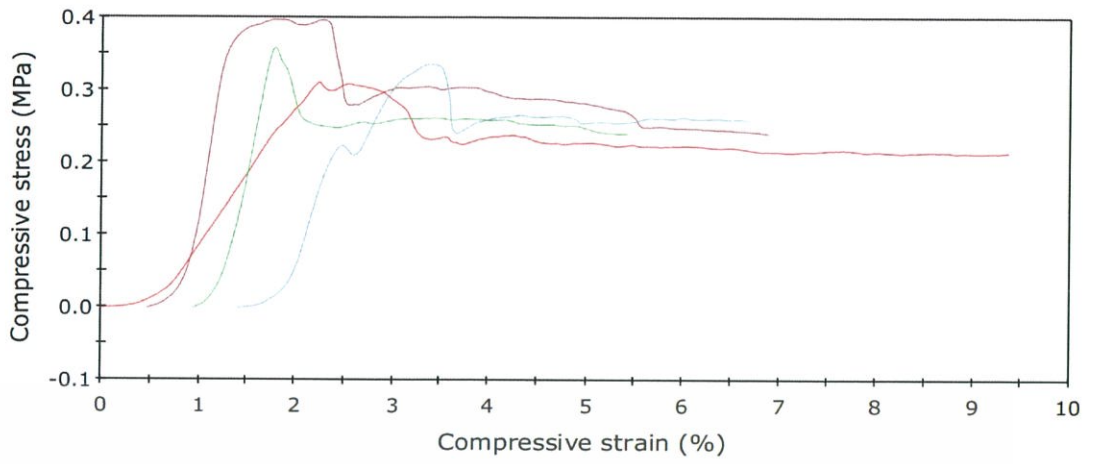


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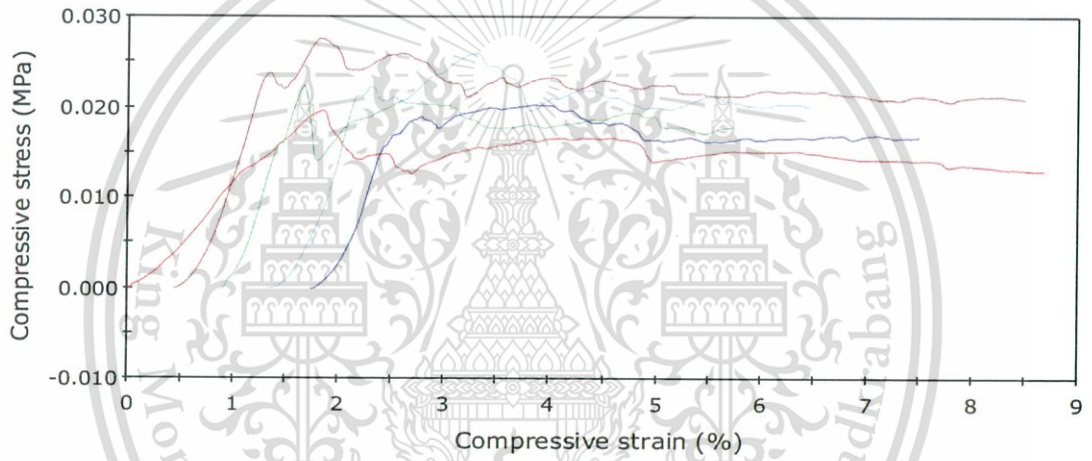


(b)

Figure B-4 Compressive strength of 28-M1-F5 foamed plaster: (a) As-cast and (b) heat treated condition

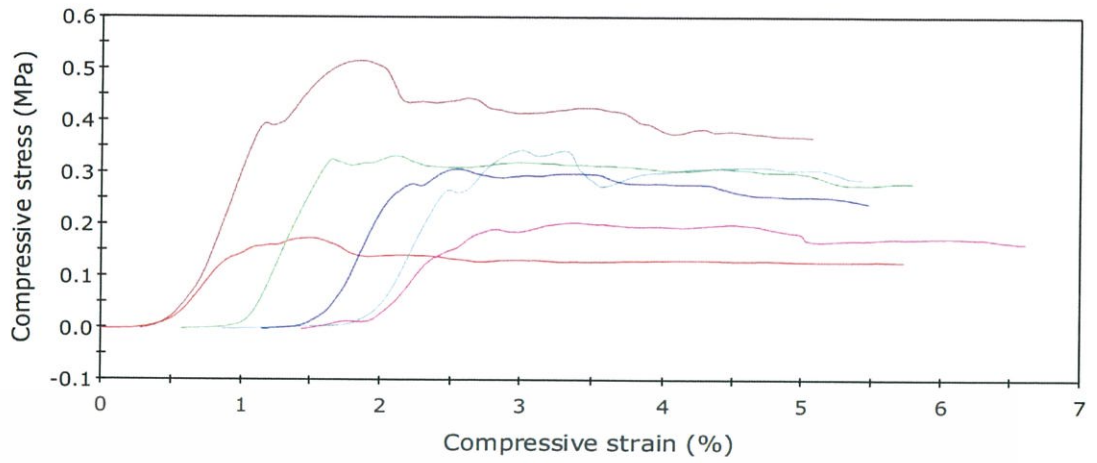


(a)

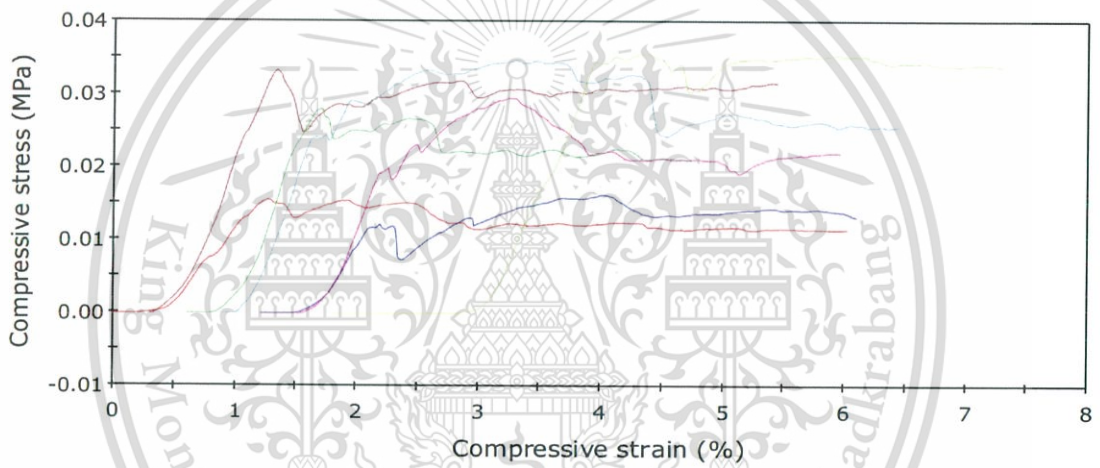


(b)

Figure B-5 Compressive strength of 28-M3-F3 foamed plaster: (a) As-cast and (b) heat treated condition

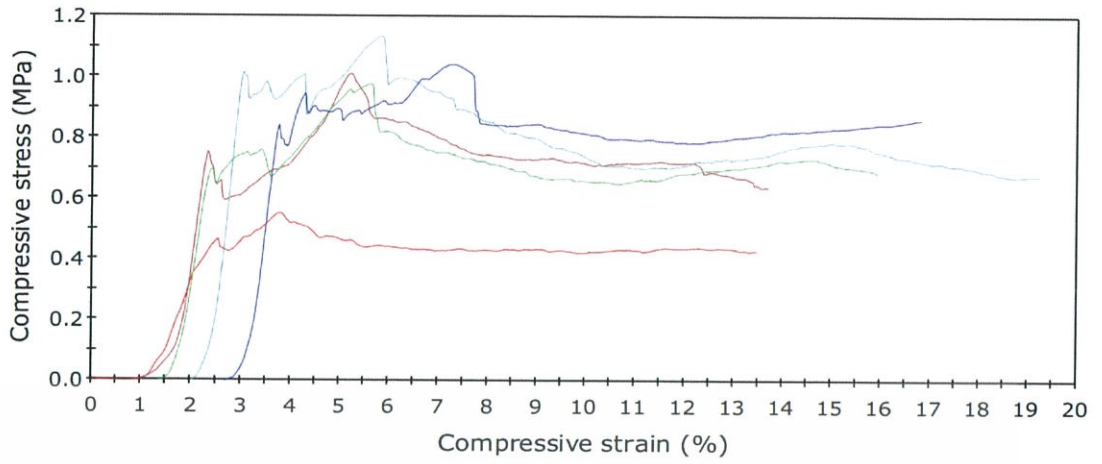


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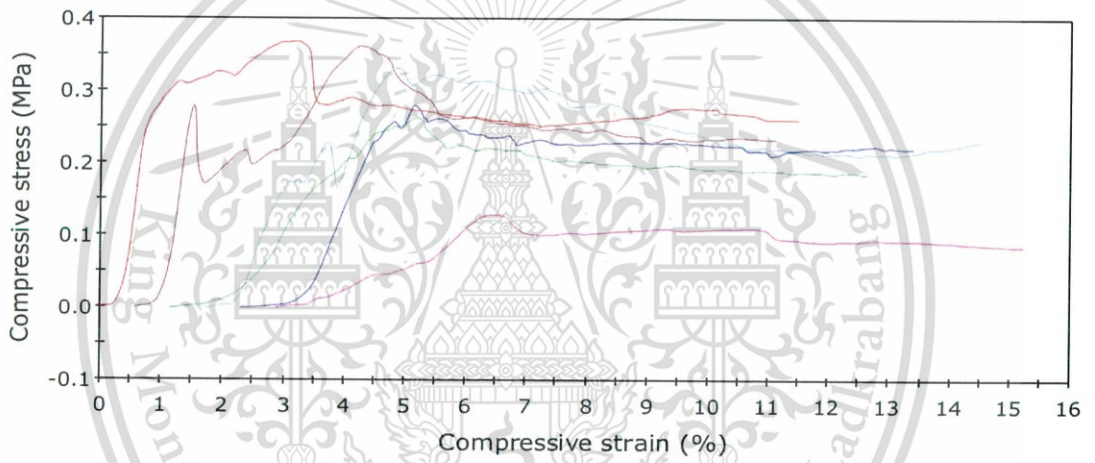


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Figure B-6 Compressive strength of 28-M5-F1 foamed plaster: (a) As-cast and (b) heat treated condition

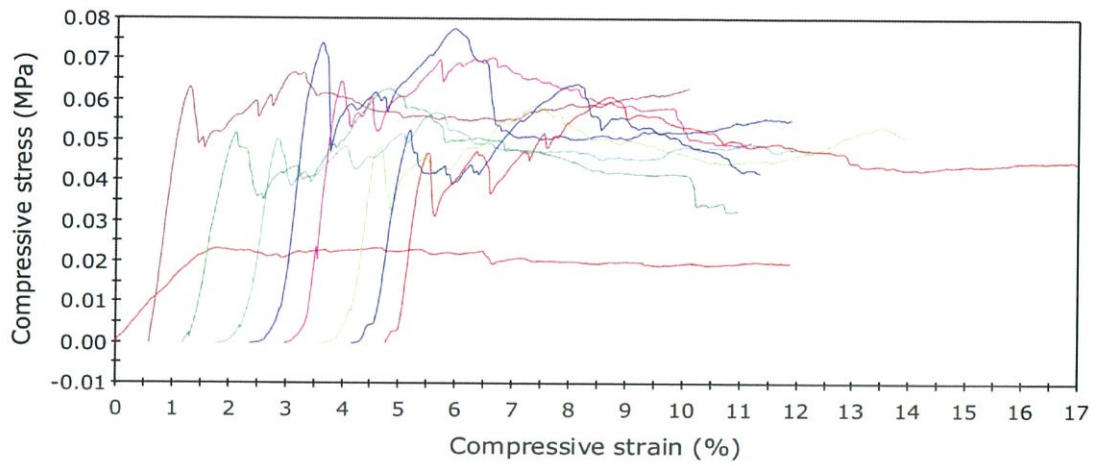


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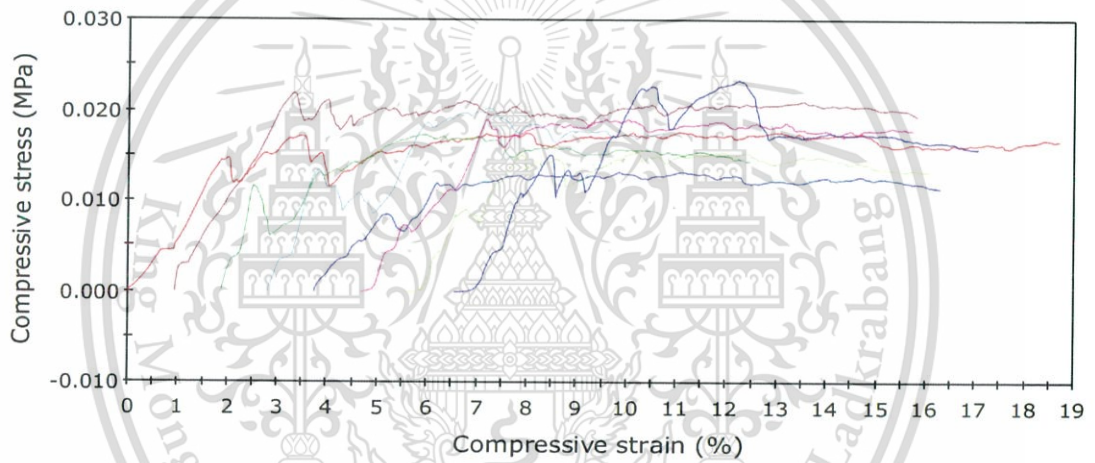


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Figure B-7 Compressive strength of 40-M1-F5 foamed plaster: (a) As-cast and (b) heat treated condition

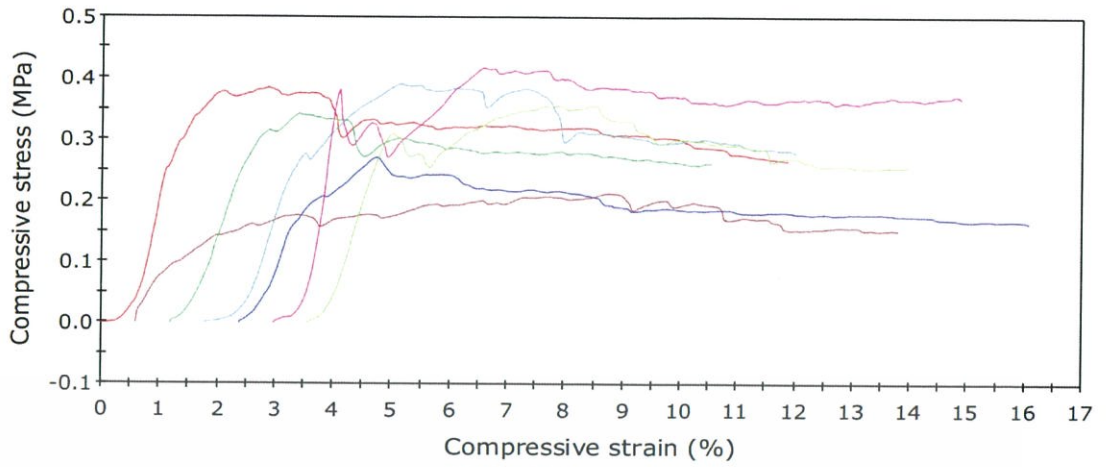


(a)

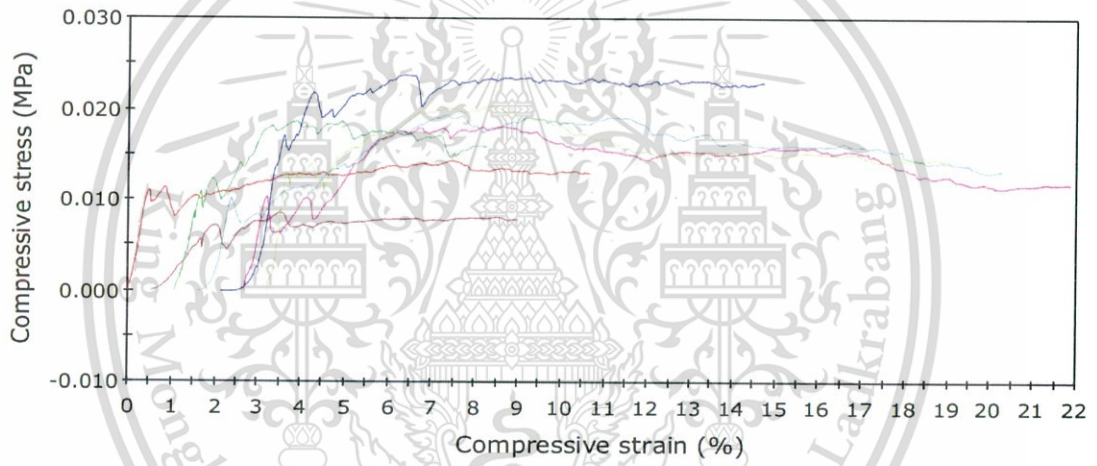


(b)

Figure B-8 Compressive strength of 40-M3-F3 foamed plaster: (a) As-cast and (b) heat treated condition



(a)



(b)

Figure B-9 Compressive strength of 40-M5-F1 foamed plaster: (a) As-cast and (b) heat treated condition

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