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THESIS

EARLY-AGE COMPRESSIVE STRENGTH OF CONCRETE AND FLY ASH CONCRETE WITH APPLICATION OF MICROWAVE CURING TECHNIQUE

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A Thesis Submitted in Partial Fulfillment of
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Microwave curing processes involving power level at 70 Watt and heating period of 3, 5 and 7 hours were used to obtain early compressive strength of concrete and fly ash concrete at 1 day. These processes were also used for compressive strength estimation of the 28-day strength of normally cured specimens. Test parameters included the amount of fly ash replacement, at 0%, 30% and 50% by weight of cement, slumps and water/binder ratios. Mix proportions were designed according to the ACI mix design using Type I cement, Mae-Moh fly ash, natural construction sand and crushed limestone.

The maximum strength of microwave cured specimens reached 74% of 28-day normally cured. The compressive strength of various mix proportions of 1-day microwave cured specimens and 28-day normally cured specimens could be used to estimate the 28-day compressive strength estimation. The estimation yielded the maximum percentage of error at 6.4%.

The 1 day of microwave cured sample (by 7 hours of application time) and normally cured of cement pastes containing fly ash 0%, 30% and 50% with W/B=0.411 were tested by microstructure analysis. From MIP result, it was shown that microwave curing technique could decrease the pore radius and total porosity. XRD analysis showed that microwave curing application accelerated cement hydration.

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EARLY-AGE COMPRESSIVE STRENGTH OF CONCRETE AND FLY ASH CONCRETE WITH APPLICATION OF MICROWAVE CURING TECHNIQUE

INTRODUCTION

At present, fly ash is used as a cement replacement for producing concrete in the construction industry. A higher rate of strength development in fly ash concrete can benefit several processes in this industry. For example, in the precast concrete factory, high early strength of fly ash concrete reduces the curing period for the production. Consequently, the moulds can be re-used and the products can be handled and delivered to the site or stock yard more quickly.

Steam curing is widely used to accelerate the strength of concrete in the precast concrete factory. However, this technique relies on the thermal conductivity of product, with heat flowing from outside to inside. The heat penetration to interior is slow for the large product and the heating throughout of product is not uniform. Microwave curing is a method in which high-frequency electromagnetic wave flips water molecules at about 5 billion times each second. This produces heat internally and accelerates cement hydration, resulting in more strength development.

In this study, the long application times are used with the low power level, in order to avoid boiling of water, and control the relative humidity during microwave application to prevent the evaporation problem.

OBJECTIVES

1. To study the correlation of the 1 day compressive strength of concrete and fly ash concrete from the microwave curing method by using the long curing times with the low power level compared with normal curing at 7, 28 and 63 days.

2. To use the results of the microwave curing method with different mix proportions and microwave curing processes to estimate the compressive strength of normal curined concrete and fly ash concrete at 28 days

3. To study the effect of microwave curing technique on the microstructure of microwave and normal curing paste samples at 1 day.

Scope of Research

1. Compressive strength investigation

1.1 Mix proportions

Parameters	Values
Percentages of fly ash replacement	0%, 30% and 50%
Target strengths	280 and 420 ksc
Slump requirements	25-50 and 150-175 mm
Total	12 mixes

1.2 Microwave curing processes

Parameters	Values
Casting time	1 hour
Percentages of full output power	10% (70 Watt)
Curing times	3, 5 and 7 hours
Total	3 processes

2. Compressive strength estimation

2.1 Mix proportions

Parameters	Values
Percentages of fly ash replacement	0%, 30% and 50%
Target strengths	280 and 420 ksc
Slump requirements	25-50 and 150-175 mm
Later age test time	28 days

2.2 Microwave curing processes

Parameters	Values
Casting time	1 hour
Percentages of full output power	10% (70 Watt)
Curing times	3, 5 and 7 hours

3. Microstructure analysis

3.1 Processes for microstructure analysis (MIP and XRD)

Parameters	Values
Process for curing	Microwave and normal
Percentages of fly ash replacement	0%, 30% and 50%
Target strengths / Slump requirements	420 ksc / 150-175 mm
Percentages of full output power	10% (70 Watt)
Curing times	3, 5 and 7 hours
Total	12 tests

LITERATURE REVIEW

1. Introduction

The strength of concrete is probably the most important overall measure of quality, although other characteristics may also be critical. Strength is an important indicator of quality because strength is directly related to the structure of hardened cement paste. Although, several processes to accelerate the early strength development are still used in many construction industries, such as stream curing process, which operates at atmosphere pressure and lower than 100°C and accelerates cement hydration and makes the curing time shorter, it has a drawback, a great increase in early strength, but the long term strength may deteriorated. A relatively new source of heat, microwave energy is used to accelerate the hydration of ordinary cement to achieve the high early age stage. There are several reasons for interest in microwave processing over conventional processing methods. In microwave process, heat is generated internally within the concrete instead of originally from external heating sources. The investigation of the accelerating hydration by microwave energy may be significant to illustrate the literature of important issues related to the strength development.

This chapter includes hydration reaction, hydration process, factors affecting the rate of hydration, strength development of normal concrete, effect of pozzolans on strength and workability of concrete, pozzolanic reaction, strength development of fly ash concrete, microwave heating mechanism and previous study on microwave curing technique of cementitious materials.

2. Hydration reaction

In the presence of water, the compounds in cement form products of hydration, which in time produce a firm and hard mass called hydrated cement paste. The reaction of 4 main compounds of cement when in contact with water can be written in chemical equations as follows.

Alite : $2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$

Belite : $2C_2S + 4H \rightarrow C_3S_2H_3 + CH$

Aluminate : $C_3A + 6H \rightarrow C_3AH_6$

Ferrite : $C_4AF + 2CH + 10H \rightarrow C_3AH_6 + C_3FH_6$

Where C = CaO, S = SiO_2, H = H_2O, CH = Ca(OH), A = Al_2O_3 and F= Fe_2O_3

The reaction of pure C_3A with water is very violent and leads to immediate stiffening of the paste, known as flash set. Thus, gypsum [$CaSO_4 \cdot 2(H_2O)$] was added to the cement during grinding in order to slow down the reaction. The chemical equation of C_3A with gypsum can be written as follows.

$$C_3A + 3(C\underline{S}H_2) + 26H \rightarrow C_3A \cdot 3C\underline{S} \cdot 32H$$

Where $\underline{S} = SO_3$

3. Hydration process

The chemical reaction is called hydration process, which is an exothermic reaction. The reactions by virtue of which Portland cement becomes a bonding agent-like-place in a water-cement paste and the hardening cement paste accelerate strengthening. The hydration process is classified into stages as follows.

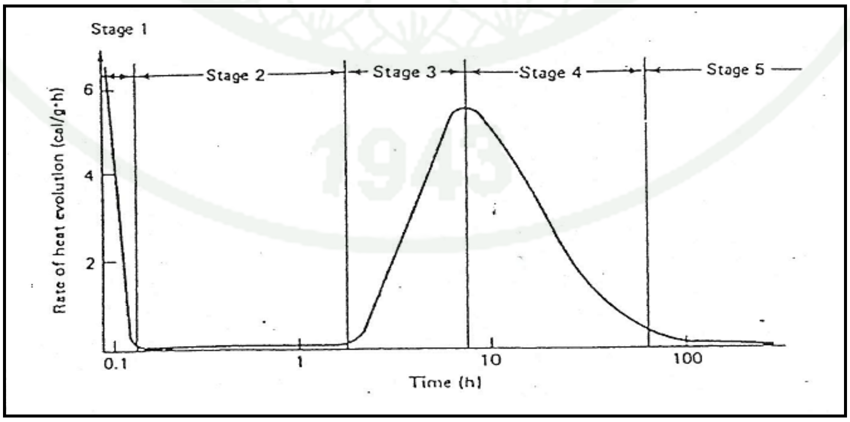

Figure 1 Idealized rate of hydration curve of hydration.

Source: Gartner and Gaidis (1989)

3.1 Initial reaction

The rapid reactions which show the larger rate of heat generation (the first peak) occur for a short time just after the cement comes into contact with water. This heat generation results from the wetting of cement particles and the dissolution of ions in water. Some semi-stable phase of C-S-H is formed and the formation of ettringite is mainly included in this phase.

3.2 Induction or dormant period

The rate of heat generation is too small and the hydration seems to be stagnant. This phase is called dormant period. This phase is brought about by formation of a protective layer on the surface of the cement particles or delaying the nucleation of hydrates. Although the concentration of ions in the solutions becomes gradually higher during this phase according to the solution of solid phase, the hydrates made the main compounds C_3S and C_2S not yet crystallized.

3.3 Acceleration period

The hydration proceeds actively where the rate of heat generation increases. This phase follows the termination of the dormant period that is induced by the increase of permeability of the protection layer and the beginning of the crystallization of the C-S-H.

3.4 Decelerator period

The rate of heat generation becomes gradually slower. In this phase, the thickness of hydrate layer which covers unhydrated particles increases and the surface area of the unhydrated parts are reduced according to the process of hydration. The layer of cement hydrates playing a role in the diffusion area, which governs the permeability of the water and dissolves ions.

3.5 Final slow reaction

This phase follows decelerator period but the rate of hydration is remarkably reduced by the thicker layer of hydrates around particles. The space originally filled by liquid water is almost all occupied by cement hydrates. Then, it becomes difficult for hydrates to be precipitated. Previous and this period are called the diffusion control phases.

4. Factors affecting the rate of hydration

The rate of hydration of Portland cement depends on many factors, and the properties of harden paste depend, to an appreciable extent, on its degree of hydration. Further hydration decreases the porosity of the hardened paste, and thereby its strength increases. The following factors affect the rate of the cement hydration.

4.1 Age of paste

The maximum hydration rate is at early ages, gradually decreasing with time until, at a curtain stage, it stops completely. Hydration continues in the presence of water. The decrease in the hydration rate may be attributed to a formation of a dense layer of C-S-H gel around the cement grains. In the presence of such a layer, further hydration involves the diffusion of water through the layer. The rate of diffusion is controlled by, among other factors, the thickness of layer (the greater thickness), the slower of diffusion and at a certain thickness, diffusion and the resulting hydration will stop completely.

4.2 Cement composition

Selective hydration, which depends on the hydration rate of the individual compounds, takes place only at early stages. C_3A reacts with water almost instantaneously and most of its hydration occurs within 24 hours. On the other hand, C_3S reacts with water rather slowly and its hydration continues for weeks or months. At later stages, however, a layer of C-S-H gel is formed around the cement grains. As the thickness of this layer increases, the rate of hydration becomes increasingly dependent on the rate of water diffusion through the layer and less on the rates of hydration of the individual compounds.

4.3 Fineness of cement

The hydration rate of cement increases with fineness of the cement. The finer the particles, the greater surface area of the cement which is exposed to water and, consequently, the higher rate of hydration, particularly at early ages.

4.4 Water to cement ratio

At early age the w/c ratio hardly affects the rate of hydration. The lower w/c ratio, however, the sooner rate of hydration begins to decrease. Consequently, both the average rate of hydration and the ultimate degree of hydration decrease with decrease in w/c ratio. The affect of the w/c ratio maybe attributed to the decrease in the space available for the hydration products at lower w/c ratio.

In fully compacted concrete, there are some entrapped air voids. At a given age and normal temperature, the strength of concrete can be taken to be inversely proportional to the w/c ratio. It will be recalled that, at a given degree of hydration, the w/c ratio determines the porosity of the cement pastes. Thus the relation of the strength accounts for the influence of the total volume of voids on strength, i.e. gel pores, capillary pores and entrapped air. This statement can also be shown in Figure 2.

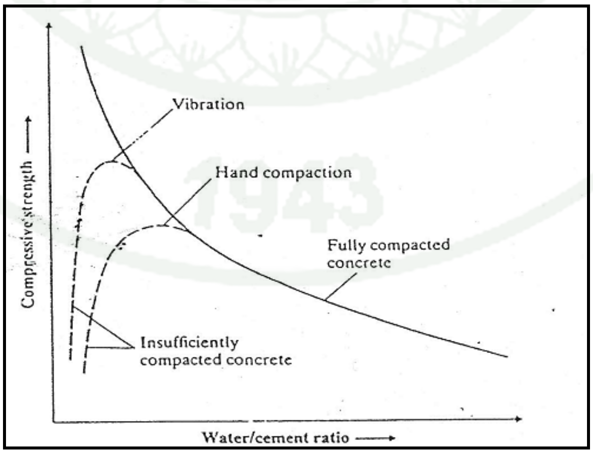

Figure 2 Relation between strength and water to cement ratio of concrete.

Source: Neville and Brooks (1987)

4.5 Temperature

The strength of concrete cured at elevated temperatures is determined by two opposing effects, i.e. concrete strength is increased due to increased hydration and is reduced due to increased porosity an internal cracking. At early stages the effect of increased hydration is predominant, and the strength of concrete is therefore increased. At later stages, however, the rate of hydration decreases, and the adverse effect of increased porosity and internal cracking gradually becomes greater than the beneficial effect of increased hydration. The greater differential thermal expansion of the concrete constituents, the higher temperature causes the expansion of the air entrapped in cement paste, hence this effect may be attributed to increased porosity and possible internal cracking. The rate of heating also affects concrete strength. A higher rate increases thermal stress as a result of an increased temperature gradient between the surface on the concrete and its interior.

4.6 Admixtures

Admixtures based on some materials, which retard the setting of cement, exist, and others accelerate it. These are known as “retarders” and “accelerators”, respectively. The effect of retarders and accelerators does not limit the setting times and, in most cases, the cement rate of hydration is also affected, i.e. the retarders and accelerators generally decrease and increase the rate of hydration, respectively.

5. Strength development of normal concrete

Curing is used to promote the hydration rate of cement, and the development of strength of concrete. The curing procedures include control of temperature and of the moisture movement from and into the concrete. Under similar conditions, the properties of concrete are determined by the degree of hydration. The porosity of the concrete decreases as hydration proceeds, and its quality is therefore improved. Hydration is conditional on the presence of moisture, and such presence can be maintained by adequate treatment of the finished concrete. Normal curing can be affected by immersion of the concrete in water or by intermittent and systematic wetting. During hydration of the cement some of the water present in the paste becomes chemically combined, and in a closed system the water content of the paste is thus decreased, i.e. self desiccation occurs.

The curing affects concrete strength through its effect on the rate of hydration, which in turn, is related to the availability of free water. As presented in Figure 2.3, it can be seen that, up to an age of about three days, strength development in concrete allowed to dry is the same as that of the water cured concrete. However, beyond this age the strength difference between the two concretes becomes noticeable, and whereas strength development in the concrete allowed to dry stops at an age of about 14 days, strength development in the water cured concrete continues to an age of 180 days. At this age the strength of the water cured concrete is about 2.5 times greater than the strength of its air cured counterpart.

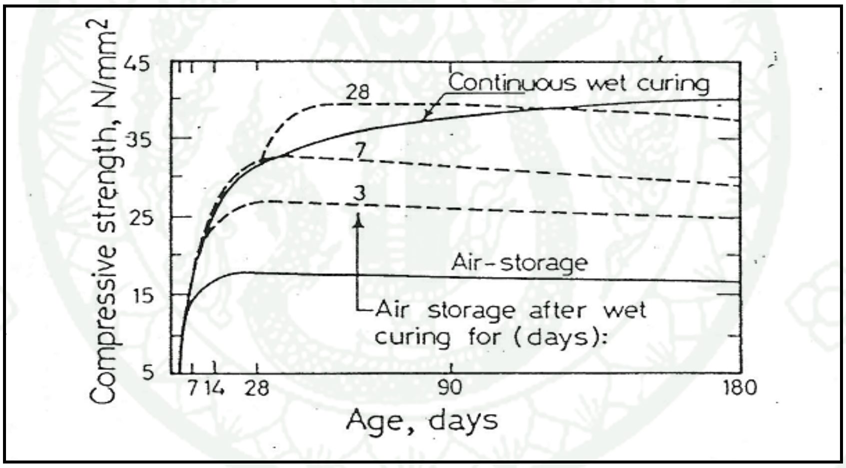

Figure 3 Effect of curing on concrete strength (w/c = 0.5).

Source: Price (1951)

6. Effect of pozzolans on strength and workability of concrete

Pozzolans are defined as siliceous or siliceous and aluminous materials, which in it possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. The pozzolans combine with free calcium hydroxide, which is formed during hydration of alite and belite. It is essential that pozzolan be in a finely divided state as it is only then that silica can combine with calcium hydroxide (liberated by hydrating Portland cement) in the presence of water to form stable calcium silicates which have cementitious properties. The pozzolanic materials can be natural in origin or artificial. The main artificial pozzolanic material, fly ash which is known also as pulverized fuel ash, is the ash precipitated electro-statically or mechanically from the exhaust gases of coal fired power stations.

Most fly ash materials are composed of spherical particles with smooth surfaces and have a very high fineness. Lane (1983) summarized the effect of fly ash on freshly mixed concrete is that the water requirement for given consistency could be reduced.

Portland pozzolan cement gains strength slowly and therefore requires curing over a comparatively long period, but the long term strength is high as in Figure 4, which shows similar behavior occurs where the pozzolan replaces part of cement, but the long tern strength depends on the level of replacement.

7. Pozzolanic reaction

The pozzolanic reaction produces additional calcium silicate hydrate, which contributes to the strength development from the reaction between relative silica in fly ash and calcium hydroxide liberated from the hydration reaction. For pure materials, the reaction can be represented by the simplified equation.

$$3CH + 2S \rightarrow C_3S_2H_3$$

Where CH = Ca(OH), S = SiO_2, C = CaO and H = H_2O

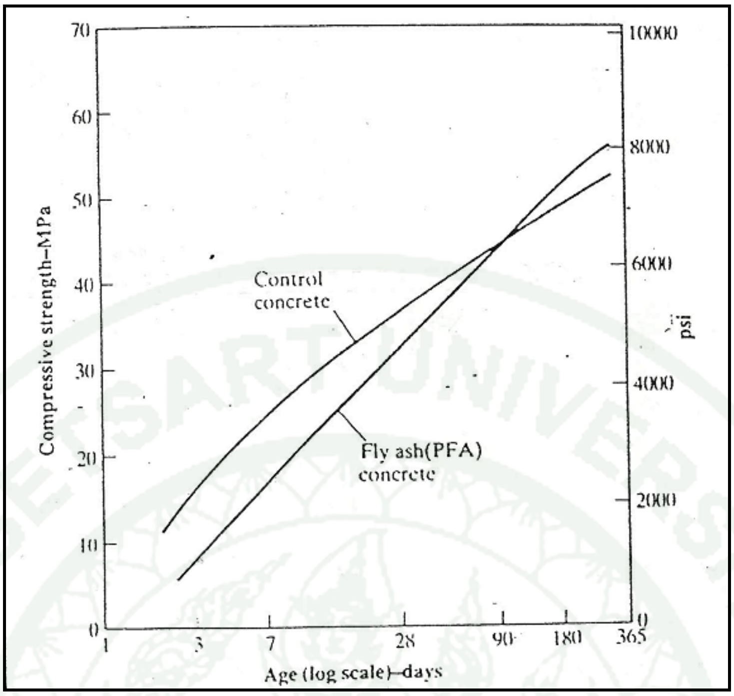

Figure 4 Typical relative rates of strength development of Portland cement (control) concrete and concrete with fly ash replacement.

Source: Neville and Brooks (1987)

The additional produced calcium silicate hydrates contribute directly to the strength development. According to Watt and Thorne (1965, 1966), after curing time of 365 days or more, the strength correlated most closely with the SiO_2 or (SiO_2 + Al_2O_3) content of the ash. This finding was interpreted that the long term pozzolanic activities depended mainly on the amount of material present that was able to react with lime, and did not react with the glass varied in composition.

According to Helmuth (1987), the amount of fly ash required to react completely with the calcium hydroxide produced by hydration of Portland cement-pozzolanic mixtures maybe estimated. At complete hydration, ordinary Portland cement yields about 0.20 kg of $Ca(OH)_2$ / kg of cement. He assumed the same fly ash composition as in the reaction with lime (50% SiO_2 and 30% Al_2O_3). The amount of fly ash required for complete reaction is calculated to be 0.29 kg of fly ash / 1 kg of cement, i.e., 22% fly ash content (0.29 kg fly ash / 1.29 kg cementitious material). This estimation is based on cement hydration as shown in section 3 and reaction of calcium hydroxide with fly ash to produce C-S-H with a C to S ratio of 1.0. However, assuming instead that the cement also hydrates to the low lime products, complete reaction is obtained with 0.5 kg of fly ash / 1 kg of cement, or 33% fly ash content (0.5 kg fly ash / 1.50 kg cementitious material).

These two proportions (22% and 33% fly ash) are the proportional specified in ASTM C311 for the pozzolanic activity index with Portland cement, which specified that 35% of volume of the Portland cement be replaced with an equal volume of pozzolan. For a fly ash specific gravity of 2.5, this is equivalent to 0.43 kg of fly ash / 1 kg of cement, or very nearly 30% fly ash content.

8. Strength development of fly ash concrete

8.1 Setting time

Samarin and Ryan (1975) compared the performance of normal concrete with concrete containing fly ash and reported that the setting time of concrete usually increases when fly ash is induced, typically of about 1 or 2 hours.

In addition, Dodson (1981) explained that the extended setting time is due to the increment of water to Portland cement ratio, even if the water demand of concrete, when mixed with fly ash, is increased. This is because the cement content is reduced due to the replacement with fly ash.

Moreover, Majko and Pistilli (1984) found that the extension of setting time is even further increased for fly ash concrete mixture containing ASTM type A water-reducing admixture and very high fly ash contents.

8.2 Early strength

Early strength development of fly ash concrete will relate directly to the hydration as well as pozzolanic reaction. Several works of Ogawa et al. (1980) and Kokubu (1984) have reported that the early hydration of C_3S was retarded with the presence of fly ash. Jawed and Skalny (1981) suggested that this retardation be a result of the following.

1) Chemisorption of some Ca^{2+} ions on the fly ash particles, which reduced Ca^{2+} concentration and delayed nucleation of calcium hydroxide.

2) The poisoning effect of soluble silicate and aluminate species on nucleation and crystal growth of calcium hydroxide and calcium silicate hydrate.

In addition, many studies have shown that C_3A hydration is also retarded by fly ash. Plowman and Cabrera (1981) have shown that sulfate was released much more rapidly into solution from a class F fly ash containing 1.25% SO_3 than from solid gypsum (of unspecified fineness) and that the hydration rates of C_3A were controlled much more effectively than with that gypsum.

8.3 Long term strength

The long term strength development is developed upon the contribution of additional calcium silicate hydrate produced by the pozzolanic reaction of Portland cement. With respect to the rate of reaction, many studies have indicated that the pozzolanic reactions begin very slowly and that only after curing for several weeks does substantial reaction occur.

Using 28-day strength as reference, Lane and Best (1982) reported strength increases of 50% at one year for fly ash concrete as compared with 30% for concrete without fly ash.

8.4 Conventional thermal curing to accelerate strength of fly ash concrete

According to Valore (1970) with tests of strength at various ages of mortar cubes at both ordinary temperatures and after stream curing and autoclaving often show pronounced maximal at particular pozzolan percentages (typically 40% pozzolan). These effects are more pronounced in the mortar than in concrete. It has been explained that higher temperature during and following the initial contact between cement and water reduces the length of the dormant period so that the overall structure of the hydrate cement paste becomes established very early.

March *et al*. (1986) reported that the higher temperature, between 20 and 80ºC accelerated the reaction of fly ash to a greater extent than in the case of alone Portland cement, however the usual retrogression of strength follows. The reduction in strength with an increase in temperature between 200 and 800ºC is also similar to, or possibly even greater than, that in concrete made with Portland cement only confirmed by Papayianni and Valiasis (1991).

The retrogression on long term strength was explained by Neville (1995) that a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a proportion of the pores will always remain unfilled. It follows from the gel/space ratio rule that this will lead to a lower strength compared with the less porous, though slowly hydrating, cement paste in which a high gel/space ratio will eventually be reached.

The explanation of the adverse effects of a high early temperature on later strength has been extended by Verbeck and Helmuth (1986), who suggested that the rapid initial rate of hydration at higher temperatures retard the subsequent hydration and produce a non-uniform distribution of the products of hydration within the paste. The reason for this is that, at the high initial rate of hydration, there is insufficient time available for the diffusion of the products of hydration away from the cement paste and for a uniform precipitation in the interstitial space (as is the case at lower temperatures). As a result, a higher concentration of the products of hydration is built up in the vicinity of the hydrating particles, and this retards the subsequent hydration and adversely affects the long term strength.

In addition, the non-uniform distribution of the products of hydration adversely affects strength because the gel/space ratio in the interstices is lower than would be otherwise the case for an equal degree of hydration. The local weaker areas lower the strength of the hydration cement paste as a whole.

Further, these curing methods rely on the thermal conductivity of the specimen, with heat flowing from the exterior to interior. That mean the large material will slow heat penetration to the interior. Consequently, long time curing is required and may lead to thermal cracking due to a non-uniform through the material.

9. Microwave heating mechanism

Microwave energy is a form of electromagnetic radiation energy that has a frequency range from 0.3 to 300 GHz with the wave length of 1 mm to 1 m. The electrical power is converted to heat that involves direct absorption of energy by the materials. The penetration of the electrical energy that penetrates through the surface of the sample is uniform. Therefore, the distribution of heat through the material is uniform and the temperature distribution is evenly. The electromagnetic wave propagation in a material is dependent on the electromagnetic properties of that material. The degree of interaction or absorption of microwave by the dielectric materials (nonmetallic), such as concrete and water, is related to the two independent electromagnetic properties, first, the material's complex permittivity ε^* (Farad/meter) and second, the complex (magnetic) permeability μ^*. In general, the independent measurements are necessary to establish the quantities of both real and imaginary part of ε^* and μ^*. However, most common dielectric materials including concrete are nonmagnetic, making a permeability μ^* very close to the permeability of free space ($\mu_0 = 4\pi\times10^{-7}$ Henry/meter). So, the focus of the discussion is on the complex permittivity ε^*, which is composed of a real part (ε', dielectric constant) and imaginary part (ε'', dielectric loss factor) by

$$\varepsilon^* = \varepsilon'' - j\varepsilon'$$

$$\varepsilon^* = \varepsilon_0(\varepsilon_r' - j\varepsilon_r'')$$

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''$$

Where $j = \sqrt{-1}$

ε_r^* = relative complex permittivity

ε_r' = the real part of relative complex permittivity

ε_r'' = the imaginary part of relative complex permittivity

ε_0 = permittivity in free space = 8.54×10^{-12} Farad/meter

The real part of relative complex permittivity, ε_r', is a measure of how much energy from an external electric field is stored in a material and is >1 for most solids and liquids. The imaginary part of relative complex permittivity, ε_r'', is a measure of how dissipative or loss a material is to an external electric field and is always >0 and usually much smaller than ε_r' for dielectric materials.

When microwave penetrates and propagates through a dielectric material, the internal electric fields generating within the affected volume induce translational motions of free or bound charges (e.g. electron or ions) and rotate charge complexes such as dipoles, which are composed of polar molecules with positive and negative poles. The vibration of polar molecules and dipoles attenuates microwave radiation and the resulting friction between molecules generates heat rapidly through the materials. It is necessary to overcome the resistance of the molecular motion and attraction, as when friction generates heat, the temperature of material is evaluated. The resistance of these induced motions due to initial, elastic and friction forces, which are frequency dependent, causes losses and attenuates the electric field. As a consequence of these losses, volumetric heating results, for convenience, the loss mechanism are all combined together in the one loss parameter, ε_r''. However, the loss tangent (tanδ) is commonly used to describe these losses as the ratio of the energy lost to the energy stored in a material. In dielectric materials, energy losses as a consequence of current conduction or dielectric hysteresis effect

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'}$$

where tanδ = loss tangent

When the dielectric losses occur as a result of conduction currents through the dielectric, the equivalent conductivity, σ, is related to the imaginary part, ε″, of the complex permittivity.

$$\sigma = \varepsilon''\omega$$

$$\tan\delta = \frac{\sigma}{2\pi f \varepsilon_0 \varepsilon_r'}$$

where σ = total effective conductivity (mho/meter)

ω = angular frequency (rad/sec)

f = frequency (Hz)

It is important to note that these electromagnetic properties are not constant. They change with frequency, moisture, temperature and mixture of material. In what follows, the electromagnetic properties of concrete measured over the frequency range from 0.1 to 18 GHz are presented.

The increased in strength due to the microwave curing is attributed to

1) Microwave heating is the internal heat dissipation associated with the excitation of molecular dipoles in electromagnetic field heating and allows faster heating rate and more uniform heating differentiated to the conventional heating techniques. A short period of heating is therefore sufficient to obtain high early strength and increases the rate of hydration for the first 24 hours compared to specimens cured at 20ºC.

2) Before the setting of concrete, microwave is attributed to removal of water from the fresh concrete which causes collapse of the capillary pores then concrete densification occur. Part of the free water is quickly moved from the fresh mixed concrete prior to the setting of cement, causing so-called plastic shrinkage which is irreversible and consistent with the reduction of capillary voids, leading to a denser concrete and can increase the later age strength.

10. Effect of microwave on steel reinforcement

Since precast components may be reinforced and steel meshes or dowel bars are commonly used in pavements, the effect of microwave on steel is an important issue to be considered. Steel, like other metals, generally reflects most of the microwave energy reaching its surface. However, energy dissipation does take place in a thin surface layer with thickness of the order of 1 to 10 μm. The heat generated by the microwave energy will then be conducted to the interior of the metal. For thick steel components or large steel bars, the heat generated on the surface is not enough to significantly heat up the component. However, for thin or small steel pieces with very sharp edges to concentrate electromagnetic fields, the whole piece can heat up rapidly. This explains the glowing of sharp edged metallic wires left accidentally in a domestic microwave oven. At Cober Electronics (a manufacturer of laboratory microwave ovens), steel rods exceeding 3.175 mm (l/8 in) in size should be large enough to act essentially as a reflector of 2.45 GHz microwave. Indeed, our microwave oven is supplied with a temperature probe that has a steel sheath 3.175 mm in diameter. The probe never heats up on its own in the oven. Therefore, common reinforcements larger than 3.175 mm should not heat up when subject to microwave energy. However, special attention has to be paid when steel reinforcements are closely spaced or when meshes with small holes are employed. Such reinforcements may be so effective in reflecting microwave energy that concrete below them cannot be properly cured. To assess such a shielding effect, numerical simulations of microwave power reflection and dissipation based on finite difference time domain (FDTD) techniques can again be employed.

11. Previous study on microwave curing technique of cementitious materials

Watson (1968) showed in pioneering work that 28-day compressive strength of microwave cured specimens displayed only half of the strength of normally cured specimen. However, this may result from the internal temperature of specimens reaching 90ºC was reached at which cracks could be generated.

Wu *et al*. (1987) applied microwave energy only 15 to 30 minutes. The increment of strength at 3 days was as high as 50% as the improvement in the rate of strength development. The strength of 28 days was still 5% higher. The microwave heating application will not deteriorate the strength at later age.

Hutchison et al. (1991) observed the strength of microwave cured specimens was found to be slightly higher than that of the conventionally cured specimens at 1, 7 and 28 days. Also, the degree of hydration was measured at 1, 3 and 9 hours and 1, 7 and 42 days. The results showed no significant effect of microwave on the compressive strength. The lack of significant strength increase at the early age of one day is probably due to the application of low microwave power in the experiment.

Pera *et al*. (1992) investigated the microwave power for 90 to 120 minutes to accelerate the curing of glass fiber reinforced cement composite. The result of flexural strength reached up to 90% in 24 hours compared to 28-day strength, while without microwave application it only reached 25% to 30%, and the microwave cured concrete slightly reduced the 28-day strength about 5%. The process is therefore also effective in improving the stability of the glass fibers.

Li and Wu (1994) studied the application of vacuum microwave composite dewatering technique in concrete and showed the hydration rate of concrete was increased during the process. The compressive strength was the highest by using microwave curing time at 45 minutes with w/c of 0.38. In terms of economics, the amount of cement content could be saved by 15% with no great effect on the properties of concrete.

Leung and Pheeraphan (1995) explained the phenomena after applying 45 minutes with microwave energy to mortar and concrete with Type I and III cement. Various parameters including power level, w/c ratio of 0.40-0.55 and application time after mixing were studied also. After applying the microwave energy, water was removed from the fresh concrete when still in plastic stage. The experiment has shown that it is possible to achieve high early strength with little or no deterioration in long term.

Leung and Pheeraphan (1997) investigated the optimal processes, which provide high strength at early and long term. They found that specimen temperature during the curing process controlled the important parameter. The feedback temperature control or approximated discrete power level was applied to reduce the overheating during application. Comparison of the results with the use of fixed power, using the variable discrete power, can provide better combination of very high early age strength (4.5 hours) with no deterioration in later age strength (7 days) and with 20% less energy consumption.

Sohn and Johnson (1999) applied microwave energy to the cementitous materials with and without pozzolanic materials. Type I Portland cement mortars, such as slag, silica fume or class F fly ash, were cured with feedback temperature controlled at 40, 60 and 80ºC. The delay time 30 minutes after mixing was used. The feedback control temperature at 40ºC was the same, but at 60 and 80ºC reached the compressive strength at 28 days about 80% and 50% of normal curing. The penetration test was introduced to investigate the possibility of less strength degradation. Three levels of them, 1, 5 and 13 Mpa., were chosen to establish the heating time. The results showed that 13 Mpa.(or 120 minutes) at 40ºC and 1 Mpa.(or 48 minutes) at 60ºC were the maximum times for which 28-day compressive strength was not degraded with and without pozzolanic materials.

Damangas (1999) predicted the long term strength of type I and type III concrete with water reducer by using early age strength of microwave cured concrete at 45 minutes after mixing and 45 minutes of heating duration. The average 3.5 hours early age strength of type III concrete was about 40% compared to the 7-day normally cured strength with an estimated percentage of errors 5%. For the case by using type I concrete, the 5.5 hours early age average strength was about 35% of 14-day strength with 7% errors of estimated and about 29% of 28-day strength with 12% of error of estimated.

Cayliani (2000) employed the optimum process of microwave cured concrete strength to predict the long term compressive strength of normal cured concrete with and without superplasticizer agent. Compressive strength was measured to establish the relationship between early age (5-10 hours) accelerated strength and later age (14 and 28 days) in different mix proportions. The temperature of specimens was measured for 24 hours to understand the temperature history on the strength development. The delay time is 30 minutes and several levels of microwave power for 45 minutes were applied. The results can affirm that the prediction is possible by using the appropriate microwave power level and early age test time by considering the second peak of temperature curve.

Wachirathamrojn (2001) predicted the 28-day strength of normal concrete containing Mae-Moh fly ash 0%, 10%, 20% and 30% by weight. The optimal microwave curing process was determined first. Then, the compressive strength of 3"×6" specimens with various mix proportions were tested at 6.5 hours early age for microwave cured specimens. From the equations, the prediction is reasonably accurate yielding the average and maximum percentage of error at 5 and 12.

Aneksrup (2001) predicted the 28-day strength of normal concrete with and without superplasticizer, accelerator and retarder by using early age strength of microwave cured concrete. The optimal power is the combination of 259 Watts for 30 minutes and 197 Watts for 15 minutes. The penetration resistance level at 3.45 Mpa. of sieved mortar was determined for delay time. The rest time of 3.5 hours was determined by considering the second peak of temperature curve. Based on the established equation, the prediction yielded the average and maximum percentage of error at 6 and 11.

Pheeraphan *et al*. (2002) predicted the later age compressive strength of normal concrete, made with rapid-hardening and ordinary Portland cement, based on the accelerated strength of concrete cured with microwave energy. To accelerate curing properly, the optimal microwave curing process for concrete was first determined and then was applied to concrete. The possible early ages for the strength prediction were found to be at 3.5 and 5.5 h for concrete made with rapid-hardening and ordinary Portland cement, respectively. Predictions of strength at 7 days for concrete made with rapid hardening Portland cement and 28 days of concrete made with ordinary Portland cement were within 15% agreement with actual test results.

Roekattakarn (2003) predicted the later age strength,at 28,56 and 91 days, of normal concrete with fly ash 0%, 20%, 30% and 40% by comparing with early age strength with microwave curing technique. The optimal power is the combination of 356 Watts for 15 minutes and 234 Watts for 30 minutes. Delay time of 30 minutes and the rest time of 4.25 hours were determined. From the relationships, prediction yielded the maximum of error at 8% and 11%.

Rattanadecho *et al*. (2007) investigated the acceleration of cement paste curing with microwave energy by using continuous belt drier. The microwave power was generated by means of 14 compressed air-cooled magnetrons of 800W each for a maximum of 11.2kW. The power setting could be adjusted individually in 800W steps. This study included the heat transfer analysis taking place during the curing of cement paste with microwave energy and the compressive strength development of cement paste. The growth rate of compressive strength of 30min-cured and water-to-cement ratio of 0.4 microwave-cured mortar after 3 days was 103% while 101 and 95% for specimens at the ages of 7 and 28 days.

Lee *et al*. (2007) studied the effects of microwave curing on the strength development and permeability of concrete. Four microwave curing times and four types of concrete mix were used in this study. The test results indicated that microwave heating could further increase the compressive strength of mortar and concrete with 10% silica fume added responded. The strength gain development of mortar and concrete appeared to level off after 40 minutes of microwave curing. Thus, a 40-minute microwave heating time appeared to be the optimal time. The microwave-cured concrete did not show an increase in permeability relative to the concrete, but showed an increase in strength. Thus, microwave heating may be a potentially attractive method for accelerating cement hydration.

MATERIALS AND METHODS

Materials

1. Determination of material properties

In this study, the materials used for making the specimens were

1.1 Ordinary Portland Cement Type I, TPI brand

1.2 Fly ash, Mae-Moh source

1.3 Natural construction sand, as fine aggregate

1.4 Crushed limestone with the maximum size of 4.75 mm, as coarse aggregate

1.5 Tap water

The materials were used after determining their physical properties and chemical compositions. ASTM standard were needed for the tests, the corresponding testing standards are summarized and shown in Table 1.

Table 1 Standard tests for physical properties and chemical compositions of materials.

Type of tests	ASTM standard
Ordinary Portland Cement	
Specific gravity	ASTM C188-95
Chemical composition	ASTM C150-02 & ASTM C144-00
Pulvarized fly ash	
Specific gravity	ASTM C188-95
Chemical composition	ASTM C618-01 & ASTM C311-0

Table 1 (Continued)

Type of tests	ASTM standard
Fine aggregate	
Fineness modulus	ASTM C33-02 & ASTM C136-01
Specific gravity and absorption test	ASTM C128-01
Coarse aggregate	
Unit weight	ASTM C29/C29M–97
Specific gravity and absorption test	ASTM C127–01

2. Material properties

The materials in this study were Ordinary Portland Cement Type I (TPI brand), Mae-Moh fly ash, natural construction sand and crushed limestone with maximum size of 4.75 mm. The procedures to determination of material properties were tested according to ASTM standard. The results of laboratory testing are shown in the Appendix Table 1 and the material properties that were used throughout this investigation can be presented.

2.1 Cement and fly ash

Physical properties and chemical compositions of Ordinary Portland Cement Type I and fly ash were examined according to ASTM standard (see Table 1) and shown in Table 2.

Generally, the amount of pozzolanic activity of fly ash is related to the amount of SiO_2 , Al_2O_3 and Fe_2O_3. According to ASTM C618-01 standard, the total amount of these oxides should not be less than 70% for pozzolanic class N and F, and not be less than 50% for pozzolanic class C. Mae-Moh fly ash, which was used in this study, shows the chemical requirement for class C of pozzolan.

Table 2 Physical properties and chemical compositions of Ordinary Portland Cement Type I and Mae-Moh fly ash.

Physical properties	OPC Type I	Fly ash
Specific gravity	3.15	2.38
Chemical compositions		
SiO_2	20.10	66.07
Al_2O_3	5.03	22.68
Fe_2O_3	3.55	3.28
CaO	65.45	1.23
MgO	1.00	0.57
SO_3	1.94	0.21
Na_2O	< 0.01	0.33
K_2O	0.53	0.94
TiO_2	0.24	1.30
P_2O_5	0.56	0.31
Moisture content	-	0.11
Loss on ignition	2.09	2.61

2.2 Aggregates

Natural construction sand and crushed limestone with maximum size of 4.75 mm were used as fine and coarse aggregate respectively. According to ASTM C33-02 standard, the gradation of the fine aggregate should be between 2.3 to 3.1. The fineness modulus for fine aggregate was tested and shown in Table 3.

The physical properties of fine and coarse aggregate were examined according to ASTM standard (see Table 1) and shown in Table 3 to 4 and Appendix Table 1.

Table 3 Sleeve analysis of fine aggregate for determining fineness modulus.

Sieve No.	Cumulative retained weight (g)	Percent cumulative retained	Percent passing	Percent passing ASTM C 33-02
3/8 in. (9.50 mm)	0.3	0	100	100
No.4 (4.75 mm)	157.7	0.02	99.98	95-100
No.8 (2.36 mm)	468.4	10.29	89.71	80-100
No.16 (1.18 mm)	909.3	30.58	69.42	50-85
No.30 (0.60 mm)	1359.9	59.36	40.64	25-60
No.50 (0.30 mm)	1510.5	88.77	11.23	5-30
No.100 (0.15 mm)	1531.9	98.60	1.40	0-10
Pan (0.00 mm)	1531.9	-	-	-
Total		287.62		
Fineness modulus		2.88		

Table 4 Physical properties of fine and coarse aggregate.

Physical properties	fine aggregate	coarse aggregate
Unit weight (kg/m^3)	-	1,385
Specific gravity	2.40	2.68
Absorption (%)	1.42	0.98

3. Mix design

The required slumps of 25-50 and 150-175 mm, the target compressive strengths of 280 and 420 ksc at 28 days and the water to cementitous ratios of 0.411 and 0.606 were used for designing the mix proportions of normal concrete containing fly ash, 0%, 30% and 50% by weight of cement, according to ACI 211.1-91. The details for mix proportions and slump result, according to ASTM C143, are shown in Table 5.

Table 5 Mix proportion for compressive strength investigation and estimation.

Mix No.	W/B	F/B	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Slump (cm)
1-6	0.606	0.00	267.00	440.59	0.00	423.81	950.79	17
7-12	0.606	0.30	267.00	308.42	132.18	423.81	918.00	22
13-18	0.606	0.50	267.00	220.30	220.30	423.81	896.14	27
19-24	0.606	0.00	220.00	363.04	0.00	423.81	1122.33	5
25-30	0.606	0.30	220.00	254.13	108.91	423.81	1095.31	11
31-36	0.606	0.50	220.00	181.52	181.52	423.81	1077.29	16
37-42	0.411	0.00	267.00	649.64	0.00	423.81	791.86	15
43-48	0.411	0.30	267.00	454.74	194.89	423.81	743.50	19
49-54	0.411	0.50	267.00	324.82	324.82	423.81	711.27	23
55-50	0.411	0.00	220.00	535.28	0.00	423.81	991.37	4
61-66	0.411	0.30	220.00	374.70	160.58	423.81	951.53	10
67-72	0.411	0.50	220.00	267.64	267.64	423.81	924.96	15

Remark: W = water, B = binder and F = fly ash

4. Equipment in experimental program

4.1 Microwave oven (LG brand) model MS-2029UW, as shown in Figure 5, with 700 Watt of full output power and 5 power levels was used.

4.2 Compressive strength test machine model ELE autotest 3000, as shown in Figure 6 and 7.

4.3 Vibration table, as shown in Figure 8.

Figure 5 Microwave oven, LG brand model MS-2029UW.

Figure 6 ELE autotest 3000 machine for compressive strength test.

Figure 7 Specimen during testing.

Figure 8 Vibration table.

Methods

1. Compressive strength investigation

To investigate the compressive strength of microwave cured specimen, 1"×2" cylindrical specimen of normal concrete containing fly ash 0%, 30% and 50% by weight of cement with target strengths of 280 and 420 ksc and slumps of 25-50 and 150-175 mm were used.

Microwave power output at 70 Watt (10% of maximum power at 700 Watt) was applied to specimens in polypropylene (PP) mould with the duration of applications of 3, 5 and 7 hours. In each case, the early compressive strength at 1 day was tested. The I day period included 60 minutes before microwave application (casting time) and 60 minutes before compressive strength test. The processes for compressive strength test are summarized and shown in Table 6.

For each mix proportion and process, twelve specimens were cast in PP moulds for each batch. To control the relative humidity during microwave application, PP cap and plastic wrap were used at top and bottom for covering specimens, as shown in Figure 9. Then, the specimens were placed in a PP container with full of water in it before placed in microwave oven. 60 minutes after water was added, nine of them were cured with microwave energy while the others were cured normally.

After microwave curing processes, each mould was removed from the cavity to continue the curing process with careful prevention of thermal shock. 60 minutes before the compression test, nine microwave cured specimens were removed from their moulds to measure the early strength at 1 day. For long term strength tests of normal cured specimens, the specimens were removed from their moulds after 1 day and cured in water at room temperature until testing time at 7, 28 and 63 days.

Figure 9 Specimen preparation before microwave curing.

Table 6 Processes for compressive strength investigation.

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)
1	280	150-175	0.606	0.00	70	3	1
2	280	150-175	0.606	0.00	70	5	1
3	280	150-175	0.606	0.00	70	7	1
4	280	150-175	0.606	0.00	-	-	7
5	280	150-175	0.606	0.00	-	-	28
6	280	150-175	0.606	0.00	-	-	63
7	280	150-175	0.606	0.30	70	3	1
8	280	150-175	0.606	0.30	70	5	1
9	280	150-175	0.606	0.30	70	7	1
10	280	150-175	0.606	0.30	-	-	7
11	280	150-175	0.606	0.30	-	-	28
12	280	150-175	0.606	0.30	-	-	63
13	280	150-175	0.606	0.50	70	3	1
14	280	150-175	0.606	0.50	70	5	1
15	280	150-175	0.606	0.50	70	7	1
16	280	150-175	0.606	0.50	-	-	7
17	280	150-175	0.606	0.50	-	-	28
18	280	150-175	0.606	0.50	-	-	63

Table 6 (Continued)

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)
19	280	25-50	0.606	0.00	70	3	1
20	280	25-50	0.606	0.00	70	5	1
21	280	25-50	0.606	0.00	70	7	1
22	280	25-50	0.606	0.00	-	-	7
23	280	25-50	0.606	0.00	-	-	28
24	280	25-50	0.606	0.00	-	-	63
25	280	25-50	0.606	0.30	70	3	1
26	280	25-50	0.606	0.30	70	5	1
27	280	25-50	0.606	0.30	70	7	1
28	280	25-50	0.606	0.30	-	-	7
29	280	25-50	0.606	0.30	-	-	28
30	280	25-50	0.606	0.30	-	-	63
31	280	25-50	0.606	0.50	70	3	1
32	280	25-50	0.606	0.50	70	5	1
33	280	25-50	0.606	0.50	70	7	1
34	280	25-50	0.606	0.50	-	-	7
35	280	25-50	0.606	0.50	-	-	28
36	280	25-50	0.606	0.50	-	-	63
37	420	150-175	0.411	0.00	70	3	1
38	420	150-175	0.411	0.00	70	5	1
39	420	150-175	0.411	0.00	70	7	1
40	420	150-175	0.411	0.00	-	-	7
41	420	150-175	0.411	0.00	-	-	28
42	420	150-175	0.411	0.00	-	-	63
43	420	150-175	0.411	0.30	70	3	1
44	420	150-175	0.411	0.30	70	5	1
45	420	150-175	0.411	0.30	70	7	1
46	420	150-175	0.411	0.30	-	-	7
47	420	150-175	0.411	0.30	-	-	28
48	420	150-175	0.411	0.30	-	-	63

Table 6 (Continued)

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)
49	420	150-175	0.411	0.50	70	3	1
50	420	150-175	0.411	0.50	70	5	1
51	420	150-175	0.411	0.50	70	7	1
52	420	150-175	0.411	0.50	-	-	7
53	420	150-175	0.411	0.50	-	-	28
54	420	150-175	0.411	0.50	-	-	63
55	420	25-50	0.411	0.00	70	3	1
56	420	25-50	0.411	0.00	70	5	1
57	420	25-50	0.411	0.00	70	7	1
58	420	25-50	0.411	0.00	-	-	7
59	420	25-50	0.411	0.00	-	-	28
60	420	25-50	0.411	0.00	-	-	63
61	420	25-50	0.411	0.30	70	3	1
62	420	25-50	0.411	0.30	70	5	1
63	420	25-50	0.411	0.30	70	7	1
64	420	25-50	0.411	0.30	-	-	7
65	420	25-50	0.411	0.30	-	-	28
66	420	25-50	0.411	0.30	-	-	63
67	420	25-50	0.411	0.50	70	3	1
68	420	25-50	0.411	0.50	70	5	1
69	420	25-50	0.411	0.50	70	7	1
70	420	25-50	0.411	0.50	-	-	7
71	420	25-50	0.411	0.50	-	-	28
72	420	25-50	0.411	0.50	-	-	63

2. Estimation

To estimate the 28-day compressive strength, twelve mix proportions were used (25-50 and 150-175 mm slumps, 280 and 420 ksc target strengths and fly ash replacement at 0%, 30% and 50% by weight of cement). Three microwave curing times of 3, 5 and 7 hours were used and the microwave power was set at 70 Watt. The processes for compressive strength estimation at 28 days are summarized and shown in Table 7.

To find the formula for estimation of long term compressive strength at 28 days, the relationship between the accelerated early age strength of microwave curing processes with application times of 3, 5 and 7 hours at 1 day and the long term compressive strength of normal curing at 28 days was established to derive a formula for the compressive strength estimation.

Table 7 Processes for compressive strength estimation.

Mix No.	Target Strength (ksc)	Slump (mm)	W/B	F/B	Power Level (Watt)	Heating Time (hours)	Test Time (day)
1	280	150-175	0.606	0.00	70	3	1
2	280	150-175	0.606	0.00	70	5	1
3	280	150-175	0.606	0.00	70	7	1
5	280	150-175	0.606	0.00	-	-	28
7	280	150-175	0.606	0.30	70	3	1
8	280	150-175	0.606	0.30	70	5	1
9	280	150-175	0.606	0.30	70	7	1
11	280	150-175	0.606	0.30	-	-	28
13	280	150-175	0.606	0.50	70	3	1
14	280	150-175	0.606	0.50	70	5	1
15	280	150-175	0.606	0.50	70	7	1
17	280	150-175	0.606	0.50	-	-	28
19	280	25-50	0.606	0.00	70	3	1
20	280	25-50	0.606	0.00	70	5	1
21	280	25-50	0.606	0.00	70	7	1
23	280	25-50	0.606	0.00	-	-	28
25	280	25-50	0.606	0.30	70	3	1
26	280	25-50	0.606	0.30	70	5	1
27	280	25-50	0.606	0.30	70	7	1
29	280	25-50	0.606	0.30	-	-	28

Table 7 (Continued)

Mix No.	Target Strength (ksc)	Slump (mm)	W/B	F/B	Power Level (Watt)	Heating Time (hours)	Test Time (day)
31	280	25-50	0.606	0.50	70	3	1
32	280	25-50	0.606	0.50	70	5	1
33	280	25-50	0.606	0.50	70	7	1
35	280	25-50	0.606	0.50	-	-	28
37	420	150-175	0.411	0.00	70	3	1
38	420	150-175	0.411	0.00	70	5	1
39	420	150-175	0.411	0.00	70	7	1
41	420	150-175	0.411	0.00	-	-	28
31	280	25-50	0.606	0.50	70	3	1
32	280	25-50	0.606	0.50	70	5	1
33	280	25-50	0.606	0.50	70	7	1
35	280	25-50	0.606	0.50	-	-	28
37	420	150-175	0.411	0.00	70	3	1
38	420	150-175	0.411	0.00	70	5	1
39	420	150-175	0.411	0.00	70	7	1
41	420	150-175	0.411	0.00	-	-	28
43	420	150-175	0.411	0.30	70	3	1
44	420	150-175	0.411	0.30	70	5	1
45	420	150-175	0.411	0.30	70	7	1
47	420	150-175	0.411	0.30	-	-	28
49	420	150-175	0.411	0.50	70	3	1
50	420	150-175	0.411	0.50	70	5	1
51	420	150-175	0.411	0.50	70	7	1
53	420	150-175	0.411	0.50	-	-	28
55	420	25-50	0.411	0.00	70	3	1
56	420	25-50	0.411	0.00	70	5	1
57	420	25-50	0.411	0.00	70	7	1
59	420	25-50	0.411	0.00	-	-	28

Table 7 (Continued)

Mix No.	Target Strength (ksc)	Slump (mm)	W/B	F/B	Power Level (Watt)	Heating Time (hours)	Test Time (day)
61	420	25-50	0.411	0.30	70	3	1
62	420	25-50	0.411	0.30	70	5	1
63	420	25-50	0.411	0.30	70	7	1
65	420	25-50	0.411	0.30	-	-	28
67	420	25-50	0.411	0.50	70	3	1
68	420	25-50	0.411	0.50	70	5	1
69	420	25-50	0.411	0.50	70	7	1
71	420	25-50	0.411	0.50	-	-	28

3. Microstructure analysis

Cement and cement containing fly ash pastes were cast with variables, shown in Table 8. The specimens were tested for mercury intrusion porosimetry (MIP) and X-ray diffraction (XRD).

Table 8 Processes for microstructure analysis (MIP and XRD).

Mix No.	Target Strength (ksc)	W/B	F/B	Power Level (Watt)	Heating Time (hours)	Test Time (day)
40	420	0.411	0.00	70	7	7
46	420	0.411	0.30	70	7	7
52	420	0.411	0.50	70	7	7
73	420	0.411	0.00	-	-	1
74	420	0.411	0.30	-	-	1
75	420	0.411	0.50	-	-	1

RESULTS AND DISCUSSION

Several microwave curing processes involving power level at 70 Watt and heating time at 3, 5 and 7 hours were used for early compressive strength of 1"×2" cylindrical specimen at 1 day and compared with normally cured specimens at 7, 28 and 63 days. These microwave curing processes are also used for compressive strength estimation of the 28 days strength of normally cured specimen. Test parameters included the amount of fly ash replacement at 0%, 30% and 50% by weight of cement, slumps and water to binder ratios. Mix proportions for the processes were included Type I cement, Mae-Moh fly ash, natural construction sand, crushed limestone and tap water. After the compressive strength tests, some of these processes were prepared in cement pastes to investigate the microstructures for discussing the results.

The results and discussion are divided into 3 parts according to the steps in experimental program. The three steps are compressive strength, estimation and microstructure.

1. Compressive strength

Mix proportions in Table 8 and microwave curing processes were used for the 1 day compressive strength and compared with normally cured specimens at 7, 28 and 63 days. The results of compressive strength for all cases are shown in Appendix Table 2 and Figure 10 to 13.

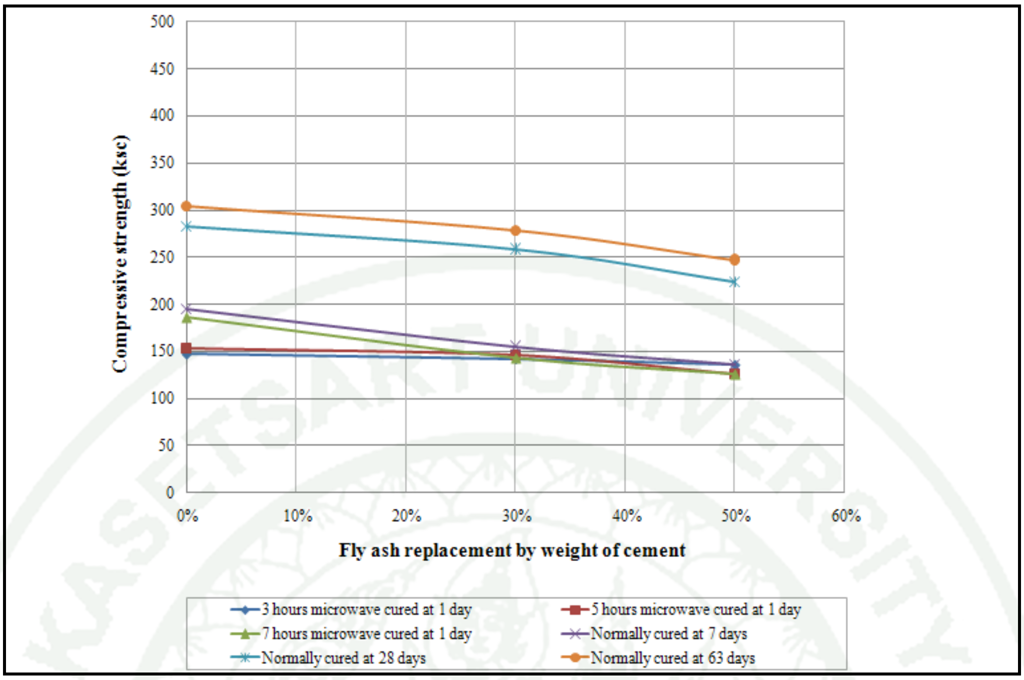

Figure 10 Effect of microwave on compressive strength with W/B=0.606 and 150-175 mm slump.

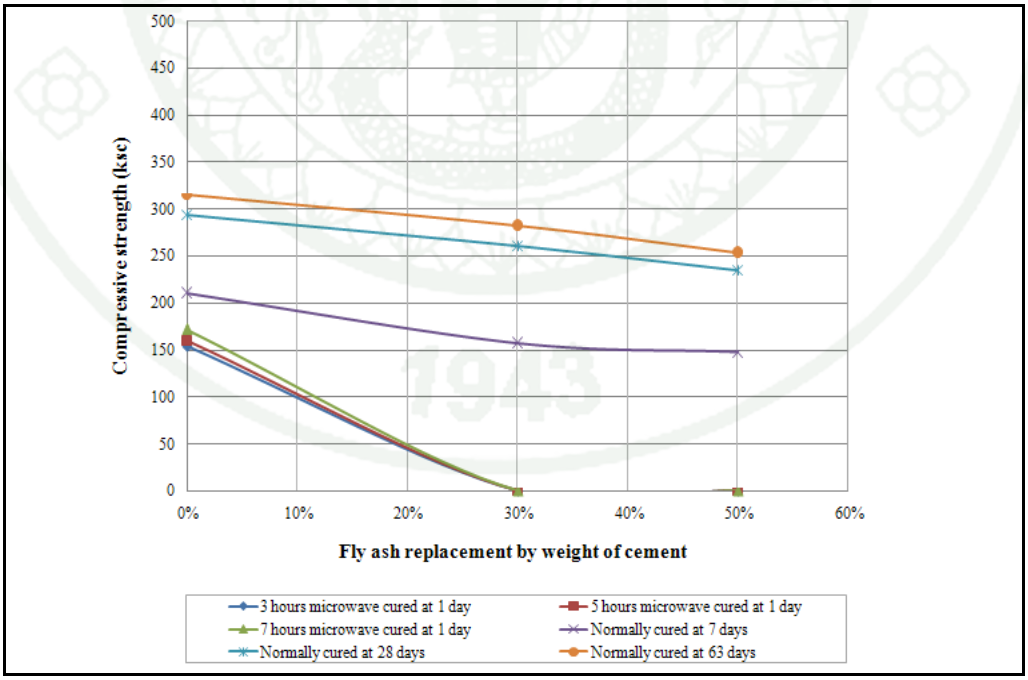

Figure 11 Effect of microwave on compressive strength with W/B=0.606 and 25-50 mm slump.

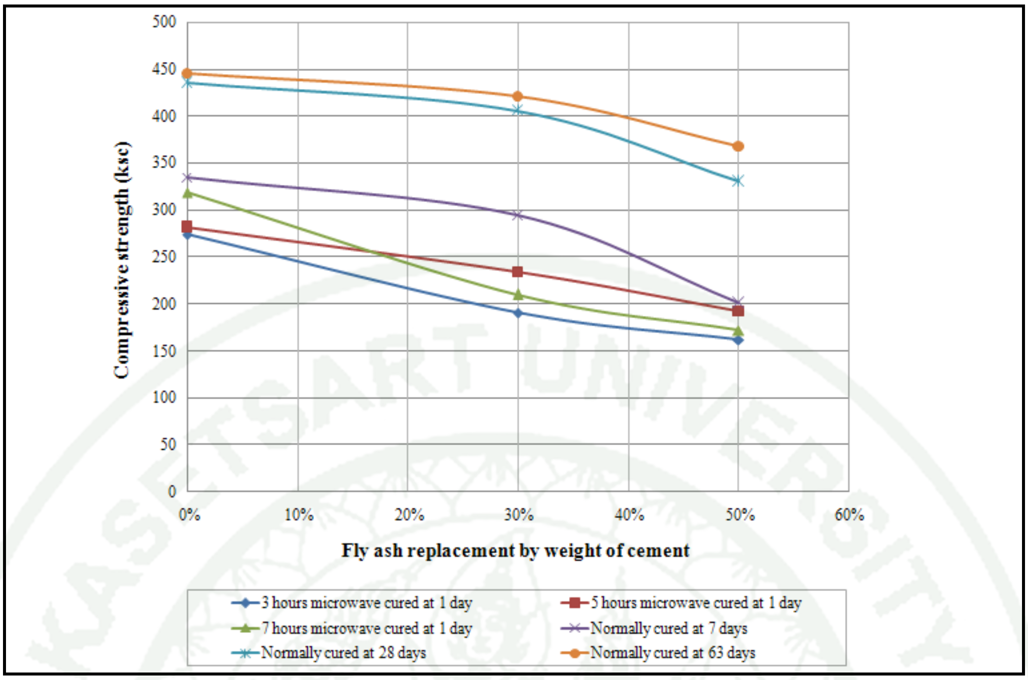

Figure 12 Effect of microwave on compressive strength with W/B=0.41 and 150-175 mm slump.

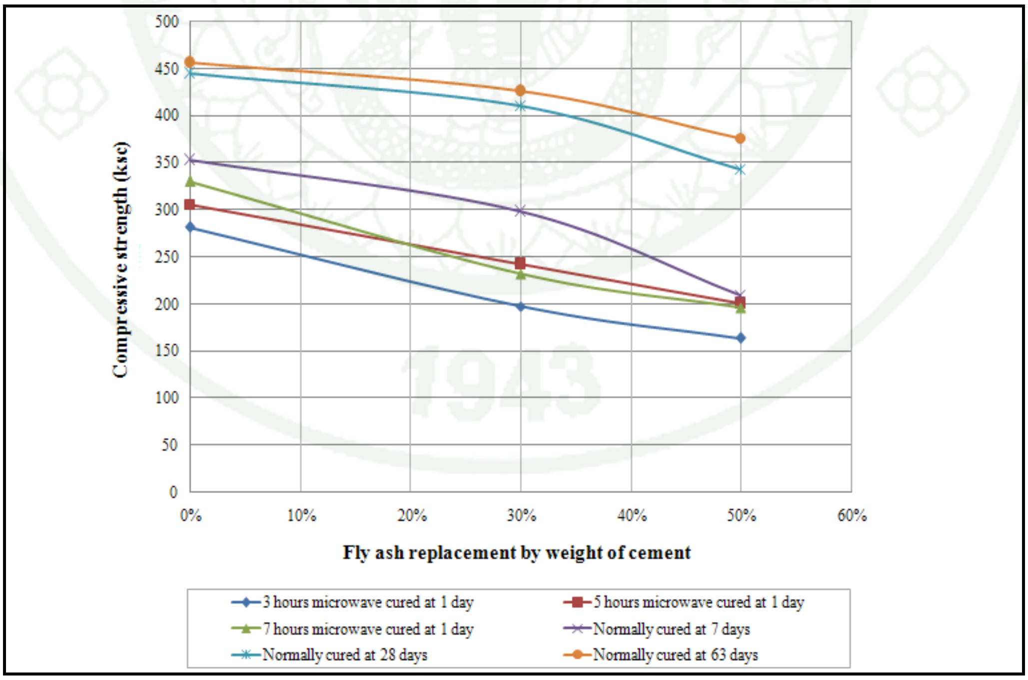

Figure 13 Effect of microwave on compressive strength with W/B=0.411 and 25-50 mm slump.

From figure 10 to 13, the percentages of 1 day microwave cured strength compared to the 28 days normally cured are shown in Table 9.

Table 9 Percentages of the 1 day microwave cured strength (for 3, 5 and 7 hours) compared with normally cured at various days.

Percent fly ash replacement	1-day microwave curing compared to 7-day normal (%)			1-day microwave curing compared to 28-day normal (%)			1-day microwave curing compared to 63-day normal (%)		
	3 hr	5 hr	7 hr	3 hr	5 hr	7 hr	3 hr	5 hr	7 hr
W/B = 0.606 and 150-175 mm slump									
0%	76	79	96	52	54	66	48	50	61
30%	92	94	92	55	56	55	51	52	51
50%	100	93	93	61	57	56	55	51	51
W/B = 0.606 and 25-50 mm slump									
0%	73	76	82	53	54	59	49	51	55
30%	0	0	0	0	0	0	0	0	0
50%	0	0	0	0	0	0	0	0	0
W/B = 0.411 and 150-175 mm slump									
0%	82	84	95	63	65	73	62	63	72
30%	65	80	71	47	58	52	45	56	50
50%	80	96	86	49	58	52	44	52	47
W/B = 0.411 and 25-50 mm slump									
0%	80	86	93	63	69	74	62	67	72
30%	66	81	78	48	59	57	46	57	54
50%	78	96	94	48	59	57	44	53	52

From the results from Figure 10 to 13 and Table 9 it can be explained that microwave curing technique could improve the effect of accelerated cement hydration for the early compressive strength of the specimens except the fly ash concrete condition where W/B = 0.606 and 25-50 mm slump requirement, which displayed 0 ksc of compressive strength. The maximum early age compressive strength of normal concrete and fly ash concrete occurred when applying microwave heating time for 7 and 5 hours respectively.

To compare the results of this investigation, other works of similar mix proportions but different microwave curing processes were selected to compare are shown in Table 10. The comparisons of microwave application on early age compressive strength with percentages fly ash replacement, W/B ratios and slump requirements are expressed in Figure 14 to 17.

Table 10 Microwave curing processes of this study and other studies.

Researchers	Microwave curing process		
	Power level (Watt)	Heating time	Test time (Hour)
Damangas (1999)	260 W + 202 W	30 min + 15 min	5.5
Cayliani (2000)	260 W + 202 W	30 min + 15 min	5.5
Wachirathamrojn (2001)	301 W + 226 W	30 min + 15 min	6.5
Aneksrup (2001)	259 W + 197 W	30 min + 15 min	7.5
Roekattakarn (2003)	356 W + 234 W	15 min + 30 min	5.25
This study	70 W	7 hours	24

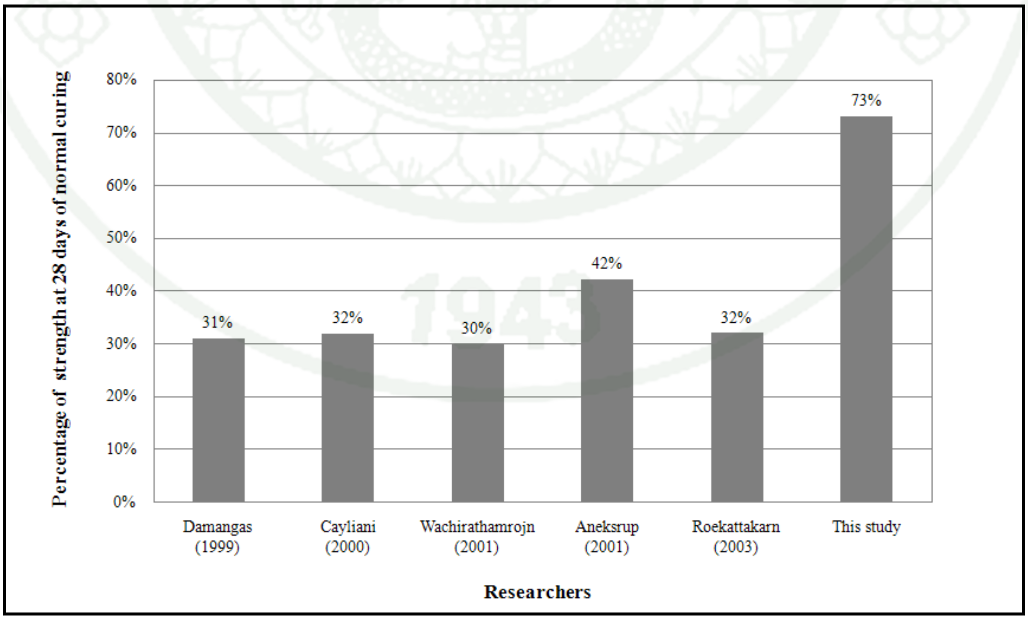

Figure 14 Comparison of microwave application on early age compressive strength with 0% fly ash replacement, W/C = 0.411 and 150-175 mm slump.

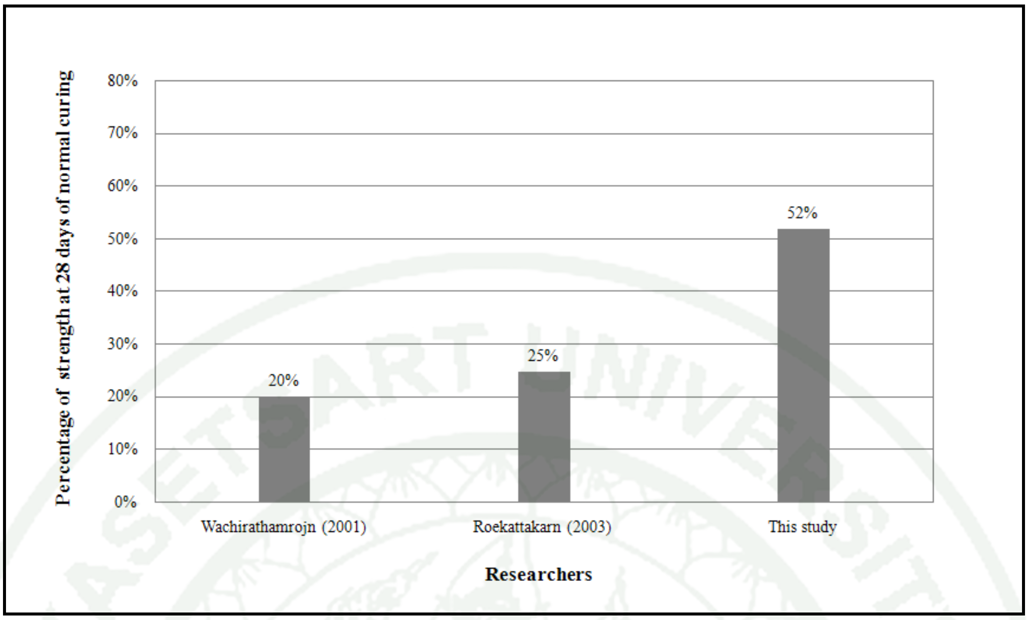

Figure 15 Comparison of microwave application on early age compressive strength with 0% fly ash replacement, W/C = 0.606 and 150-175 mm slump.

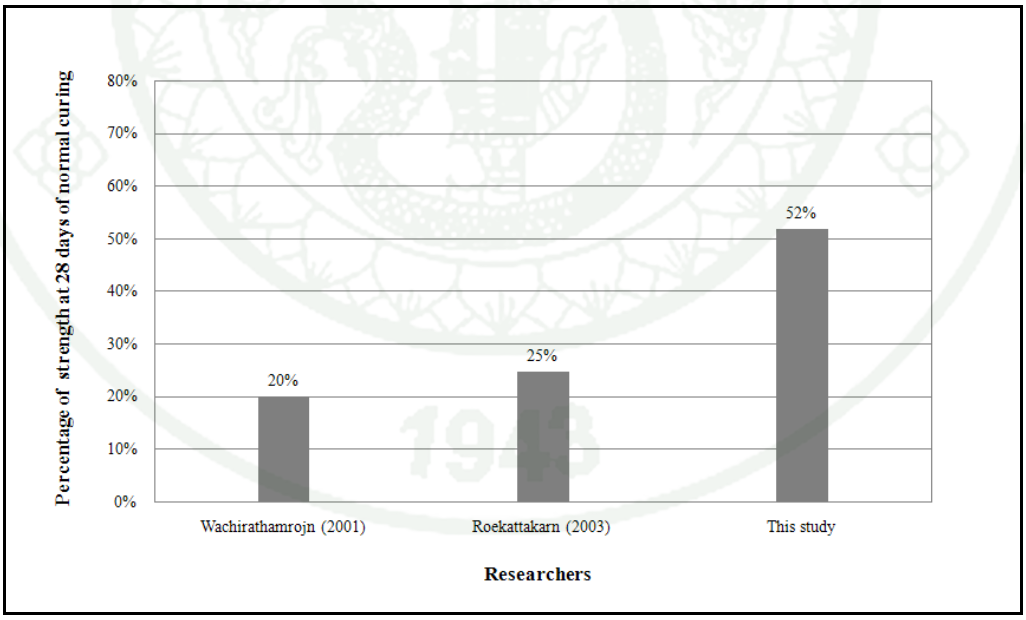

Figure 16 Comparison of microwave application on early age compressive strength with 30% fly ash replacement, W/B = 0.411 and 150-175 mm slump.

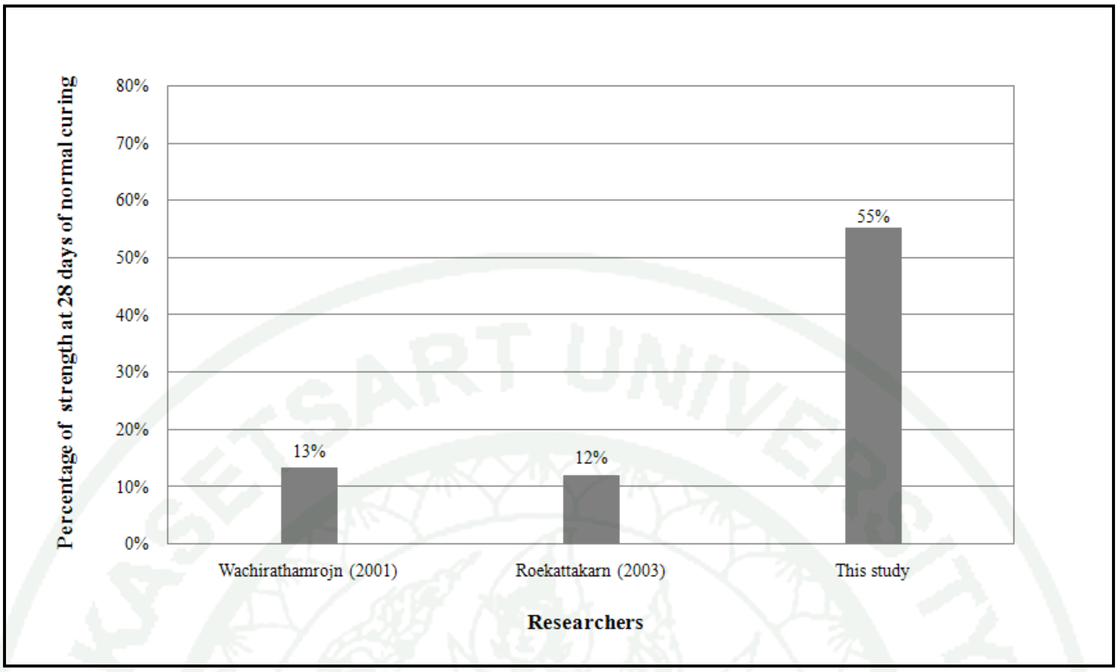

Figure 17 Comparison of microwave application on early age compressive strength with 30% fly ash replacement, W/B = 0.606 and 150-175 mm slump.

From Figure 14 to 17, the early microwave cured strength results of this study were better than other researchers. One of the reason was the early age test time, which was more than the others around 16 to 18 hours.

Another reason probably was the long application time with the low power level, in order to avoid boiling of water, of this study compared with the other works in Table 10.

To prevent the evaporation problem in this study, the relative humidity during microwave application was controlled by cap the specimens with PP cap at top and bottom then covered by plastic wrap. Before microwave application, the specimens were placed in a PP container full of water. After microwave curing processes, each mould was removed from the cavity to continue the curing process with careful prevention of thermal shock before the compression test at 1 day.

2. Estimation

The accelerated early age strength and the long term strength of normally cured concrete were then measured and compared to establish the relationships for long term strength prediction. The equations for later age prediction were determined for each mix proportion. The applicability of the equation to late rage strength estimation was assessed by considering the difference between the predicted and the measured values.

The early testing age was found to be at 1 day, while the long term was set at 28 days. To derive the equations for long term strength prediction, the accelerated strength at 1 day and the long term strength at 28 days, with different percentage of fly ash replacements, microwave processes and mix proportions, were plotted to relate with water to binder ratio (see Figure 18 to 20).

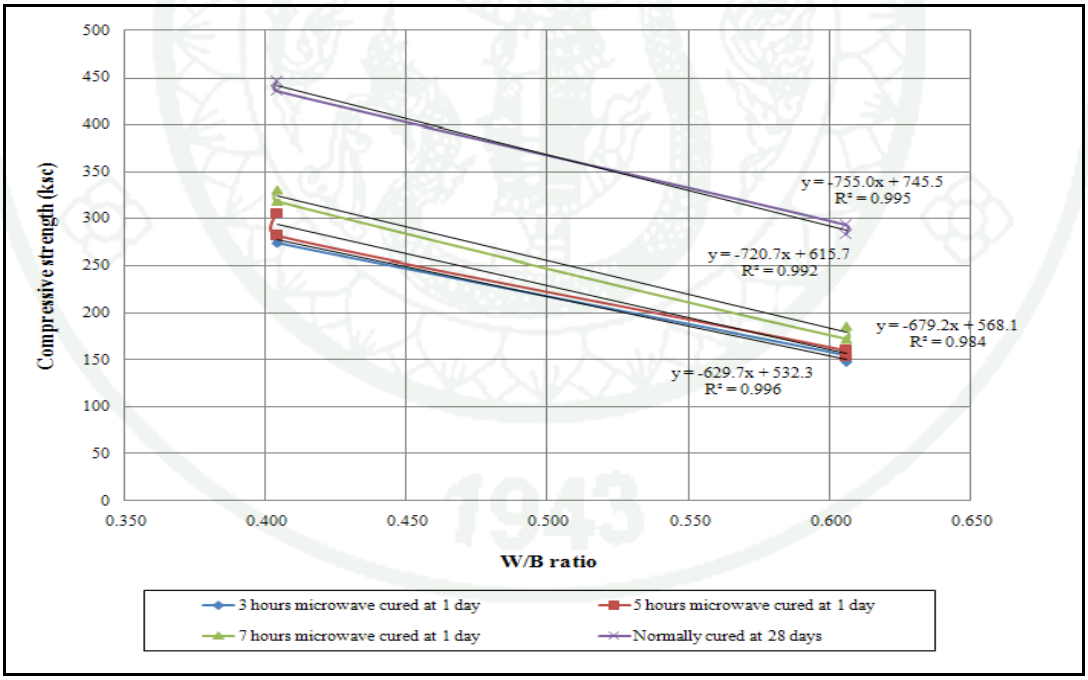

Figure 18 Compressive strength of early age microwave and later age normal curing with 0% fly ash replacement and different mix proportions.

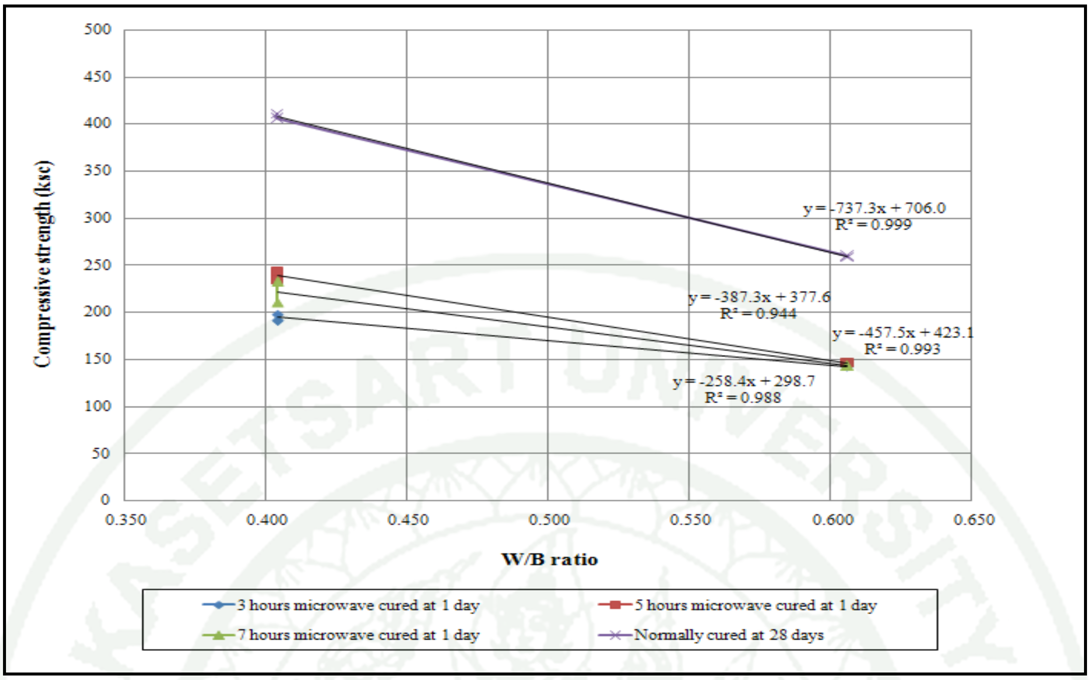

Figure 19 Compressive strength of early age microwave and later age normal curing with 30% fly ash replacement and different mix proportions.

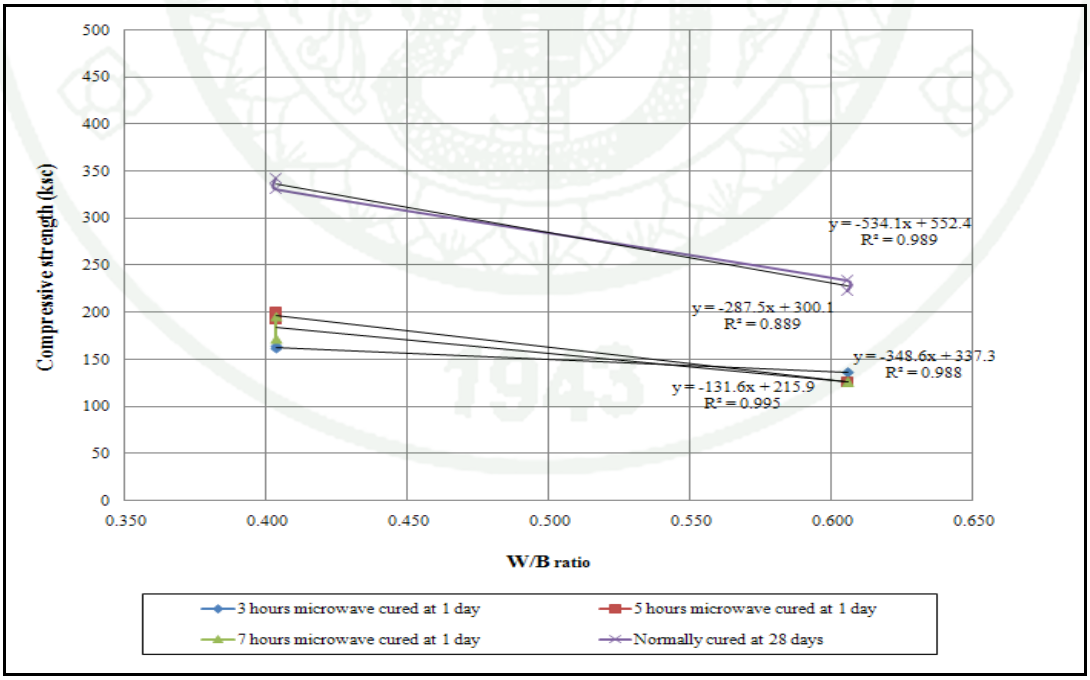

Figure 20 Compressive strength of early age microwave and later age normal curing with 50% fly ash replacement and different mix proportions.

From the Figure 18 to 20, the relationship for the compressive strength, microwave processes and mix proportions can be shown as following.

4.1 For 0% fly ash replacement

$$S_{M\text{-}3h} = -629.7\ (W/B) + 532.3$$
$$S_{M\text{-}5h} = -679.2\ (W/B) + 568.1$$
$$S_{M\text{-}7h} = -720.7\ (W/B) + 615.7$$
$$S_{N\text{-}0\%} = -755.0\ (W/B) + 745.5$$

4.2 For 30% fly ash replacement

$$S_{M\text{-}3h} = -258.4\ (W/B) + 298.7$$
$$S_{M\text{-}5h} = -457.5\ (W/B) + 423.1$$
$$S_{M\text{-}7h} = -378.3\ (W/B) + 377.6$$
$$S_{N\text{-}30\%} = -737.3\ (W/B) + 706.0$$

4.3 For 50% fly ash replacement

$$S_{M\text{-}3h} = -131.6\ (W/B) + 215.9$$
$$S_{M\text{-}5h} = -348.6\ (W/B) + 337.3$$
$$S_{M\text{-}7h} = -287.5\ (W/B) + 300.1$$
$$S_{N\text{-}50\%} = -534.1\ (W/B) + 552.4$$

The general equation for each case can be written below as

$$S_{M\text{-}3h} = -K_1\ (W/B) + K_2 \quad (1)$$
$$S_{M\text{-}5h} = -K_1\ (W/B) + K_2 \quad (2)$$
$$S_{M\text{-}7h} = -K_1\ (W/B) + K_2 \quad (3)$$
$$S_{N\text{-}x\%} = -K_3\ (W/B) + K_4 \quad (4)$$

where $S_{M\text{-}xh}$ = 1-day strength of microwave cured at x hours.

$S_{N\text{-}x\%}$ = 28-days strength of normally cured with x% of fly ash replacement.

The parameters K in general equation (1) to (4) with different percentage of fly ash replacements and microwave processes are shown in Table 11.

Table 11 Parameters K in general equation.

Percent fly ash replacement	$S_{M\text{-}3h}$		$S_{M\text{-}5h}$		$S_{M\text{-}7h}$		$S_{N\text{-}x\%}$	
	K_1	K_2	K_1	K_2	K_1	K_2	K_3	K_4
0%	629.7	532.3	679.2	568.1	720.7	615.7	755.0	745.5
30%	258.4	298.7	457.5	423.1	378.3	377.6	737.3	706.0
50%	131.6	215.9	348.6	337.3	287.5	300.1	534.1	552.4

The general equation (1) to (4) can be concluded to estimate the 28-days compressive strength of normally cured concrete or fly ash concrete as follows

$$S_{N-x\%} = \frac{K_3}{K_1}(S_{M-xh} - K_2) + K_4 \qquad (5)$$

The estimation of 28-day compressive strength can be calculated by substituting the parameters K (from Table 7) and the 1-day compressive strength into equation (5). By using this method the maximum percentage of errors from different cases are summarized in Appendix Table 3 and Table 12.

Table 12 Estimation of 28-days compressive strength with different microwave cured times and fly ash replacements.

Percent fly ash replacement	28-day true strengths related with curing time (ksc)			28-day estimated strengths with curing time (ksc)			Maximum percentage of errors with curing time (%)		
	3 hr	5 hr	7 hr	3 hr	5 hr	7 hr	3 hr	5 hr	7 hr
0%	282.6	435.5	282.6	284.0	427.6	295.1	0.5	-1.8	4.4
30%	405.9	410.4	405.9	398.7	415.1	379.7	-1.8	1.2	-6.4
50%	223.1	223.1	330.9	228.5	228.8	314.7	2.4	2.6	-4.9

The results of 28-days compressive strength estimation from Table 12 shown here clearly indicated the possibility of using this estimation method with 3, 5 and 7 hours of microwave heating time, which yielded the maximum percentage of errors at 2.4%, 2.6% and 6.4% (for fly ash replacement of 50%, 50% and 30%) respectively.

From the estimation, it was shown that by using the method with 3 hours of microwave curing time the results yielded minimum value for fly ash replacement of 0% and 50%. But for fly ash replacement of 30% the result yielded minimum value when using 5 hours of microwave curing time.

3. Microstructure

To discuss the results of compressive strength, 1 day microwave curing (at 7 hours) and normal curing of cement pastes containing fly ash 0%, 30% and 50% with W/B=0.411 were tested for mercury intrusion porosimetry (MIP) and X-ray diffraction (XRD), which is the analysis of porosity and hydration products respectively.

Table 13 and Figure 21 to 23 show the mercury intrusion porosimetry (MIP) results of 1-day samples that microwave curing application decreased the pore size and porosity compared with normally cured for all samples. The pore size of fly ash replacement at 50% sample was less than fly ash replacements at 0% and 30% sample by using the microwave curing technique.

Table 13 The results of pore size and porosity.

Percent Fly ash	MIP results of 1-day samples			
	Microwave curing (at 7 hours)		Normal curing	
	Pore diameter (μm)	Total porosity (%)	Pore diameter (μm)	Total porosity (%)
0%	0.033	25.98	0.079	32.09
30%	0.037	33.99	0.109	39.19
50%	0.026	36.50	0.175	40.64

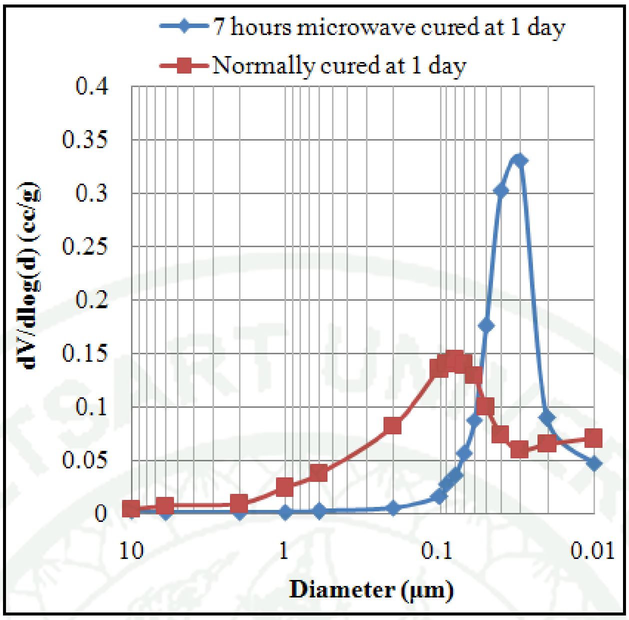

Figure 21 Porosity at 1 day of cement paste containing fly ash 0% with 7 hours of microwave curing and normal curing.

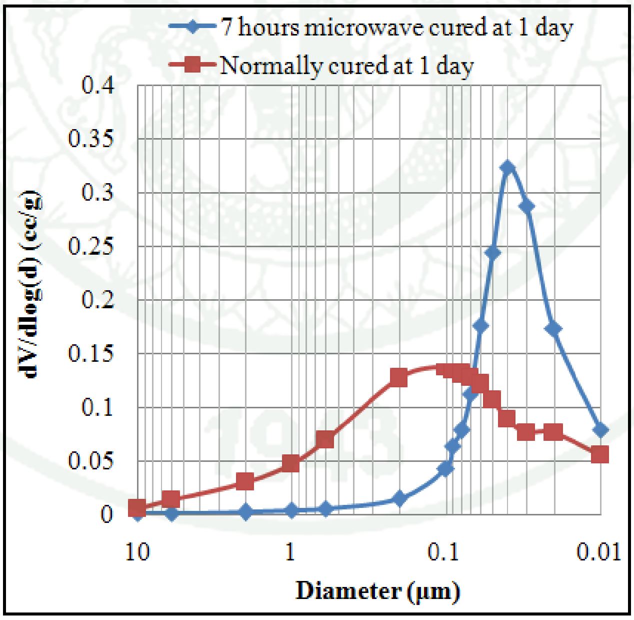

Figure 22 Porosity at 1 day of cement paste containing fly ash 30% with 7 hours of microwave curing and normal curing.

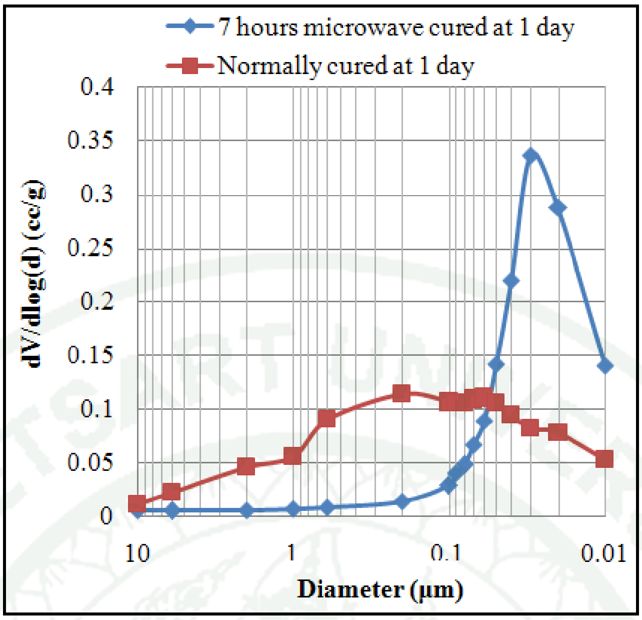

Figure 23 Porosity at 1 day of cement paste containing fly ash 50% with 7 hours of microwave curing and normal curing.

The MIP results of 1-day samples show that microwave cured technique can decrease the pore radius and total porosity of cement and cement containing fly ash pastes compared with normally cured. The results of normally cured sample are consistent with the research of Xu *et al*. (2001) that pore diameter and total porosity were increased with fly ash replacement.

The X-ray diffraction (XRD) patterns expressed for the 1 day normally cured samples where the ettringite ($Ca_6(Al(OH)_6)_2(SO_4)(H_2O)_{26}$), calcium hydroxide ($Ca(OH)_2$) and calcium silicate ($Ca_3SiO_5$) peaks were observed. For the 1 day samples with microwave cured time at 7 hours, it was observed that the diffraction peak due to the products of $Ca(OH)_2$ and Ca_3SiO_5 only, as shown in Figure 24 to 29.

From XRD analysis, the main hydrates formed of normally cured cement and fly ash cement pastes were C-S-H and ettringite. For the microwave treatment, the quantity of ettringite disappeared. This result can prove that microwave curing application accelerated hydration reaction of cement and fly ash cement, a similar result to the work from Pera *et al*. (1997).

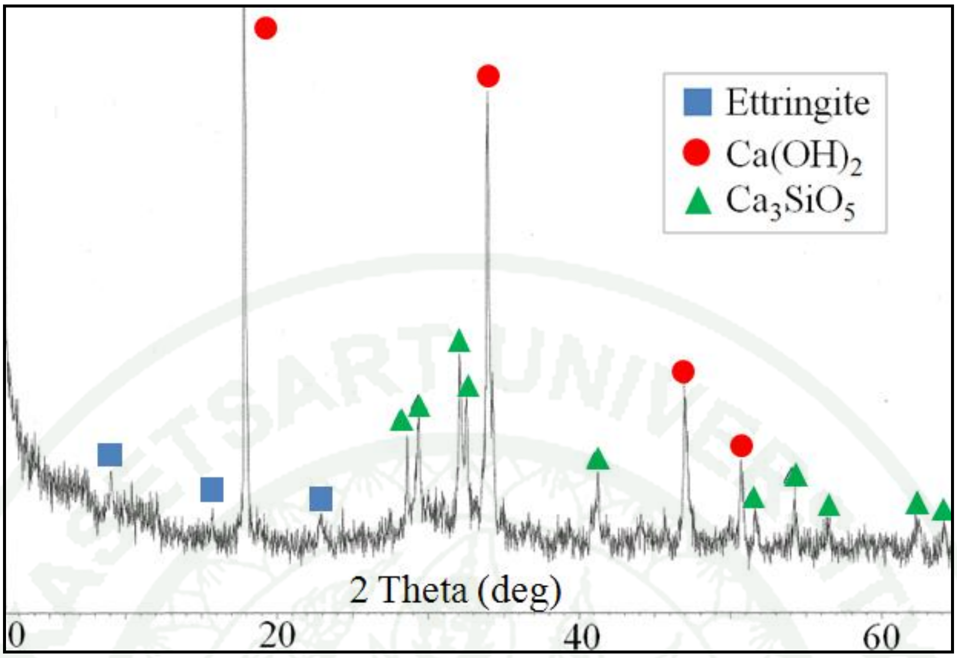

Figure 24 XRD patterns at 1 day of cement paste containing fly ash 0% with 7 hours of normal curing.

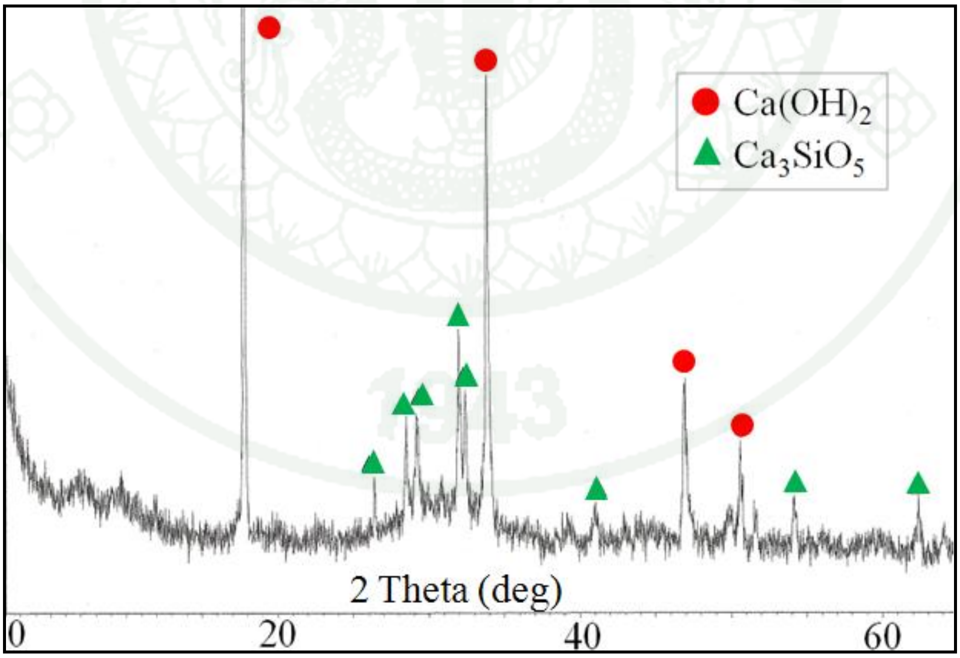

Figure 25 XRD patterns at 1 day of cement paste containing fly ash 0% with 7 hours of microwave curing.

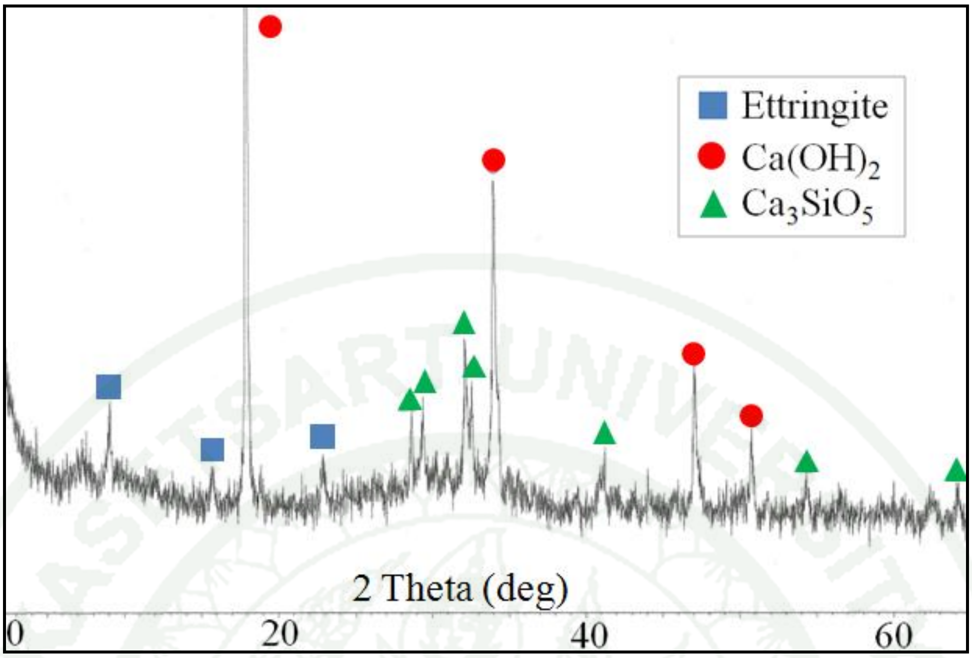

Figure 26 XRD patterns at 1 day of cement paste containing fly ash 30% with 7 hour of normal curing.

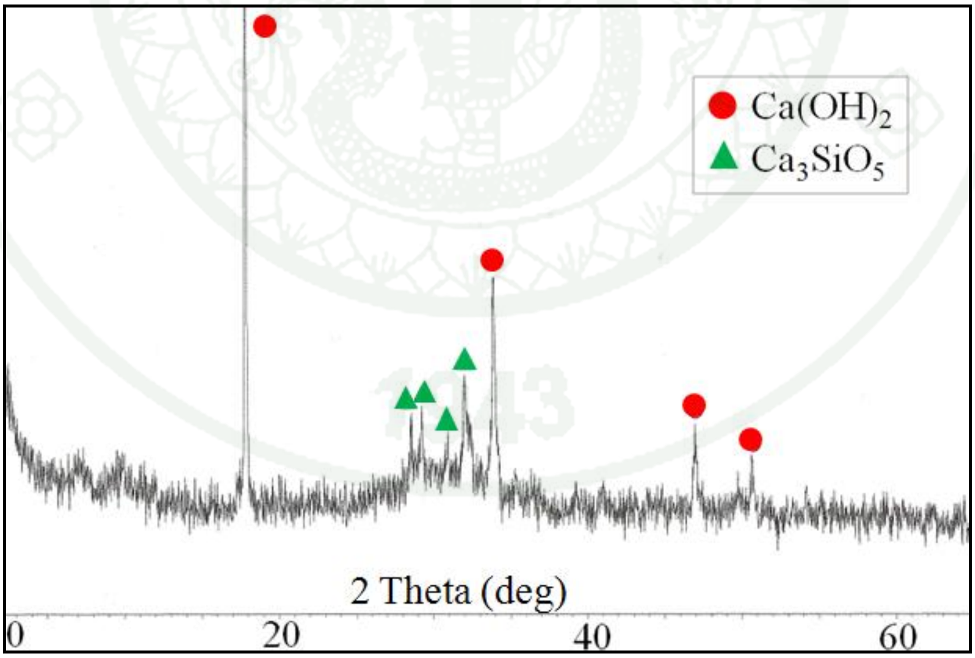

Figure 27 XRD patterns at 1 day of cement paste containing fly ash 30% with 7 hour of microwave curing .

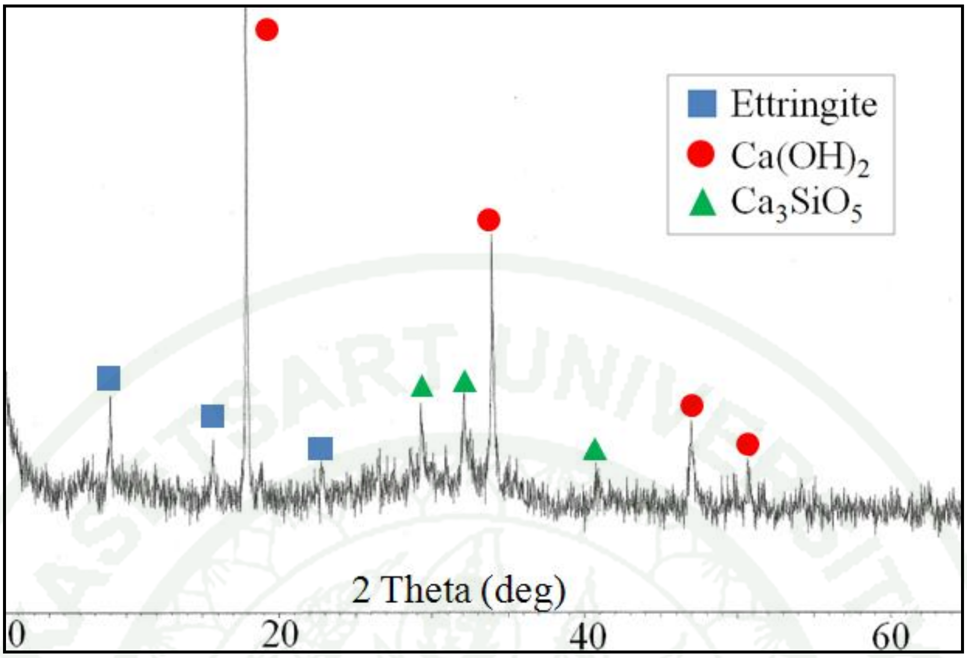

Figure 28 XRD patterns at 1 day of cement paste containing fly ash 50% with 7 hours of normal curing.

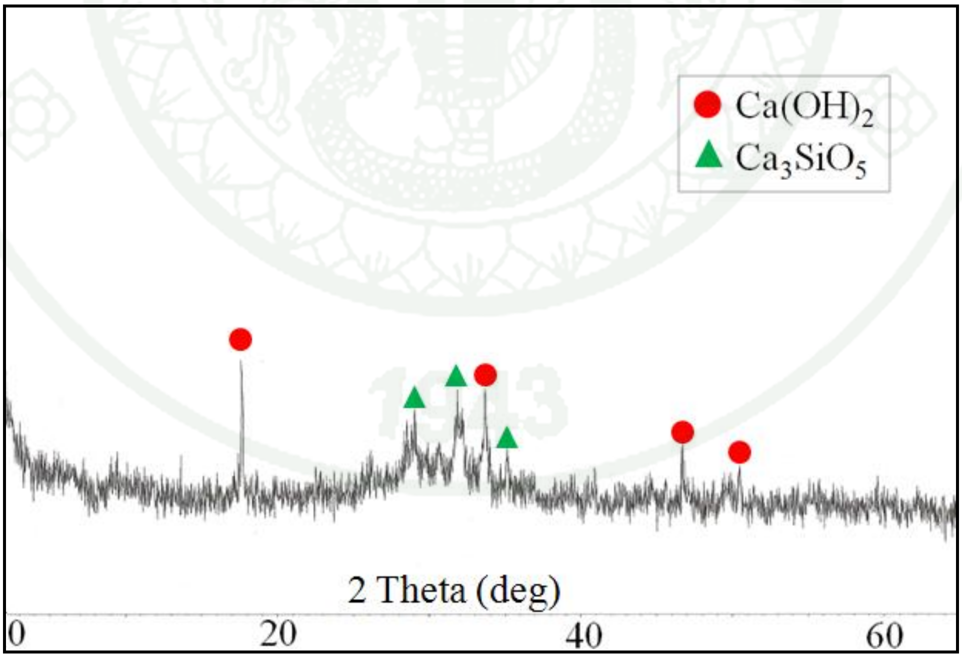

Figure 29 XRD patterns at 1 day of cement paste containing fly ash 50% with 7 hours of microwave curing.

CONCLUSIONS AND RECOMMENDATION

Conclusions

1. 70 Watt of microwave energy for 3, 5 and 7 hours improved the 1 day compressive strength of concrete and fly ash concrete with the high maximum result (52%-73%) of 28 days normally cured strength compared with results from other researchers (19%-42%).

2. The maximum early age compressive strength of normal concrete and fly ash concrete occurred when microwave was applied for 7 and 5 hours respectively. Fly ash concrete strength by microwave curing for 7 hours slightly decreased, less than curing for 5 hours in every mix proportions and fly ash replacements.

3. By using the microwave curing method, it was possible to estimate the 28 days compressive strength of normally cured specimens from compression test at 1 day. The estimation yielded the maximum percentage of error at 6.4%.

4. For the mix with fly ash replacement of 0% and 50%, the estimation yielded the minimum percentage of error by using the microwave curing application for 3 hours. For fly ash replacement of 30%, the estimation yielded minimum error by using the application for 5 hours.

5. By using the microwave curing application for 7 hours, it was shown that pore size and porosity decreased when compared with normally cured samples at 1 day. The pore size from the sample of fly ash replacement at 50% was less than 0% and 30%.

6. From XRD analysis, it can prove that microwave curing application accelerates cement hydration, resulting in strength development.

Recommendation

Early-age compressive strength of concrete and fly ash concrete with application of microwave curing technique needs further investigation. A similar approach can be applied to the recommendation for future research works which are

1. There should be more study on high microwave power level and different microwave curing time.

2. Study the effect of another type of cement and fly ash with different chemical composition on strength development by using microwave curing technique.

3. Estimate the long term compressive strength from different early age compression test date.

4. Investigation of microstructure with different mix proportions and microwave curing processes.

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APPENDIX

Appendix Table 1 Determination of physical properties of fine and coarse aggregate.

Description for physical properties	Result
Weight of bottle (g)	161.00
Weight of bottle + water (g), D	659.00
Weight of bottle + water + fine aggregate (g), C	955.00
Weight of fine aggregate at SSD (g), B	500.00
Weight of fine aggregate at oven dry (g), A	493.00
Specific gravity of fine aggregate at SSD, B/(B+D-C)	2.45
Specific gravity of fine aggregate at oven dry, A/(B+D-C)	2.42
Absorption (%) of fine aggregate, [(B-A)/A]×100	1.42
Weight of coarse aggregate at oven dry (g), A	305.00
Weight of coarse aggregate at SSD (g), B	308.00
Weight of coarse aggregate saturated in water (g), C	194.00
Specific gravity of coarse aggregate at SSD, B/(B-C)	2.70
Specific gravity of coarse aggregate at oven dry, A/(B-C)	2.68
Absorption (%) of coarse aggregate, [(B-A)/A]×100	0.98
Diameter of container (cm)	20.50
Height of container (cm)	28.00
Weight of container (kg)	7.20
Weight of container + sample (kg)	20.00
Unit weight of coarse aggregate (kg/m^3)	1385.00

Appendix Table 2 Compressive strength of investigation.

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)	Compressive strength (ksc)
1	280	150-175	0.606	0.00	70	3	1	147.4
2	280	150-175	0.606	0.00	70	5	1	153.4
3	280	150-175	0.606	0.00	70	7	1	185.8
4	280	150-175	0.606	0.00	-	-	7	194.5
5	280	150-175	0.606	0.00	-	-	28	282.6
6	280	150-175	0.606	0.00	-	-	63	304.0
7	280	150-175	0.606	0.30	70	3	1	142.1
8	280	150-175	0.606	0.30	70	5	1	145.9
9	280	150-175	0.606	0.30	70	7	1	142.9
10	280	150-175	0.606	0.30	-	-	7	154.9
11	280	150-175	0.606	0.30	-	-	28	258.4
12	280	150-175	0.606	0.30	-	-	63	278.0
13	280	150-175	0.606	0.50	70	3	1	136.1
14	280	150-175	0.606	0.50	70	5	1	126.1
15	280	150-175	0.606	0.50	70	7	1	125.9
16	280	150-175	0.606	0.50	-	-	7	135.8
17	280	150-175	0.606	0.50	-	-	28	223.1
18	280	150-175	0.606	0.50	-	-	63	246.9
19	280	25-50	0.606	0.00	70	3	1	154.1
20	280	25-50	0.606	0.00	70	5	1	159.7
21	280	25-50	0.606	0.00	70	7	1	172.0
22	280	25-50	0.606	0.00	-	-	7	210.7
23	280	25-50	0.606	0.00	-	-	28	293.4
24	280	25-50	0.606	0.00	-	-	63	314.8
25	280	25-50	0.606	0.30	70	3	1	0.0
26	280	25-50	0.606	0.30	70	5	1	0.0
27	280	25-50	0.606	0.30	70	7	1	0.0
28	280	25-50	0.606	0.30	-	-	7	157.3
29	280	25-50	0.606	0.30	-	-	28	260.0
30	280	25-50	0.606	0.30	-	-	63	282.6

Appendix Table 2 (Continued)

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)	Compressive strength (ksc)
31	280	25-50	0.606	0.50	70	3	1	0.0
32	280	25-50	0.606	0.50	70	5	1	0.0
33	280	25-50	0.606	0.50	70	7	1	0.0
34	280	25-50	0.606	0.50	-	-	7	147.7
35	280	25-50	0.606	0.50	-	-	28	234.4
36	280	25-50	0.606	0.50	-	-	63	253.8
37	420	150-175	0.411	0.00	70	3	1	274.1
38	420	150-175	0.411	0.00	70	5	1	282.1
39	420	150-175	0.411	0.00	70	7	1	318.5
40	420	150-175	0.411	0.00	-	-	7	334.3
41	420	150-175	0.411	0.00	-	-	28	435.5
42	420	150-175	0.411	0.00	-	-	63	445.3
43	420	150-175	0.411	0.30	70	3	1	191.0
44	420	150-175	0.411	0.30	70	5	1	234.1
45	420	150-175	0.411	0.30	70	7	1	210.2
46	420	150-175	0.411	0.30	-	-	7	294.1
47	420	150-175	0.411	0.30	-	-	28	405.9
48	420	150-175	0.411	0.30	-	-	63	420.7
49	420	150-175	0.411	0.50	70	3	1	161.7
50	420	150-175	0.411	0.50	70	5	1	192.2
51	420	150-175	0.411	0.50	70	7	1	172.2
52	420	150-175	0.411	0.50	-	-	7	201.1
53	420	150-175	0.411	0.50	-	-	28	330.9
54	420	150-175	0.411	0.50	-	-	63	367.3
55	420	25-50	0.411	0.00	70	3	1	281.8
56	420	25-50	0.411	0.00	70	5	1	305.4
57	420	25-50	0.411	0.00	70	7	1	330.5
58	420	25-50	0.411	0.00	-	-	7	353.8
59	420	25-50	0.411	0.00	-	-	28	445.6
60	420	25-50	0.411	0.00	-	-	63	457.2

Appendix Table 2 (Continued)

Mix No.	Target strength (ksc)	Slump (mm)	W/B	F/B	Power level (Watt)	Heating time (hours)	Test time (day)	Compressive strength (ksc)
61	420	25-50	0.411	0.30	70	3	1	197.6
62	420	25-50	0.411	0.30	70	5	1	242.6
63	420	25-50	0.411	0.30	70	7	1	232.1
64	420	25-50	0.411	0.30	-	-	7	299.2
65	420	25-50	0.411	0.30	-	-	28	410.4
66	420	25-50	0.411	0.30	-	-	63	427.0
67	420	25-50	0.411	0.50	70	3	1	163.7
68	420	25-50	0.411	0.50	70	5	1	200.9
69	420	25-50	0.411	0.50	70	7	1	195.8
70	420	25-50	0.411	0.50	-	-	7	208.9
71	420	25-50	0.411	0.50	-	-	28	342.4
72	420	25-50	0.411	0.50	-	-	63	375.6

Appendix Table 3 28-day compressive strength estimation.

Mix No.	Slump (mm)	W/B	F/B	Heating time (hours)	1-day (microwave) strength (ksc)	28-day true strength (ksc)	28-day estimated strength (ksc)	Error (%)
1	150-175	0.606	0.00	3	147.4	282.6	284.0	0.48
2	150-175	0.606	0.00	5	153.4	282.6	284.5	0.66
3	150-175	0.606	0.00	7	185.8	282.6	295.1	4.44
7	150-175	0.606	0.30	3	142.1	258.4	259.2	0.30
8	150-175	0.606	0.30	5	145.9	258.4	259.3	0.34
9	150-175	0.606	0.30	7	142.9	258.4	248.6	-3.80
13	150-175	0.606	0.50	3	136.1	223.1	228.5	2.43
14	150-175	0.606	0.50	5	126.1	223.1	228.8	2.56
15	150-175	0.606	0.50	7	125.9	223.1	228.8	2.55
19	25-50	0.606	0.00	3	154.1	293.4	292.0	-0.46
20	25-50	0.606	0.00	5	159.7	293.4	291.5	-0.64
21	25-50	0.606	0.00	7	172.0	293.4	280.7	-4.33
25	25-50	0.606	0.30	3	0.0	260.0	-	-
26	25-50	0.606	0.30	5	0.0	260.0	-	-
27	25-50	0.606	0.30	7	0.0	260.0	-	-
31	25-50	0.606	0.50	3	0.0	234.4	-	-
32	25-50	0.606	0.50	5	0.0	234.4	-	-
33	25-50	0.606	0.50	7	0.0	234.4	-	-
37	150-175	0.411	0.00	3	274.1	435.5	435.9	0.10
38	150-175	0.411	0.00	5	282.1	435.5	427.6	-1.82
39	150-175	0.411	0.00	7	318.5	435.5	434.2	-0.31
43	150-175	0.411	0.30	3	191.0	405.9	398.7	-1.77
44	150-175	0.411	0.30	5	234.1	405.9	401.3	-1.13
45	150-175	0.411	0.30	7	210.2	405.9	379.7	-6.44
49	150-175	0.411	0.50	3	161.7	330.9	332.4	0.46
50	150-175	0.411	0.50	5	192.2	330.9	330.0	-0.27
51	150-175	0.411	0.50	7	172.2	330.9	314.7	-4.90
55	25-50	0.411	0.00	3	281.8	445.6	445.1	-0.10
56	25-50	0.411	0.00	5	305.4	445.6	453.4	1.77
57	25-50	0.411	0.00	7	330.5	445.6	446.7	0.26

Appendix Table 3 (Continued)

Mix No.	Slump (mm)	W/B	F/B	Heating time (hours)	1-day (microwave) strength (ksc)	28-day true strength (ksc)	28-day estimated strength (ksc)	Error (%)
61	25-50	0.411	0.30	3	197.6	410.4	417.5	1.74
62	25-50	0.411	0.30	5	242.6	410.4	415.1	1.15
63	25-50	0.411	0.30	7	232.1	410.4	422.4	2.93
67	25-50	0.411	0.50	3	163.7	342.4	340.5	-0.54
68	25-50	0.411	0.50	5	200.9	342.4	343.4	0.30
69	25-50	0.411	0.50	7	195.8	342.4	358.6	4.74

Appendix Table 4 Pore size distribution by volume at 1 day of cement paste containing fly ash 0% with microwave curing at 7 hours.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	1.90E+02	0.0000	4.30E-06	2.89E-03
2	1.65E+02	0.0001	4.86E-06	3.07E-03
3	1.34E+02	0.0005	6.77E-06	3.25E-03
4	1.09E+02	0.0009	9.94E-05	3.36E-03
5	9.09E+01	0.0011	1.41E-05	3.44E-03
6	7.77E+01	0.0014	1.89E-05	3.45E-03
7	6.86E+01	0.0016	2.63E-05	3.82E-03
8	6.09E+01	0.0018	3.11E-05	3.95E-03
9	5.46E+01	0.0020	3.32E-05	3.90E-03
10	4.94E+01	0.0022	3.55E-05	3.79E-03
11	4.51E+01	0.0024	3.83E-05	3.71E-03
12	4.15E+01	0.0025	4.09E-05	3.62E-03
13	3.84E+01	0.0026	4.22E-05	3.47E-03
14	3.58E+01	0.0027	4.28E-05	3.31E-03
15	3.35E+01	0.0028	4.30E-05	3.14E-03
16	3.15E+01	0.0029	4.31E-05	2.99E-03
17	3.98E+01	0.0030	4.13E-05	2.65E-03
18	2.82E+01	0.0030	3.81E-05	2.29E-03
19	2.68E+01	0.0031	3.48E-05	1.96E-03
20	2.55E+01	0.0031	3.00E-05	1.61E-03
21	2.44E+01	0.0032	2.73E-05	1.38E-03
22	2.34E+01	0.0032	2.38E-05	1.13E-03
23	2.25E+01	0.0032	2.04E-05	9.15E-04
24	2.16E+01	0.0032	1.61E-05	6.84E-04
25	2.08E+01	0.0032	1.09E-06	4.40E-04
26	2.00E+01	0.0032	5.86E+00	2.25E-04
27	1.93E+01	0.0032	0.00E+00	0.00E+00
28	1.87E+01	0.0032	0.00E+00	0.00E+00
29	1.81E+01	0.0032	0.00E+00	0.00E+00
30	1.75E+01	0.0032	0.00E+00	0.00E+00
31	1.70E+01	0.0032	0.00E+00	0.00E+00
32	1.65E+01	0.0032	0.00E+00	0.00E+00
33	1.61E+01	0.0032	0.00E+00	0.00E+00
34	1.57E+01	0.0032	0.00E+00	0.00E+00
35	1.53E+01	0.0032	0.00E+00	0.00E+00

Appendix Table 4 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
36	1.49E+01	0.0032	0.00E+00	0.00E+00
37	1.46E+01	0.0032	3.35E-06	1.26E-04
38	1.43E+01	0.0032	6.83E-05	2.48E-04
39	1.40E+01	0.0032	1.41E-05	5.00E-04
40	1.38E+01	0.0032	2.21E-05	7.60E-04
41	1.34E+01	0.0032	3.03E-05	1.01E-03
42	1.31E+01	0.0032	3.92E-05	1.27E-03
43	1.29E+01	0.0032	5.24E-05	1.65E-03
44	1.27E+01	0.0032	6.60E-05	2.03E-03
45	1.24E+01	0.0032	8.13E-05	2.43E-03
46	1.22E+01	0.0033	9.83E-05	2.86E-03
47	1.19E+01	0.0033	1.17E-04	3.30E-03
48	1.17E+01	0.0033	1.27E-04	3.48E-03
49	1.15E+01	0.0034	1.38E-04	3.68E-03
50	1.13E+01	0.0034	1.32E-04	3.70E-03
51	1.11E+01	0.0034	1.39E-04	3.52E-03
52	1.09E+01	0.0035	1.39E-04	3.46E-03
53	1.07E+01	0.0035	1.39E-04	3.39E-03
54	1.05E+01	0.0035	1.29E-04	3.06E-03
55	1.04E+01	0.0035	1.17E-04	2.75E-03
56	1.02E+01	0.0035	1.04E-05	2.41E-03
57	1.01E+01	0.0036	8.75E-05	2.03E-03
58	9.96E+00	0.0036	6.99E-05	1.64E-03
59	9.46E+00	0.0036	5.97E-05	1.39E-03
60	8.30E+00	0.0036	5.38E-05	1.15E-03
61	6.33E+00	0.0037	6.73E-04	1.09E-03
62	4.31E+00	0.0038	1.02E-04	1.04E-03
63	2.74E+00	0.0039	1.70E-04	1.04E-03
64	1.77E+00	0.0040	2.39E-04	1.07E-03
65	1.19E+00	0.0042	4.73E-04	1.30E-03
66	8.32E-01	0.0044	7.46E-03	1.52E-03
67	6.09E-01	0.0046	1.12E-03	1.77E-03
68	4.62E-01	0.0048	1.79E-03	2.18E-03
69	3.60E-01	0.0051	2.78E-03	2.67E-03
70	2.89E-01	0.0054	4.22E-03	3.26E-03
71	2.37E-01	0.0056	6.32E-03	4.01E-03
72	1.98E-01	0.0059	9.21E-03	4.92E-03

Appendix Table 4 (Continued)

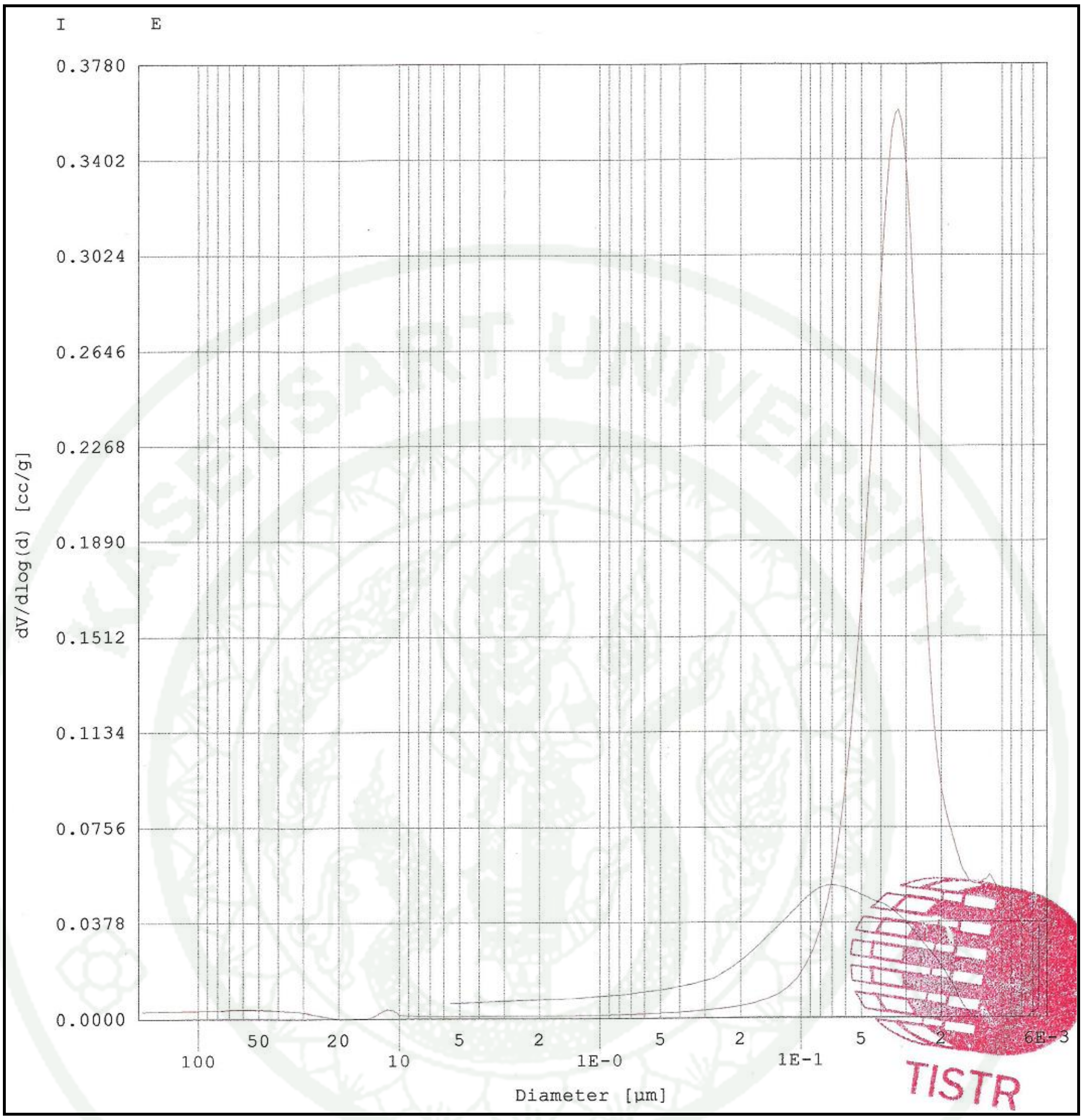
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
73	1.69E-01	0.0062	1.33E-02	6.04E-03
74	1.46E-01	0.0066	1.89E-02	7.56E-03
75	1.29E-01	0.0070	2.69E-02	9.52E-03
76	1.15E-01	0.0075	3.85E-02	1.23E-02
77	1.04E-01	0.0080	5.55E-02	1.60E-02
78	9.43E-02	0.0085	8.08E-02	2.11E-02
79	8.66E-02	0.0092	1.15E-01	2.74E-02
80	7.99E-02	0.0101	1.62E-01	3.53E-02
81	7.42E-02	0.0111	2.25E-01	4.51E-02
82	6.92E-02	0.0125	3.06E-01	5.66E-02
83	6.49E-02	0.0142	4.14E-01	7.07E-02
84	6.10E-02	0.0161	5.50E-01	8.74E-02
85	5.75E-02	0.0185	7.16E-01	1.06E-01
86	5.44E-02	0.0212	9.21E-01	1.28E-01
87	5.17E-02	0.0244	1.16E+00	1.51E-01
88	4.91E-02	0.0280	1.43E+00	1.76E-01
89	4.68E-02	0.0321	1.74E+00	2.01E-01
90	4.47E-02	0.0365	2.08E+00	2.28E-01
91	4.28E-02	0.0415	2.44E+00	2.54E-01
92	4.10E-02	0.0468	2.82E+00	2.79E-01
93	3.94E-02	0.0524	3.21E+00	3.03E-01
94	3.79E-02	0.0583	3.59E+00	3.23E-01
95	3.65E-02	0.0643	3.95E+00	3.40E-01
96	3.51E-02	0.0705	4.28E+00	3.52E-01
97	3.39E-02	0.0766	4.54E+00	3.59E-01
98	3.27E-02	0.0826	4.75E+00	3.60E-01
99	3.16E-02	0.0884	4.88E+00	3.55E-01
100	3.06E-02	0.0939	4.93E+00	3.45E-01
101	2.96E-02	0.0990	4.91E+00	3.31E-01
102	2.87E-02	0.1036	4.80E+00	3.12E-01
103	2.78E-02	0.1077	4.63E+00	2.90E-01
104	2.69E-02	0.1113	4.40E+00	2.67E-01
105	2.61E-02	0.1144	4.12E+00	2.41E-01
106	2.54E-02	0.1171	3.82E+00	2.17E-01
107	2.46E-02	0.1193	3.50E+00	1.93E-01
108	2.39E-02	0.1212	3.19E+00	1.71E-01

Appendix Table 4 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
109	2.33E-02	0.1229	2.91E+00	1.52E-01
110	2.26E-02	0.1242	2.66E+00	1.36E-01
111	2.20E-02	0.1255	2.46E+00	1.22E-01
112	2.15E-02	0.1266	2.28E+00	1.11E-01
113	2.09E-02	0.1277	2.16E+00	1.03E-01
114	2.04E-02	0.1287	2.06E+00	9.60E-02
115	1.99E-02	0.1297	1.97E+00	8.95E-02
116	1.94E-02	0.1306	1.91E+00	8.51E-02
117	1.89E-02	0.1315	1.87E+00	8.12E-02
118	1.85E-02	0.1323	1.84E+00	7.79E-02
119	1.80E-02	0.1331	1.81E+00	7.50E-02
120	1.76E-02	0.1338	1.79E+00	7.21E-02
121	6.72E-02	0.1345	1.75E+00	6.91E-02
122	1.68E-02	0.1351	1.72E+00	6.62E-02
123	1.64E-02	0.1358	1.68E+00	6.33E-02
124	1.60E-02	0.1364	1.65E+00	6.06E-02
125	1.56E-02	0.1370	1.62E+00	5.84E-02
126	1.52E-02	0.1376	1.63E+00	5.72E-02
127	1.49E-02	0.1382	1.62E+00	5.57E-02
128	1.45E-02	0.1388	1.62E+00	5.43E-02
129	1.42E-02	0.1393	1.64E+00	5.37E-02
130	1.38E-02	0.1398	1.67E+00	5.34E-02
131	1.35E-02	0.1404	1.70E+00	5.31E-02
132	1.32E-02	0.1408	1.73E+00	5.31E-02
133	1.29E-02	0.1413	1.78E+00	5.33E-02
134	1.27E-02	0.1418	1.83E+00	5.38E-02
135	1.24E-02	0.1422	1.89E+00	5.44E-02
136	1.22E-02	0.1427	1.94E+00	5.48E-02
137	1.20E-02	0.1432	1.98E+00	5.48E-02
138	1.18E-02	0.1436	2.05E+00	5.57E-02
139	1.16E-02	0.1441	2.12E+00	5.68E-02
140	1.14E-02	0.1445	2.14E+00	5.63E-02
141	1.12E-02	0.1449	2.14E+00	5.51E-02
142	1.10E-02	0.1453	2.13E+00	5.40E-02
143	1.08E-02	0.1457	2.12E+00	5.26E-02
144	1.06E-02	0.1461	2.09E+00	5.12E-02

Appendix Table 4 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
145	1.05E-02	0.1465	2.06E+00	4.96E-02
146	1.03E-02	0.1468	2.04E+00	4.82E-02
147	1.01E-02	0.1471	2.03E+00	4.72E-02
148	9.97E-03	0.1474	2.00E+00	4.60E-02
149	9.81E-03	0.1476	1.96E+00	4.44E-02
150	9.67E-03	0.1479	1.91E+00	4.27E-02
151	9.52E-03	0.1482	1.91E+00	4.21E-02
152	9.38E-03	0.1485	1.93E+00	4.20E-02
153	9.24E-03	0.1487	1.95E+00	4.18E-02
154	9.10E-03	0.1490	2.00E+00	4.21E-02
155	8.97E-03	0.1493	2.03E+00	4.22E-02
156	8.84E-03	0.1495	2.05E+00	4.19E-02
157	8.71E-03	0.1498	2.06E+00	4.15E-02
158	8.59E-03	0.1501	2.05E+00	4.04E-02
159	8.47E-03	0.1503	2.06E+00	4.07E-02
160	8.35E-03	0.1506	2.06E+00	3.94E-02
161	8.23E-03	0.1508	2.05E+00	3.89E-02
162	8.12E-03	0.1511	2.03E+00	3.80E-02
163	7.01E-03	0.1513	2.02E+00	3.73E-02
164	7.90E-03	0.1515	2.01E+00	3.66E-02
165	7.79E-03	0.1517	1.97E+00	3.54E-02
166	7.69E-03	0.1519	1.94E+00	3.45E-02
167	7.59E-03	0.1521	1.95E+00	3.41E-02
168	7.49E-03	0.1523	1.95E+00	3.37E-02
169	7.39E-03	0.1525	1.96E+00	3.34E-02
170	7.29E-03	0.1526	1.96E+00	3.31E-02
171	7.20E-03	0.1528	2.00E+00	3.33E-02
172	7.11E-03	0.1530	2.04E+00	3.35E-02
173	7.02E-03	0.1532	2.07E+00	3.37E-02
174	7.93E-03	0.1534	2.10E+00	3.37E-02
175	6.85E-03	0.1535	2.18E+00	3.46E-02
176	6.77E-03	0.1537	2.24E+00	3.49E-02
177	6.69E-03	0.1539	2.30E+00	3.53E-02
178	6.61E-03	0.1541	2.35E+00	3.54E-02
179	6.54E-03	0.1542	2.41E+00	3.56E-02
180	6.51E-03	0.1543	2.47E+00	3.61E-02



Appendix Figure 1 Porosity at 1 day of cement paste containing fly ash 0% with 7 hours of microwave curing.

Appendix Table 5 Pore size distribution by volume at 1 day of cement paste containing fly ash 0% with normal curing.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	2.06E+02	0.0000	6.03E-05	3.42E-02
2	1.77E+02	0.0093	6.45E-05	3.38E-02
3	1.41E+02	0.0119	8.45E-04	3.07E-02
4	1.13E+02	0.0132	1.20E-04	2.83E-02
5	9.30E+01	0.0141	1.64E-04	2.62E-02
6	8.07E+01	0.0148	2.09E-04	2.45E-02
7	7.15E+01	0.0164	2.74E-04	2.52E-02
8	6.38E+01	0.0169	1.12E-05	1.28E-02
9	5.76E+01	0.0173	9.76E-04	1.11E-02
10	5.25E+01	0.0176	1.00E-04	1.06E-02
11	4.82E+01	0.0178	1.07E-04	1.03E-02
12	4.47E+01	0.0181	1.13E-05	1.00E-02
13	4.19E+01	0.0183	8.31E-05	7.72E-03
14	3.95E+01	0.0185	8.46E-05	7.48E-03
15	3.73E+01	0.0187	8.60E-05	7.28E-03
16	3.52E+01	0.0189	8.96E-05	7.18E-03
17	3.33E+01	0.0191	9.23E-05	6.99E-03
18	3.16E+01	0.0192	9.53E-05	6.82E-03
19	3.00E+01	0.0194	9.79E-04	6.65E-03
20	2.86E+01	0.0195	1.01E-05	6.51E-03
21	2.72E+01	0.0196	9.80E-05	6.02E-03
22	2.60E+01	0.0197	9.75E-05	5.73E-03
23	2.49E+01	0.0198	9.81E-04	5.55E-03
24	2.38E+01	0.0200	1.11E-04	6.19E-03
25	2.28E+01	0.0201	1.30E-04	7.10E-03
26	2.18E+01	0.0201	1.53E-04	8.14E-03
27	2.10E+01	0.0202	1.76E-04	9.03E-03
28	2.02E+01	0.0203	2.05E-04	1.01E-02
29	1.95E+01	0.0205	2.36E-04	1.12E-02
30	1.89E+01	0.0210	2.76E-04	1.24E-02
31	1.83E+01	0.0217	3.10E-04	1.37E-02
32	1.78E+01	0.0212	3.56E-04	1.51E-02
33	1.73E+01	0.0214	4.03E-04	1.64E-02
34	1.68E+01	0.0216	4.42E-04	1.73E-02
35	1.64E+01	0.0228	4.34E-04	1.64E-02

Appendix Table 5 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
36	1.60E+01	0.0220	4.14E-04	1.51E-02
37	1.56E+01	0.0222	3.87E-04	1.34E-02
38	1.52E+01	0.0224	3.65E-04	1.24E-02
39	1.49E+01	0.0226	3.34E-04	1.10E-02
40	1.45E+01	0.0226	2.99E-04	9.52E-03
41	1.42E+01	0.0226	2.56E-04	7.87E-03
42	1.38E+01	0.0227	2.12E-04	6.33E-03
43	1.35E+01	0.0227	1.63E-04	4.75E-03
44	1.32E+01	0.0227	1.11E-05	3.20E-03
45	1.29E+01	0.0227	7.10E-05	2.11E-03
46	1.26E+01	0.0227	7.08E-05	2.09E-03
47	1.23E+01	0.0227	7.72E-05	2.23E-03
48	1.21E+01	0.0228	8.42E-05	2.38E-03
49	1.18E+01	0.0228	8.52E-05	2.37E-03
50	1.16E+01	0.0228	8.99E-05	2.44E-03
51	1.14E+01	0.0228	9.28E-05	2.47E-03
52	1.11E+01	0.0229	9.99E-05	2.59E-03
53	1.09E+01	0.0229	1.02E-04	2.62E-03
54	1.07E+01	0.0229	1.06E-04	2.75E-03
55	1.06E+01	0.0229	1.12E-04	3.12E-03
56	1.01E+01	0.0230	1.18E-04	3.58E-03
57	9.26E+00	0.0231	1.30E-04	4.02E-03
58	8.02E+00	0.0232	1.57E-04	5.42E-03
59	6.31E+00	0.0235	2.21E-04	1.06E-02
60	4.57E+00	0.0244	3.84E-04	8.65E-03
61	3.12E+00	0.0258	7.63E-03	1.12E-02
62	2.08E+00	0.0276	1.66E-03	1.45E-02
63	1.42E+00	0.0300	3.57E-03	1.87E-02
64	1.00E+00	0.0328	7.35E-02	2.39E-02
65	7.34E-01	0.0362	1.38E-02	3.01E-02
66	5.55E-01	0.0399	2.34E-02	3.68E-02
67	4.32E-01	0.0441	3.72E-02	4.42E-02
68	3.45E-01	0.0488	5.69E-02	5.25E-02
69	2.82E-01	0.0540	8.35E-01	6.14E-02
70	2.35E-01	0.0597	1.19E-01	7.12E-02
71	1.99E-01	0.0654	1.63E-01	8.14E-02
72	1.72E-01	0.0711	2.17E-01	9.19E-02

Appendix Table 5 (Continued)

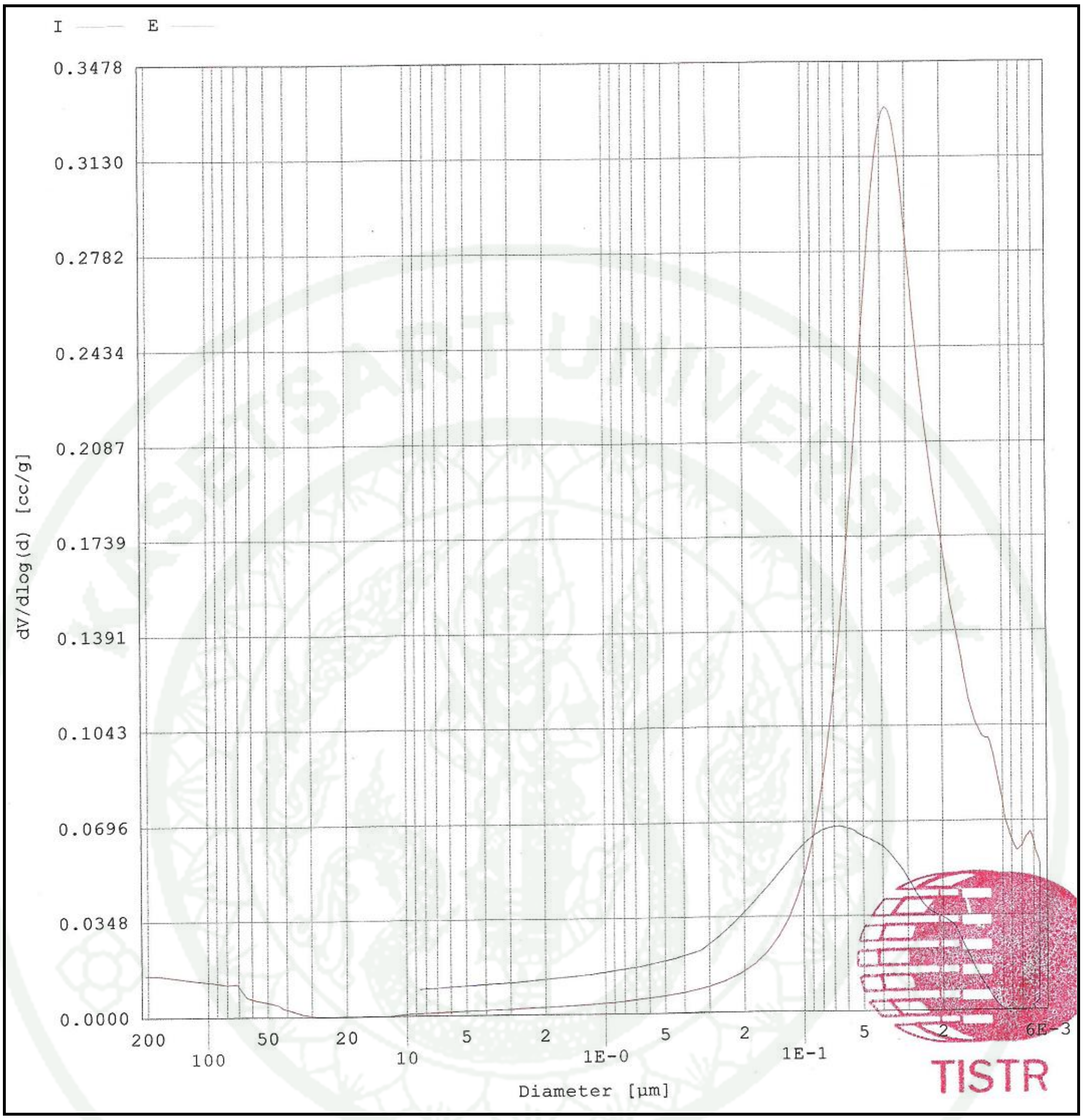
Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
73	1.51E-01	0.0770	2.81E-01	1.03E-01
74	1.34E-01	0.0827	3.51E-01	1.13E-01
75	1.20E-01	0.0886	4.26E-01	1.21E-01
76	1.09E-01	0.0944	5.03E-01	1.29E-01
77	9.96E-02	0.1002	5.82E-01	1.35E-01
78	9.17E-02	0.1058	6.62E-01	1.40E-01
79	8.48E-02	0.1111	7.36E-01	1.43E-01
80	7.89E-02	0.1161	8.05E-01	1.44E-01
81	7.36E-02	0.1206	8.61E-01	1.43E-01
82	6.90E-02	0.1249	9.05E-01	1.40E-01
83	6.48E-02	0.1287	9.35E-01	1.35E-01
84	6.11E-02	0.1322	9.49E-01	1.29E-01
85	5.77E-02	0.1352	9.51E-01	1.21E-01
86	5.47E-02	0.1379	9.49E-01	1.15E-01
87	5.19E-02	0.1402	9.33E-01	1.07E-01
88	4.94E-02	0.1423	9.12E-01	1.00E-01
89	4.70E-02	0.1441	8.87E-01	9.30E-02
90	4.49E-02	0.1457	8.64E-01	8.67E-02
91	4.29E-02	0.1473	8.42E-01	8.13E-02
92	4.10E-02	0.1487	8.29E-01	7.70E-02
93	3.93E-02	0.1500	8.21E-01	7.33E-02
94	3.76E-02	0.1512	8.16E-01	7.02E-02
95	3.63E-02	0.1523	8.21E-01	6.81E-02
96	3.49E-02	0.1533	8.25E-01	6.60E-02
97	3.36E-02	0.1544	8.25E-01	6.37E-02
98	3.24E-02	0.1553	8.30E-01	6.19E-02
99	3.13E-02	0.1563	8.42E-01	6.06E-02
100	3.03E-02	0.1572	8.60E-01	5.99E-02
101	2.93E-02	0.1581	8.80E-01	5.94E-02
102	2.83E-02	0.1588	9.04E-01	5.92E-02
103	2.74E-02	0.1596	9.29E-01	5.90E-02
104	2.66E-02	0.1603	9.58E-01	5.91E-02
105	2.58E-02	0.1611	9.90E-01	5.93E-02
106	2.50E-02	0.1619	1.02E+00	5.97E-02
107	2.43E-02	0.1627	1.07E+00	6.04E-02
108	2.36E-02	0.1634	1.12E+00	6.17E-02

Appendix Table 5 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
109	2.30E-02	0.1642	1.17E+00	6.28E-02
110	2.24E-02	0.1649	1.23E+00	6.39E-02
111	2.18E-02	0.1657	1.27E+00	6.44E-02
112	2.12E-02	0.1665	1.32E+00	6.49E-02
113	2.07E-02	0.1672	1.36E+00	6.50E-02
114	2.02E-02	0.1680	1.39E+00	6.48E-02
115	1.97E-02	0.1687	1.42E+00	6.45E-02
116	1.92E-02	0.1694	1.45E+00	6.43E-02
117	1.87E-02	0.1701	1.48E+00	6.38E-02
118	1.83E-02	0.1707	1.51E+00	6.39E-02
119	1.79E-02	0.1713	1.55E+00	6.41E-02
120	1.75E-02	0.1719	1.58E+00	6.42E-02
121	1.71E-02	0.1725	1.63E+00	6.46E-02
122	1.67E-02	0.1731	1.68E+00	6.52E-02
123	1.63E-02	0.1737	1.73E+00	6.59E-02
124	1.60E-02	0.1744	1.80E+00	6.72E-02
125	1.56E-02	0.1751	1.89E+00	6.08E-02
126	1.53E-02	0.1758	1.98E+00	7.04E-02
127	1.49E-02	0.1765	2.06E+00	7.16E-02
128	1.46E-02	0.1772	2.15E+00	7.30E-02
129	1.43E-02	0.1779	2.20E+00	7.30E-02
130	1.40E-02	0.1786	2.25E+00	7.30E-02
131	1.36E-02	0.1793	2.29E+00	7.28E-02
132	1.34E-02	0.1800	2.33E+00	7.23E-02
133	1.32E-02	0.1806	2.37E+00	7.18E-02
134	1.29E-02	0.1812	2.39E+00	7.11E-02
135	1.27E-02	0.1818	2.40E+00	6.98E-02
136	1.24E-02	0.1823	2.40E+00	6.85E-02
137	1.22E-02	0.1829	2.40E+00	6.74E-02
138	1.20E-02	0.1834	2.40E+00	6.65E-02
139	1.18E-02	0.1838	2.42E+00	6.59E-02
140	1.16E-02	0.1843	2.47E+00	6.61E-02
141	1.14E-02	0.1848	2.50E+00	6.60E-02
142	1.12E-02	0.1852	2.56E+00	6.65E-02
143	1.10E-02	0.1857	2.62E+00	6.68E-02
144	1.08E-02	0.1862	2.68E+00	6.72E-02

Appendix Table 5 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
145	1.07E-02	0.1867	2.74E+00	6.78E-02
146	1.05E-02	0.1872	2.83E+00	6.88E-02
147	1.03E-02	0.1877	2.91E+00	6.96E-02
148	1.02E-02	0.1882	2.97E+00	6.99E-02
149	1.00E-02	0.1886	3.02E+00	7.00E-02
150	9.85E-03	0.1891	3.05E+00	6.96E-02
151	9.70E-03	0.1896	3.06E+00	6.87E-02
152	9.56E-03	0.1900	3.08E+00	6.80E-02
153	9.42E-03	0.1905	3.07E+00	6.67E-02
154	9.28E-03	0.1909	3.07E+00	6.58E-02
155	9.14E-03	0.1913	3.07E+00	6.49E-02
156	9.01E-03	0.1917	3.07E+00	6.38E-02
157	8.88E-03	0.1921	3.03E+00	6.21E-02
158	8.75E-03	0.1925	2.99E+00	6.05E-02
159	8.63E-03	0.1928	2.98E+00	5.93E-02
160	8.51E-03	0.1932	2.96E+00	5.82E-02
161	8.39E-03	0.1935	2.94E+00	5.70E-02
162	8.27E-03	0.1939	2.93E+00	5.59E-02
163	8.16E-03	0.1942	2.93E+00	5.52E-02
164	8.05E-03	0.1945	2.94E+00	5.46E-02
165	7.94E-03	0.1948	2.94E+00	5.40E-02
166	7.84E-03	0.1951	2.94E+00	5.33E-02
167	7.73E-03	0.1954	2.95E+00	5.27E-02
168	7.63E-03	0.1957	2.97E+00	5.24E-02
169	7.53E-03	0.1960	3.00E+00	5.23E-02
170	7.43E-03	0.1963	3.02E+00	5.19E-02
171	7.34E-03	0.1966	3.06E+00	5.20E-02
172	7.24E-03	0.1969	3.13E+00	5.26E-02
173	7.15E-03	0.1972	3.19E+00	5.28E-02
174	7.06E-03	0.1975	3.22E+00	5.26E-02
175	6.97E-03	0.1978	3.28E+00	5.30E-02
176	6.89E-03	0.1981	3.39E+00	5.41E-02
177	6.80E-03	0.1984	3.47E+00	5.44E-02
178	6.72E-03	0.1986	3.55E+00	5.47E-02
179	6.64E-03	0.1989	3.64E+00	5.50E-02
180	6.56E-03	0.1992	3.73E+00	5.53E-02
181	6.48E-03	0.1995	3.84E+00	5.60E-02



Appendix Figure 2 Porosity at 1 day of cement paste containing fly ash 0% with normal curing.

Appendix Table 6 Pore size distribution by volume at 1 day of cement paste containing fly ash 30% with microwave curing at 7 hours.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	2.06E+02	0.0000	2.60E-05	1.53E-02
2	1.77E+02	0.0037	2.80E-05	1.53E-02
3	1.41E+02	0.0049	3.72E-05	1.42E-02
4	1.13E+02	0.0058	5.30E-05	1.33E-02
5	9.30E+01	0.0063	7.32E-05	1.26E-02
6	8.07E+01	0.0067	9.46E-04	1.19E-02
7	7.15E+01	0.0075	1.25E-05	1.22E-02
8	6.38E+01	0.0079	6.18E-05	7.18E-03
9	5.76E+01	0.0082	5.78E-05	6.36E-03
10	5.25E+01	0.0084	5.66E-05	5.76E-03
11	4.82E+01	0.0086	5.72E-05	5.20E-03
12	4.47E+01	0.0087	5.62E-05	4.62E-03
13	4.19E+01	0.0087	4.02E-05	3.26E-03
14	3.95E+01	0.0088	3.47E-05	2.65E-03
15	3.73E+01	0.0089	2.90E-05	2.09E-03
16	3.52E+01	0.0089	2.31E-05	1.58E-03
17	3.33E+01	0.0089	1.73E-05	1.12E-03
18	3.16E+01	0.0089	1.31E-05	8.00E-04
19	3.00E+01	0.0089	1.02E-06	5.80E-04
20	2.86E+01	0.0089	6.38E-06	3.43E-04
21	2.72E+01	0.0089	2.53E-06	1.32E-04
22	2.60E+01	0.0089	1.84E-07	9.00E-05
23	2.49E+01	0.0089	9.80E+00	4.50E-05
24	2.38E+01	0.0089	0.00E+00	0.00E+00
25	2.28E+01	0.0089	0.00E+00	0.00E+00
26	2.18E+01	0.0089	0.00E+00	0.00E+00
27	2.10E+01	0.0089	0.00E+00	0.00E+00
28	2.02E+01	0.0089	0.00E+00	0.00E+00
29	1.95E+01	0.0089	0.00E+00	0.00E+00
30	1.89E+01	0.0089	0.00E+00	0.00E+00
31	1.83E+01	0.0089	0.00E+00	0.00E+00
32	1.78E+01	0.0089	0.00E+00	0.00E+00
33	1.73E+01	0.0089	0.00E+00	0.00E+00
34	1.68E+01	0.0089	0.00E+00	0.00E+00
35	1.64E+01	0.0089	0.00E+00	0.00E+00

Appendix Table 6 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
36	1.60E+01	0.0089	0.00E+00	0.00E+00
37	1.56E+01	0.0089	0.00E+00	0.00E+00
38	1.52E+01	0.0089	0.00E+00	0.00E+00
39	1.49E+01	0.0089	0.00E+00	0.00E+00
40	1.45E+01	0.0089	0.00E+00	0.00E+00
41	1.42E+01	0.0089	0.00E+00	0.00E+00
42	1.38E+01	0.0089	0.00E+00	0.00E+00
43	1.35E+01	0.0089	0.00E+00	0.00E+00
44	1.32E+01	0.0089	0.00E+00	0.00E+00
45	1.29E+01	0.0089	0.00E+00	0.00E+00
46	1.26E+01	0.0089	0.00E+00	0.00E+00
47	1.23E+01	0.0089	0.00E+00	0.00E+00
48	1.21E+01	0.0089	1.59E-06	5.20E-05
49	1.18E+01	0.0089	4.12E-06	1.39E-04
50	1.16E+01	0.0089	6.53E-06	2.33E-04
51	1.14E+01	0.0089	8.99E-06	3.53E-04
52	1.09E+01	0.0089	1.15E-05	5.07E-04
53	1.00E+01	0.0089	1.19E-05	6.99E-04
54	8.60E+00	0.0090	2.41E-05	9.63E-04
55	6.63E+00	0.0091	3.18E-05	1.28E-03
56	4.60E+00	0.0093	7.67E-04	1.68E-03
57	2.99E+00	0.0096	1.09E-04	2.19E-03
58	1.93E+00	0.0100	4.63E-04	2.82E-03
59	1.29E+00	0.0105	9.21E-03	3.55E-03
60	9.03E-01	0.0111	7.24E-03	4.37E-03
61	6.57E-01	0.0117	3.77E-03	5.38E-03
62	4.95E-01	0.0124	4.10E-03	6.53E-03
63	3.85E-01	0.0131	7.94E-02	7.84E-03
64	3.07E-01	0.0140	1.77E-02	9.51E-03
65	2.51E-01	0.0149	1.13E-02	1.16E-02
66	2.09E-01	0.0158	2.74E-02	1.43E-02
67	1.77E-01	0.0168	3.58E-02	1.77E-02
68	1.53E-01	0.0178	5.67E-02	2.20E-02
69	1.34E-01	0.0190	7.28E-01	2.74E-02
70	1.19E-01	0.0203	1.44E-01	3.40E-02
71	1.07E-01	0.0218	1.05E-01	4.23E-02
72	9.76E-02	0.0236	1.48E-01	5.22E-02

Appendix Table 6 (Continued)

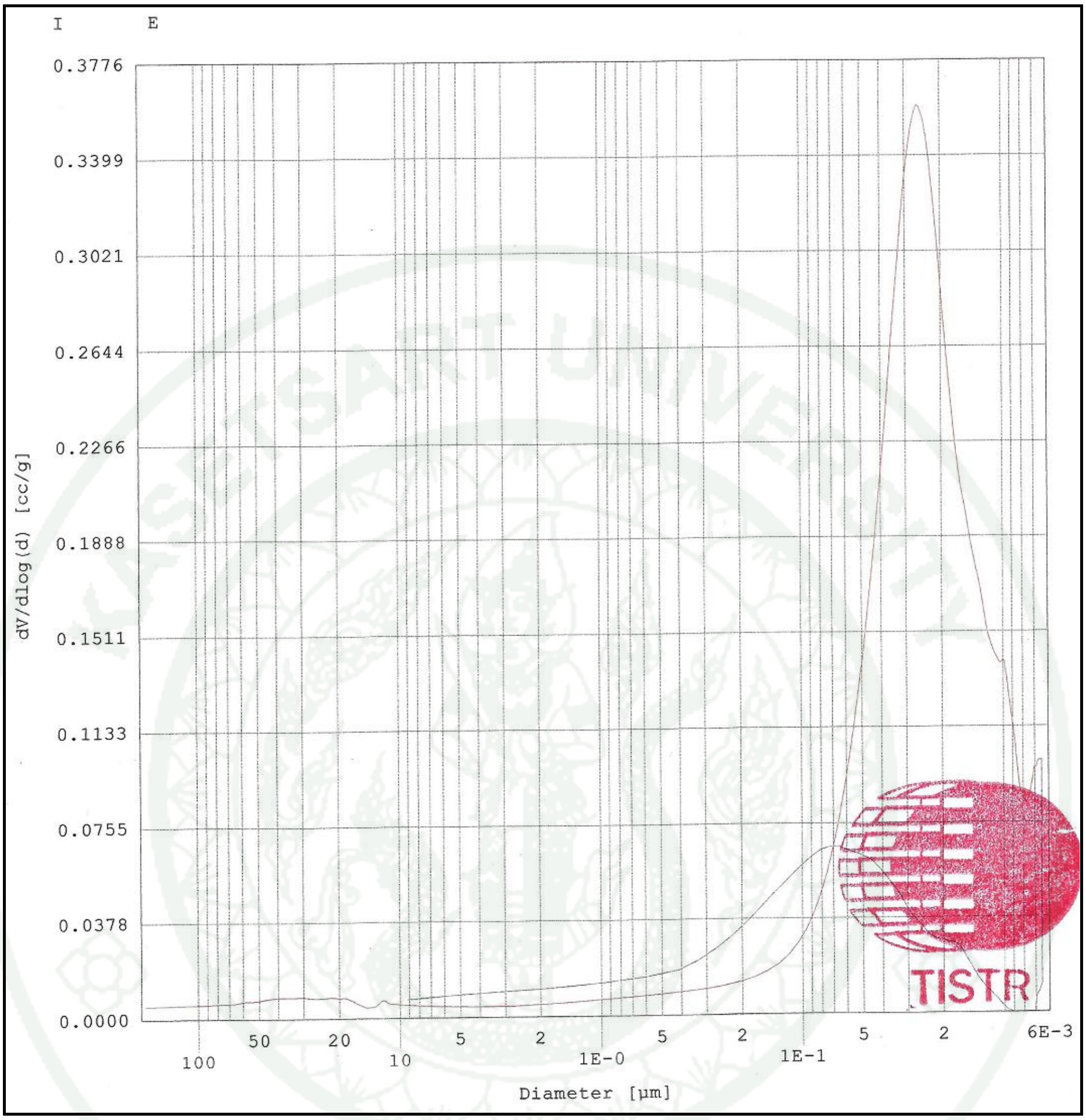
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
73	8.94E-02	0.0256	2.98E-01	6.40E-02
74	8.25E-02	0.0279	2.69E-01	7.81E-02
75	7.65E-02	0.0306	3.52E-01	9.41E-02
76	7.14E-02	0.0336	4.71E-01	1.12E-01
77	6.68E-02	0.0371	6.16E-01	1.32E-01
78	6.28E-02	0.0409	7.72E-01	1.54E-01
79	5.93E-02	0.0453	9.79E+00	1.76E-01
80	5.61E-02	0.0500	1.14E+00	1.99E-01
81	5.32E-02	0.0551	1.41E+00	2.23E-01
82	5.06E-02	0.0606	1.80E+00	2.45E-01
83	4.82E-02	0.0665	1.99E+00	2.66E-01
84	4.61E-02	0.0725	2.30E+00	2.85E-01
85	4.40E-02	0.0786	2.59E+00	3.01E-01
86	4.22E-02	0.0849	2.86E+00	3.14E-01
87	4.05E-02	0.0912	3.12E+00	3.24E-01
88	3.89E-02	0.0973	3.44E+00	3.29E-01
89	3.74E-02	0.1034	3.62E+00	3.31E-01
90	3.60E-02	0.1091	3.87E+00	3.30E-01
91	3.47E-02	0.1145	3.99E+00	3.26E-01
92	3.35E-02	0.1196	3.05E+00	3.19E-01
93	3.23E-02	0.1245	4.19E+00	3.10E-01
94	3.12E-02	0.1289	4.19E+00	2.99E-01
95	3.02E-02	0.1331	4.17E+00	2.87E-01
96	2.92E-02	0.1370	4.13E+00	2.76E-01
97	2.83E-02	0.1406	4.19E+00	2.65E-01
98	2.74E-02	0.1440	4.04E+00	2.53E-01
99	2.66E-02	0.1472	4.09E+00	2.43E-01
100	2.58E-02	0.1501	4.95E+00	2.34E-01
101	2.51E-02	0.2530	3.92E+00	2.25E-01
102	2.43E-02	0.2557	3.89E+00	2.18E-01
103	2.37E-02	0.2582	3.86E+00	2.10E-01
104	2.34E-02	0.2606	3.83E+00	2.03E-01
105	2.28E-02	0.2630	3.81E+00	1.96E-01
106	2.12E-02	0.2652	3.79E+00	1.90E-01
107	2.17E-02	0.2674	3.77E+00	1.84E-01
108	2.01E-02	0.2693	3.75E+00	1.78E-01

Appendix Table 6 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
109	2.07E-02	0.2712	3.74E+00	1.74E-01
110	1.97E-02	0.2730	3.72E+00	1.68E-01
111	1.92E-02	0.2747	3.69E+00	1.63E-01
112	1.88E-02	0.2763	3.65E+00	1.58E-01
113	1.83E-02	0.2779	3.61E+00	1.52E-01
114	1.79E-02	0.2794	3.59E+00	1.48E-01
115	1.75E-02	0.2808	3.57E+00	1.44E-01
116	1.71E-02	0.2822	3.56E+00	1.40E-01
117	1.67E-02	0.2835	3.54E+00	1.36E-01
118	1.64E-02	0.2847	3.53E+00	1.33E-01
119	1.60E-02	0.2849	3.50E+00	1.29E-01
120	1.57E-02	0.2851	3.46E+00	1.25E-01
121	1.53E-02	0.2872	3.42E+00	1.21E-01
122	1.50E-02	0.2883	3.39E+00	1.17E-01
123	1.47E-02	0.2904	3.36E+00	1.14E-01
124	1.44E-02	0.2914	3.36E+00	1.12E-01
125	1.41E-02	0.2924	3.35E+00	1.09E-01
126	1.38E-02	0.2933	3.35E+00	1.07E-01
127	1.35E-02	0.2942	3.36E+00	1.05E-01
128	1.32E-02	0.2951	3.38E+00	1.04E-01
129	1.30E-02	0.2960	3.40E+00	1.02E-01
130	1.27E-02	0.2969	3.43E+00	1.01E-01
131	1.25E-02	0.2977	3.47E+00	1.00E-01
132	1.22E-02	0.2986	3.53E+00	9.98E-02
133	1.20E-02	0.2995	3.60E+00	9.98E-02
134	1.18E-02	0.2003	3.67E+00	9.98E-02
135	1.16E-02	0.2011	3.69E+00	9.84E-02
136	1.14E-02	0.2018	3.67E+00	9.61E-02
137	1.12E-02	0.2025	3.66E+00	9.40E-02
138	1.10E-02	0.2033	3.63E+00	9.15E-02
139	1.08E-02	0.2039	3.58E+00	8.88E-02
140	1.06E-02	0.2045	3.53E+00	8.63E-02
141	1.04E-02	0.2051	3.49E+00	8.38E-02
142	1.03E-02	0.2056	3.44E+00	8.13E-02
143	1.01E-02	0.2061	3.37E+00	7.85E-02
144	9.96E-03	0.2066	3.29E+00	7.54E-02

Appendix Table 6 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
145	9.80E-03	0.2071	3.19E+00	7.22E-02
146	9.67E-03	0.2076	3.14E+00	6.99E-02
147	9.52E-03	0.2080	3.12E+00	6.84E-02
148	9.37E-03	0.2085	3.09E+00	6.68E-02
149	9.24E-03	0.2089	3.06E+00	6.52E-02
150	9.10E-03	0.2093	3.04E+00	6.28E-02
151	8.97E-03	0.2097	3.02E+00	6.24E-02
152	8.84E-03	0.2101	2.99E+00	6.11E-02
153	8.71E-03	0.2104	2.99E+00	6.02E-02
154	8.59E-03	0.2108	2.99E+00	5.93E-02
155	8.46E-03	0.2111	3.00E+00	5.87E-02
156	8.35E-03	0.2115	3.06E+00	5.90E-02
157	8.23E-03	0.2118	3.12E+00	5.94E-02
158	8.12E-03	0.2122	3.18E+00	5.98E-02
159	8.01E-03	0.2125	3.25E+00	6.03E-02
160	7.90E-03	0.2129	3.34E+00	6.12E-02
161	7.79E-03	0.2133	3.44E+00	6.22E-02
162	7.69E-03	0.2136	3.54E+00	6.32E-02
163	7.59E-03	0.2140	3.63E+00	6.38E-02
164	7.49E-03	0.2144	3.70E+00	6.41E-02
165	7.39E-03	0.2148	3.78E+00	6.47E-02
166	7.29E-03	0.2152	3.87E+00	6.54E-02
167	7.20E-03	0.2155	3.90E+00	6.49E-02
168	7.11E-03	0.2159	3.89E+00	6.39E-02
169	7.02E-03	0.2163	3.85E+00	6.23E-02
170	6.93E-03	0.2166	3.81E+00	6.07E-02
171	6.85E-03	0.2169	3.73E+00	5.87E-02
172	6.77E-03	0.2172	3.72E+00	5.76E-02
173	6.69E-03	0.2175	3.71E+00	5.65E-02
174	6.61E-03	0.2178	3.71E+00	5.56E-02
175	6.54E-03	0.2180	3.70E+00	5.45E-02
176	6.51E-03	0.2181	3.63E+00	5.31E-02



Appendix Figure 3 Porosity at 1 day of cement paste containing fly ash 30% with 7 hours of microwave curing.

Appendix Table 7 Pore size distribution by volume at 1 day of cement paste containing fly ash 30% with with normal curing.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	1.90E+02	0.0000	1.39E-04	7.05E-02
2	1.65E+02	0.0185	1.45E-04	6.85E-02
3	1.34E+02	0.0229	1.82E-04	6.13E-02
4	1.09E+02	0.0253	2.48E-04	5.58E-02
5	9.09E+01	0.0270	3.30E-04	5.12E-02
6	7.77E+01	0.0281	4.23E-04	4.74E-02
7	6.86E+01	0.0312	5.62E-04	4.81E-02
8	6.09E+01	0.0317	2.00E-04	2.06E-02
9	5.46E+01	0.0323	1.67E-04	1.67E-02
10	4.94E+01	0.0327	1.61E-04	1.47E-02
11	4.51E+01	0.0331	1.61E-04	1.32E-02
12	4.15E+01	0.0334	1.63E-05	1.20E-02
13	3.84E+01	0.0336	9.32E-05	7.34E-03
14	3.58E+01	0.0338	8.99E-05	6.64E-03
15	3.35E+01	0.0339	8.54E-05	6.03E-03
16	3.15E+01	0.0341	8.21E-05	5.60E-03
17	2.98E+01	0.0342	8.03E-05	5.29E-03
18	2.82E+01	0.0343	7.83E-05	4.98E-03
19	2.68E+01	0.0343	7.86E-05	4.81E-03
20	2.55E+01	0.0344	8.17E-05	4.82E-03
21	2.45E+01	0.0345	8.64E-05	4.92E-03
22	2.35E+01	0.0346	9.14E-05	5.03E-03
23	2.27E+01	0.0347	9.91E-04	5.26E-03
24	2.19E+01	0.0348	1.06E-04	5.46E-03
25	2.11E+01	0.0349	1.17E-04	5.75E-03
26	2.14E+01	0.0350	1.24E-04	5.90E-03
27	1.98E+01	0.0351	1.29E-04	5.97E-03
28	1.91E+01	0.0351	1.35E-04	6.03E-03
29	1.86E+01	0.0352	1.45E-04	6.29E-03
30	1.80E+01	0.0353	1.57E-04	6.59E-03
31	1.75E+01	0.0354	1.64E-04	6.68E-03
32	1.70E+01	0.0355	1.72E-04	6.81E-03
33	1.66E+01	0.0355	1.78E-04	6.84E-03
34	1.61E+01	0.0356	1.89E-04	7.10E-03
35	1.57E+01	0.0357	1.97E-04	7.20E-03

Appendix Table 7 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
36	1.54E+01	0.0358	2.05E-04	7.30E-03
37	1.50E+01	0.0359	2.10E-04	7.32E-03
38	1.47E+01	0.0359	2.10E-04	7.11E-03
39	1.44E+01	0.0360	2.09E-04	6.92E-03
40	1.42E+01	0.0361	2.04E-04	6.60E-03
41	1.39E+01	0.0361	1.98E-04	6.31E-03
42	1.37E+01	0.0362	1.97E-04	6.16E-03
43	1.34E+01	0.0362	1.94E-04	5.95E-03
44	1.32E+01	0.0362	1.90E-04	5.74E-03
45	1.29E+01	0.0363	1.75E-04	5.18E-03
46	1.27E+01	0.0363	1.64E-04	4.75E-03
47	1.24E+01	0.0364	1.55E-04	4.43E-03
48	1.22E+01	0.0364	1.51E-04	4.25E-03
49	1.19E+01	0.0364	1.56E-04	4.30E-03
50	1.17E+01	0.0365	1.61E-04	4.37E-03
51	1.15E+01	0.0365	1.64E-04	4.34E-03
52	1.13E+01	0.0365	1.59E-04	4.13E-03
53	1.11E+01	0.0366	1.54E-04	3.92E-03
54	1.09E+01	0.0366	1.59E-04	3.74E-03
55	1.07E+01	0.0366	1.45E-04	4.63E-03
56	1.05E+01	0.0367	2.89E-04	5.15E-03
57	1.04E+01	0.0367	2.00E-04	5.35E-03
58	1.02E+01	0.0367	2.30E-04	5.26E-03
59	1.01E+01	0.0367	2.10E-04	5.24E-03
60	9.96E+00	0.0368	2.27E-04	5.52E-03
61	9.74E+00	0.0369	2.28E-04	6.06E-03
62	9.37E+00	0.0370	2.38E-04	6.91E-03
63	8.73E+00	0.0371	2.59E-04	8.35E-03
64	7.74E+00	0.0373	3.96E-04	1.06E-02
65	6.34E+00	0.0380	5.80E-04	1.40E-02
66	4.74E+00	0.0394	7.34E-03	1.76E-02
67	3.32E+00	0.0414	1.80E-03	2.28E-02
68	2.28E+00	0.0444	2.30E-03	2.97E-02
69	1.59E+00	0.0487	6.97E-02	3.80E-02
70	1.15E+00	0.0544	1.13E-02	4.75E-02
71	1.51E-01	0.0613	2.21E-02	5.78E-02
72	6.47E-01	0.0693	3.21E-02	6.88E-02

Appendix Table 7 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
73	5.05E-01	0.0780	5.77E-02	8.06E-02
74	4.02E-01	0.0873	5.92E-02	9.27E-02
75	3.27E-01	0.0971	9.12E-01	1.04E-01
76	2.71E-01	0.1071	1.31E-01	1.13E-01
77	2.28E-01	0.1168	1.85E-01	1.21E-01
78	1.96E-01	0.1264	2.34E-01	1.27E-01
79	1.71E-01	0.1354	2.96E-01	1.32E-01
80	1.50E-01	0.1436	3.57E-01	1.35E-01
81	1.34E-01	0.1508	4.17E-01	1.38E-01
82	1.20E-01	0.1571	4.73E-01	1.39E-01
83	1.09E-01	0.1627	5.36E-01	1.39E-01
84	9.98E-02	0.1680	5.90E-01	1.38E-01
85	9.18E-02	0.1728	6.27E-01	1.35E-01
86	8.50E-02	0.1774	6.62E-01	1.33E-01
87	7.90E-02	0.1817	7.08E-01	1.31E-01
88	7.37E-02	0.1857	7.38E-01	1.29E-01
89	6.91E-02	0.1893	7.76E-01	1.27E-01
90	6.49E-02	0.1927	7.10E-01	1.25E-01
91	6.12E-02	0.1959	8.60E-01	1.22E-01
92	5.79E-02	0.1988	8.73E-01	1.18E-01
93	5.48E-02	0.2016	8.02E-01	1.14E-01
94	5.20E-02	0.2041	9.26E-01	1.10E-01
95	4.95E-02	0.2063	9.31E-01	1.07E-01
96	4.72E-02	0.2084	9.53E-01	1.03E-01
97	4.50E-02	0.2104	9.69E-01	9.90E-02
98	4.31E-02	0.2122	9.63E-01	9.53E-02
99	4.12E-02	0.2139	9.75E-01	9.16E-02
100	3.93E-02	0.2155	9.71E-01	8.85E-02
101	3.80E-02	0.2175	9.80E+00	8.59E-02
102	3.65E-02	0.2188	1.00E+00	8.36E-02
103	3.51E-02	0.2191	1.01E+00	8.17E-02
104	3.36E-02	0.2212	1.03E+00	8.04E-02
105	3.25E-02	0.2222	1.05E+00	7.90E-02
106	3.14E-02	0.2230	1.07E+00	7.78E-02
107	3.04E-02	0.2244	1.09E+00	7.66E-02
108	2.94E-02	0.2254	1.12E+00	7.61E-02

Appendix Table 7 (Continued)

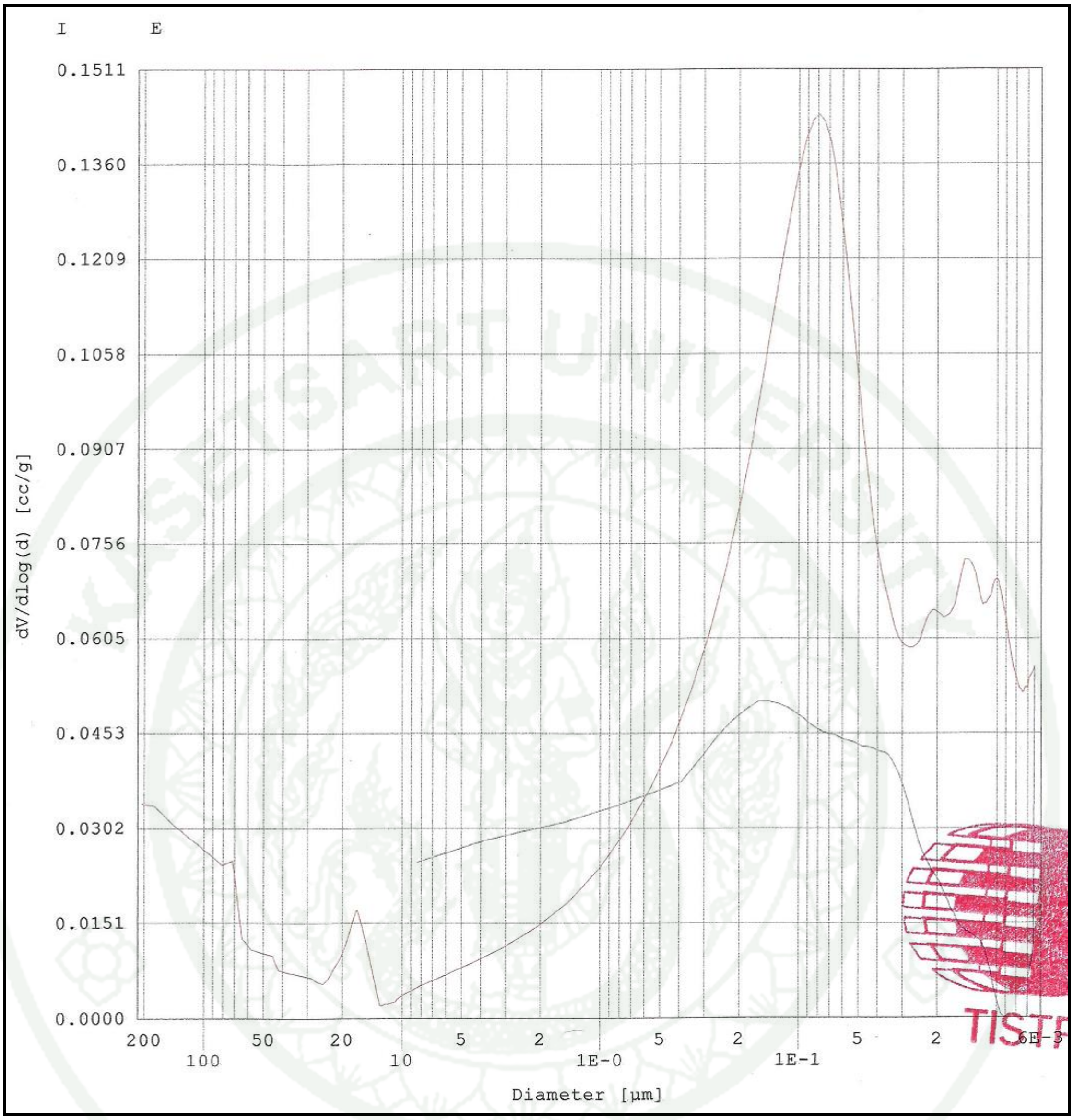
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
109	2.87E-02	0.2269	1.15E+00	7.60E-02
110	2.76E-02	0.2270	1.19E+00	7.61E-02
111	2.68E-02	0.2286	1.23E+00	7.64E-02
112	2.60E-02	0.2296	1.27E+00	7.67E-02
113	2.52E-02	0.2300	1.32E+00	7.71E-02
114	2.45E-02	0.2318	1.36E+00	7.75E-02
115	2.38E-02	0.2329	1.39E+00	7.69E-02
116	2.31E-02	0.2334	1.43E+00	7.69E-02
117	2.25E-02	0.2342	1.47E+00	7.68E-02
118	2.19E-02	0.2352	1.52E+00	7.71E-02
119	2.14E-02	0.2355	1.56E+00	7.70E-02
120	2.08E-02	0.2361	1.59E+00	7.68E-02
121	2.03E-02	0.2379	1.63E+00	7.65E-02
122	1.98E-02	0.2389	1.66E+00	7.61E-02
123	1.93E-02	0.2392	1.69E+00	7.58E-02
124	1.89E-02	0.2406	1.72E+00	7.53E-02
125	1.84E-02	0.2412	1.75E+00	7.49E-02
126	1.80E-02	0.2419	1.79E+00	7.48E-02
127	1.76E-02	0.2429	1.82E+00	7.43E-02
128	1.72E-02	0.2430	1.84E+00	7.31E-02
129	1.68E-02	0.2441	1.84E+00	7.13E-02
130	1.64E-02	0.2444	1.85E+00	7.00E-02
131	1.61E-02	0.2458	1.85E+00	6.84E-02
132	1.57E-02	0.2462	1.85E+00	6.69E-02
133	1.54E-02	0.2467	1.84E+00	6.54E-02
134	1.50E-02	0.2473	1.83E+00	6.34E-02
135	1.47E-02	0.2480	1.82E+00	6.15E-02
136	1.44E-02	0.2488	1.81E+00	5.99E-02
137	1.41E-02	0.2497	1.82E+00	5.92E-02
138	1.38E-02	0.2497	1.85E+00	5.89E-02
139	1.35E-02	0.2508	1.89E+00	5.92E-02
140	1.32E-02	0.2501	1.95E+00	5.98E-02
141	1.30E-02	0.2515	2.00E+00	6.03E-02
142	1.27E-02	0.2510	2.07E+00	6.11E-02
143	1.25E-02	0.2526	2.13E+00	6.17E-02
144	1.23E-02	0.2523	2.20E+00	6.24E-02

Appendix Table 7 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
145	1.20E-02	0.2531	2.28E+00	6.36E-02
146	1.18E-02	0.2530	2.38E+00	6.51E-02
147	1.16E-02	0.2540	2.44E+00	6.57E-02
148	1.14E-02	0.2540	2.47E+00	6.51E-02
149	1.12E-02	0.2551	2.48E+00	6.43E-02
150	1.10E-02	0.2553	2.49E+00	6.33E-02
151	1.09E-02	0.2561	2.49E+00	6.22E-02
152	1.07E-02	0.2566	2.48E+00	6.11E-02
153	1.05E-02	0.2570	2.47E+00	5.97E-02
154	1.03E-02	0.2574	2.45E+00	5.84E-02
155	1.02E-02	0.2577	2.44E+00	5.71E-02
156	1.00E-02	0.2581	2.39E+00	5.53E-02
157	9.87E-03	0.2585	2.34E+00	5.33E-02
158	9.72E-03	0.2588	2.30E+00	5.17E-02
159	9.58E-03	0.2591	2.29E+00	5.07E-02
160	9.44E-03	0.2595	2.27E+00	4.96E-02
161	9.30E-03	0.2598	2.27E+00	4.87E-02
162	9.16E-03	0.2601	2.27E+00	4.80E-02
163	9.03E-03	0.2604	2.26E+00	4.71E-02
164	8.90E-03	0.2606	2.27E+00	4.66E-02
165	8.77E-03	0.2609	2.28E+00	4.62E-02
166	8.65E-03	0.2612	2.28E+00	4.56E-02
167	8.53E-03	0.2615	2.30E+00	4.53E-02
168	8.41E-03	0.2617	2.32E+00	4.52E-02
169	8.29E-03	0.2620	2.36E+00	4.53E-02
170	8.18E-03	0.2623	2.38E+00	4.50E-02
171	8.07E-03	0.2626	2.42E+00	4.51E-02
172	7.96E-03	0.2628	2.46E+00	4.54E-02
173	7.85E-03	0.2631	2.51E+00	4.56E-02
174	7.75E-03	0.2634	2.58E+00	4.63E-02
175	7.65E-03	0.2636	2.63E+00	4.66E-02
176	7.55E-03	0.2639	2.67E+00	4.67E-02
177	7.45E-03	0.2641	2.73E+00	4.71E-02
178	7.36E-03	0.2644	2.78E+00	4.75E-02
179	7.26E-03	0.2647	2.86E+00	4.81E-02
180	7.17E-03	0.2650	2.95E+00	4.91E-02

Appendix Table 7 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
181	7.08E-03	0.2652	3.01E+00	4.93E-02
182	6.99E-03	0.2655	3.02E+00	4.87E-02
183	6.90E-03	0.2658	3.04E+00	4.85E-02
184	6.82E-03	0.2660	3.09E+00	4.84E-02
185	6.74E-03	0.2663	3.13E+00	4.82E-02
186	6.66E-03	0.2666	3.18E+00	4.80E-02
187	6.58E-03	0.2668	3.25E+00	4.82E-02
188	6.50E-03	0.2670	3.30E+00	4.81E-02



Appendix Figure 4 Porosity at 1 day of cement paste containing fly ash 30% with normal curing.

Appendix Table 8 Pore size distribution by volume at 1 day of cement paste containing fly ash 50% with microwave curing at 7 hours.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	1.83E+02	0.0000	7.36E-06	5.12E-03
2	1.28E+02	0.0014	1.08E-05	5.63E-03
3	1.06E+02	0.0020	1.75E-05	5.74E-03
4	8.87E+01	0.0023	2.43E-05	5.91E-03
5	7.60E+01	0.0027	3.28E-05	6.12E-03
6	6.64E+01	0.0030	4.26E-05	6.29E-03
7	5.92E+01	0.0034	5.81E-05	7.08E-03
8	5.38E+01	0.0037	5.85E-05	7.07E-03
9	4.94E+01	0.0039	6.47E-05	7.36E-03
10	4.57E+01	0.0042	7.42E-05	7.85E-03
11	4.25E+01	0.0045	8.45E-05	8.28E-03
12	3.99E+01	0.0047	9.35E-05	8.50E-03
13	3.78E+01	0.0049	9.77E-04	8.48E-03
14	3.60E+01	0.0051	1.04E-04	8.53E-03
15	3.44E+01	0.0053	1.09E-04	8.50E-03
16	3.29E+01	0.0055	1.13E-04	8.53E-03
17	3.15E+01	0.0057	1.19E-04	8.60E-03
18	3.01E+01	0.0058	1.24E-04	8.63E-03
19	2.88E+01	0.0060	1.27E-04	8.39E-03
20	2.77E+01	0.0061	1.29E-04	8.20E-03
21	2.66E+01	0.0062	1.32E-04	8.09E-03
22	2.55E+01	0.0064	1.36E-04	8.09E-03
23	2.46E+01	0.0065	1.42E-04	8.11E-03
24	2.37E+01	0.0066	1.47E-04	8.12E-03
25	2.28E+01	0.0068	1.57E-04	8.33E-03
26	2.19E+01	0.0069	1.66E-04	8.48E-03
27	2.11E+01	0.0071	1.70E-04	8.30E-03
28	2.04E+01	0.0072	1.74E-04	8.20E-03
29	1.98E+01	0.0073	1.77E-04	8.09E-03
30	1.92E+01	0.0074	1.87E-04	8.22E-03
31	1.86E+01	0.0075	1.92E-04	8.20E-03
32	1.81E+01	0.0076	1.89E-04	7.81E-03
33	1.76E+01	0.0077	1.84E-04	7.41E-03
34	1.72E+01	0.0078	1.82E-04	7.12E-03
35	1.68E+01	0.0079	1.76E-04	6.70E-03

Appendix Table 8 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
36	1.64E+01	0.0079	1.67E-04	6.20E-03
37	1.60E+01	0.0080	1.59E-04	5.77E-03
38	1.56E+01	0.0080	1.54E-04	5.45E-03
39	1.53E+01	0.0081	1.47E-04	5.11E-03
40	1.50E+01	0.0081	1.40E-04	4.75E-03
41	1.46E+01	0.0082	1.31E-04	4.38E-03
42	1.43E+01	0.0082	1.31E-04	4.36E-03
43	1.40E+01	0.0082	1.36E-04	4.44E-03
44	1.37E+01	0.0083	1.41E-04	4.53E-03
45	1.34E+01	0.0083	1.46E-04	4.62E-03
46	1.31E+01	0.0083	1.60E-04	4.96E-03
47	1.29E+01	0.0084	1.82E-04	5.52E-03
48	1.26E+01	0.0085	2.04E-04	6.09E-03
49	1.24E+01	0.0085	2.31E-04	6.74E-03
50	1.22E+01	0.0086	2.49E-04	7.11E-03
51	1.19E+01	0.0086	2.51E-04	6.98E-03
52	1.17E+01	0.0087	2.51E-04	6.80E-03
53	1.15E+01	0.0088	2.39E-04	6.34E-03
54	1.13E+01	0.0088	2.31E-04	6.10E-03
55	1.12E+01	0.0089	2.22E-04	5.89E-03
56	1.06E+01	0.0090	2.17E-04	5.69E-03
57	9.64E+00	0.0090	2.19E-04	5.38E-03
58	8.10E+00	0.0092	2.31E-04	4.94E-03
59	6.11E+00	0.0096	2.78E-04	4.58E-03
60	4.21E+00	0.0101	3.72E-04	4.38E-03
61	2.74E+00	0.0109	5.32E-03	4.48E-03
62	1.79E+00	0.0117	1.07E-03	5.20E-03
63	1.21E+00	0.0125	2.09E-03	6.09E-03
64	8.52E-01	0.0135	3.93E-03	7.13E-03
65	6.24E-01	0.0145	6.06E-03	7.98E-03
66	4.73E-01	0.0156	8.69E-02	8.79E-03
67	3.70E-01	0.0167	1.21E-02	9.60E-03
68	2.96E-01	0.0179	1.65E-02	1.05E-02
69	2.43E-01	0.0190	2.22E-02	1.17E-02
70	2.03E-01	0.0200	2.92E-02	1.31E-02
71	1.72E-01	0.0209	3.79E-02	1.49E-02
72	1.49E-01	0.0217	4.85E-02	1.72E-02

Appendix Table 8 (Continued)

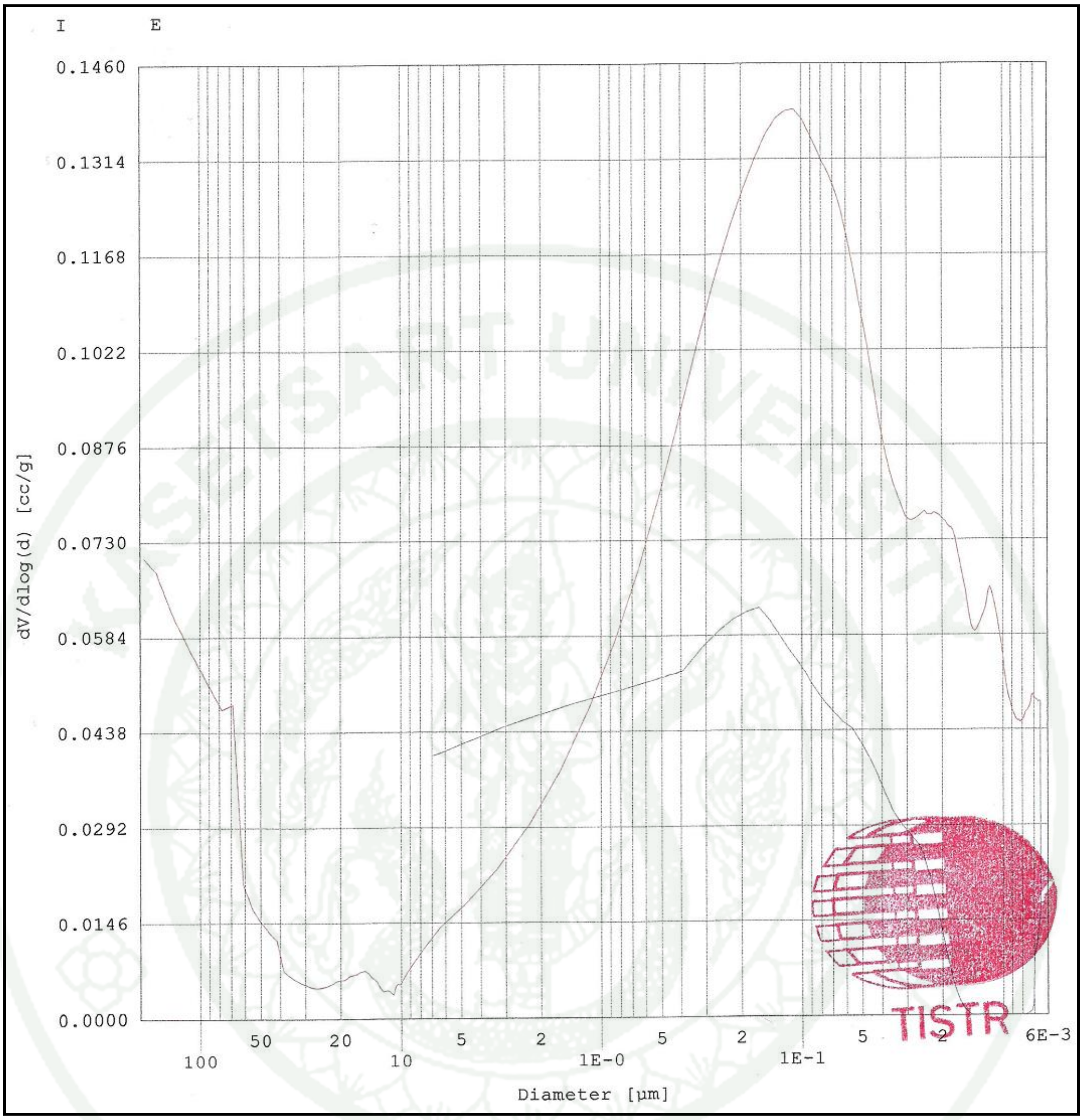
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
73	1.31E-01	0.0225	6.20E-02	2.00E-02
74	1.17E-01	0.0234	6.94E-02	2.36E-02
75	1.05E-01	0.0244	7.02E-01	2.80E-02
76	9.58E-02	0.0255	1.33E-01	3.34E-02
77	8.78E-02	0.0268	1.73E-01	4.00E-02
78	8.10E-02	0.0282	1.25E-01	4.76E-02
79	7.52E-02	0.0299	2.91E-01	5.64E-02
80	7.01E-02	0.0318	2.71E-01	6.63E-02
81	6.56E-02	0.0338	3.66E-01	7.72E-02
82	6.17E-02	0.0361	4.73E-01	8.84E-02
83	5.82E-02	0.0386	5.97E-01	1.00E-01
84	5.50E-02	0.0413	6.40E-01	1.14E-01
85	5.22E-02	0.0442	8.98E-01	1.27E-01
86	4.96E-02	0.0473	9.17E+00	1.41E-01
87	4.72E-02	0.0506	1.37E+00	1.56E-01
88	4.50E-02	0.0539	1.58E+00	1.71E-01
89	4.30E-02	0.0576	1.81E+00	1.87E-01
90	4.12E-02	0.0614	1.06E+00	2.03E-01
91	3.95E-02	0.0653	1.33E+00	2.20E-01
92	3.79E-02	0.0695	2.60E+00	2.35E-01
93	3.65E-02	0.0737	2.91E+00	2.52E-01
94	3.51E-02	0.0782	2.23E+00	2.69E-01
95	3.39E-02	0.0829	2.55E+00	2.84E-01
96	3.27E-02	0.0876	3.88E+00	2.99E-01
97	3.16E-02	0.0923	3.23E+00	3.14E-01
98	3.05E-02	0.0972	3.55E+00	3.26E-01
99	2.95E-02	0.1022	4.87E+00	3.37E-01
100	2.86E-02	0.1072	4.17E+00	3.45E-01
101	2.77E-02	0.1121	5.45E+00	3.52E-01
102	2.69E-02	0.1171	5.70E+00	3.56E-01
103	2.61E-02	0.1219	5.94E+00	3.60E-01
104	2.57E-02	0.1265	6.12E+00	3.59E-01
105	2.49E-02	0.1311	6.25E+00	3.56E-01
106	2.34E-02	0.1355	6.37E+00	3.52E-01
107	2.36E-02	0.1397	6.45E+00	3.46E-01
108	2.21E-02	0.1438	6.48E+00	3.38E-01

Appendix Table 8 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
109	2.26E-02	0.1477	6.49E+00	3.30E-01
110	2.15E-02	0.1513	6.47E+00	3.20E-01
111	2.10E-02	0.1547	6.44E+00	3.10E-01
112	2.05E-02	0.1580	6.36E+00	2.99E-01
113	2.00E-02	0.1612	6.27E+00	2.87E-01
114	1.95E-02	0.1641	6.18E+00	2.76E-01
115	1.90E-02	0.1669	6.10E+00	2.66E-01
116	1.86E-02	0.1695	6.03E+00	2.57E-01
117	1.81E-02	0.1719	5.95E+00	2.48E-01
118	1.77E-02	0.1743	5.86E+00	2.39E-01
119	1.73E-02	0.1766	5.79E+00	2.31E-01
120	1.69E-02	0.1789	5.72E+00	2.23E-01
121	1.65E-02	0.1812	5.68E+00	2.16E-01
122	1.61E-02	0.1833	5.64E+00	2.10E-01
123	1.57E-02	0.1853	5.66E+00	2.05E-01
124	1.54E-02	0.1873	5.68E+00	2.01E-01
125	1.50E-02	0.1891	5.66E+00	1.97E-01
126	1.47E-02	0.1909	5.64E+00	1.91E-01
127	1.44E-02	0.1927	5.62E+00	1.87E-01
128	1.41E-02	0.1945	5.63E+00	1.83E-01
129	1.38E-02	0.1963	5.63E+00	1.79E-01
130	1.35E-02	0.1978	5.65E+00	1.76E-01
131	1.32E-02	0.1993	5.67E+00	1.73E-01
132	1.30E-02	0.2007	5.66E+00	1.69E-01
133	1.27E-02	0.2021	5.65E+00	1.66E-01
134	1.25E-02	0.2034	5.60E+00	1.61E-01
135	1.23E-02	0.2047	5.54E+00	1.57E-01
136	1.20E-02	0.2059	5.50E+00	1.53E-01
137	1.18E-02	0.2071	5.49E+00	1.50E-01
138	1.16E-02	0.2082	5.52E+00	1.48E-01
139	1.14E-02	0.2093	5.53E+00	1.46E-01
140	1.12E-02	0.2103	5.56E+00	1.44E-01
141	1.10E-02	0.2112	5.59E+00	1.43E-01
142	1.09E-02	0.2122	5.63E+00	1.42E-01
143	1.07E-02	0.2132	5.68E+00	1.40E-01
144	1.06E-02	0.2142	5.72E+00	1.39E-01

Appendix Table 8 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
145	1.03E-02	0.2152	5.79E+00	1.39E-01
146	1.01E-02	0.2162	5.89E+00	1.39E-01
147	1.00E-02	0.2172	6.03E+00	1.40E-01
148	1.86E-03	0.2181	6.10E+00	1.39E-01
149	9.71E-03	0.2190	6.05E+00	1.36E-01
150	9.56E-03	0.2199	5.99E+00	1.32E-01
151	9.42E-03	0.2208	5.89E+00	1.28E-01
152	9.28E-03	0.2217	5.77E+00	1.23E-01
153	9.14E-03	0.2226	5.67E+00	1.19E-01
154	9.01E-03	0.2232	5.57E+00	1.15E-01
155	8.87E-03	0.2239	5.47E+00	1.12E-01
156	8.72E-03	0.2245	5.35E+00	1.08E-01
157	8.62E-03	0.2251	5.15E+00	1.02E-01
158	8.50E-03	0.2257	4.92E+00	9.64E-02
159	8.38E-03	0.2263	4.74E+00	9.15E-02
160	8.27E-03	0.2268	4.65E+00	8.86E-02
161	8.15E-03	0.2274	4.64E+00	8.73E-02
162	8.04E-03	0.2278	4.65E+00	8.63E-02
163	7.93E-03	0.2283	4.68E+00	8.56E-02
164	7.82E-03	0.2287	4.62E+00	8.35E-02
165	7.72E-03	0.2292	4.66E+00	8.33E-02
166	7.62E-03	0.2297	4.75E+00	8.33E-02
167	7.52E-03	0.2302	4.87E+00	8.60E-02
168	7.42E-03	0.2307	5.04E+00	8.60E-02
169	7.32E-03	0.2311	5.22E+00	8.89E-02
170	7.23E-03	0.2316	5.43E+00	9.17E-02
171	7.14E-03	0.2322	5.64E+00	9.33E-02
172	7.05E-03	0.2327	5.90E+00	9.65E-02
173	6.96E-03	0.2333	6.05E+00	9.77E-02
174	6.87E-03	0.2338	6.10E+00	9.71E-02
175	6.79E-03	0.2344	6.35E+00	9.91E-02
176	6.70E-03	0.2349	6.53E+00	1.00E-01
177	6.62E-03	0.2356	6.64E+00	9.99E-02
178	6.54E-03	0.2361	6.75E+00	9.98E-02
179	6.46E-03	0.2365	6.90E+00	1.00E-02



Appendix Figure 5 Porosity at 1 day of cement paste containing fly ash 50% with 7 hours of microwave curing.

Appendix Table 9 Pore size distribution by volume at 1 day of cement paste containing fly ash 50% with with normal curing.

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
1	1.83E+02	0.0000	7.48E-05	4.54E-02
2	1.28E+02	0.0217	1.06E-04	4.85E-02
3	1.06E+02	0.0266	1.59E-04	4.37E-02
4	8.87E+01	0.0291	2.06E-04	3.99E-02
5	7.60E+01	0.0306	2.60E-04	3.68E-02
6	6.64E+01	0.0316	3.19E-04	3.43E-02
7	5.92E+01	0.0350	4.12E-04	3.50E-02
8	5.38E+01	0.0354	2.46E-04	2.30E-02
9	4.94E+01	0.0358	1.98E-04	1.84E-02
10	4.57E+01	0.0361	1.83E-04	1.61E-02
11	4.25E+01	0.0363	1.80E-04	1.48E-02
12	3.99E+01	0.0366	1.83E-04	1.39E-02
13	3.78E+01	0.0368	1.02E-04	8.56E-03
14	3.60E+01	0.0369	1.03E-04	8.33E-03
15	3.44E+01	0.0371	1.04E-04	8.08E-03
16	3.29E+01	0.0372	1.07E-04	7.99E-03
17	3.16E+01	0.0374	1.09E-04	7.92E-03
18	3.04E+01	0.0375	1.12E-04	7.83E-03
19	2.92E+01	0.0377	1.15E-04	7.73E-03
20	2.81E+01	0.0378	1.17E-04	7.58E-03
21	2.71E+01	0.0379	1.41E-04	9.06E-03
22	2.61E+01	0.0380	1.64E-04	1.03E-02
23	2.53E+01	0.0381	1.91E-04	1.17E-02
24	2.44E+01	0.0382	2.22E-04	1.32E-02
25	2.37E+01	0.0383	2.61E-04	1.51E-02
26	2.30E+01	0.0386	3.06E-04	1.71E-02
27	2.23E+01	0.0389	3.49E-04	1.89E-02
28	2.16E+01	0.0392	3.99E-04	2.08E-02
29	2.09E+01	0.0396	4.56E-04	2.28E-02
30	2.03E+01	0.0399	5.21E-04	2.50E-02
31	1.97E+01	0.0403	5.93E-04	2.73E-02
32	1.91E+01	0.0407	5.92E-04	2.63E-02
33	1.86E+01	0.0410	5.95E-04	2.55E-02
34	1.81E+01	0.0414	5.91E-04	2.44E-02
35	1.76E+01	0.0417	5.81E-04	2.32E-02

Appendix Table 9 (Continued)

Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
36	1.72E+01	0.0421	5.56E-04	2.15E-02
37	1.68E+01	0.0422	5.19E-04	1.95E-02
38	1.64E+01	0.0423	4.84E-04	1.77E-02
39	1.60E+01	0.0425	4.43E-04	1.58E-02
40	1.56E+01	0.0426	4.01E-04	1.40E-02
41	1.53E+01	0.0427	3.45E-04	1.19E-02
42	1.50E+01	0.0427	2.83E-04	9.69E-03
43	1.46E+01	0.0428	2.75E-04	9.22E-03
44	1.43E+01	0.0429	2.63E-04	8.65E-03
45	1.40E+01	0.0430	2.53E-04	8.16E-03
46	1.37E+01	0.0431	2.48E-04	7.88E-03
47	1.34E+01	0.0431	2.50E-04	7.78E-03
48	1.31E+01	0.0432	2.59E-04	7.86E-03
49	1.29E+01	0.0433	2.62E-04	7.76E-03
50	1.26E+01	0.0433	2.79E-04	8.14E-03
51	1.24E+01	0.0434	2.82E-04	8.09E-03
52	1.22E+01	0.0434	2.92E-04	8.27E-03
53	1.20E+01	0.0435	3.94E-04	8.48E-03
54	1.18E+01	0.0435	3.06E-04	8.97E-03
55	1.16E+01	0.0436	3.26E-04	9.38E-03
56	1.14E+01	0.0437	3.40E-04	9.85E-03
57	1.13E+01	0.0438	3.78E-04	9.87E-03
58	1.11E+01	0.0438	3.78E-04	9.97E-03
59	1.09E+01	0.0439	3.88E-04	1.01E-02
60	1.08E+01	0.0440	4.96E-04	1.03E-02
61	1.07E+01	0.0440	3.14E-04	9.40E-03
62	1.05E+01	0.0441	3.86E-04	8.82E-03
63	1.04E+01	0.0441	3.68E-04	8.29E-03
64	1.03E+01	0.0442	3.49E-04	8.26E-03
65	1.02E+01	0.0442	3.38E-04	8.82E-03
66	1.01E+01	0.0442	3.24E-04	1.04E-02
67	9.45E+00	0.0443	3.23E-04	1.30E-02
68	7.82E+00	0.0446	4.39E-04	1.72E-02
69	5.72E+00	0.0460	7.26E-03	2.24E-02
70	4.00E+00	0.0488	1.04E-03	2.87E-02
71	2.74E+00	0.0536	2.36E-03	3.60E-02
72	1.89E+00	0.0601	5.64E-03	4.52E-02

Appendix Table 9 (Continued)

Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
73	1.35E+00	0.0682	1.81E-02	5.56E-02
74	9.77E-01	0.0775	1.25E-02	6.73E-02
75	7.28E-01	0.0874	2.37E-02	7.91E-02
76	5.56E-01	0.0979	4.12E-02	8.99E-02
77	4.35E-01	0.1090	6.70E-01	9.88E-02
78	3.48E-01	0.1203	1.01E-01	1.06E-01
79	2.85E-01	0.1318	1.45E-01	1.10E-01
80	2.38E-01	0.1427	1.83E-01	1.13E-01
81	2.02E-01	0.1524	2.32E-01	1.14E-01
82	1.75E-01	0.1605	2.82E-01	1.15E-01
83	1.53E-01	0.1673	3.38E-01	1.15E-01
84	1.35E-01	0.1727	3.77E-01	1.14E-01
85	1.21E-01	0.1773	4.17E-01	1.11E-01
86	1.10E-01	0.1814	4.48E-01	1.09E-01
87	9.98E-02	0.1854	4.68E-01	1.06E-01
88	9.16E-02	0.1892	4.83E-01	1.05E-01
89	8.46E-02	0.1928	4.13E-01	1.05E-01
90	7.85E-02	0.1962	5.45E-01	1.05E-01
91	7.33E-02	0.1996	5.85E-01	1.07E-01
92	6.86E-02	0.2027	5.40E-01	1.09E-01
93	6.44E-02	0.2058	6.81E-01	1.10E-01
94	6.07E-02	0.2087	6.40E-01	1.10E-01
95	5.74E-02	0.2115	7.97E-01	1.10E-01
96	5.44E-02	0.2141	7.39E-01	1.09E-01
97	5.16E-02	0.2167	8.74E-01	1.08E-01
98	4.91E-02	0.2191	8.15E-01	1.06E-01
99	4.68E-02	0.2213	9.41E-01	1.04E-01
100	4.47E-02	0.2233	9.76E-01	1.02E-01
101	4.27E-02	0.2253	1.92E+00	9.94E-02
102	4.09E-02	0.2270	1.04E+00	9.72E-02
103	3.92E-02	0.2287	1.05E+00	9.42E-02
104	3.73E-02	0.2302	1.06E+00	9.17E-02
105	3.68E-02	0.2317	1.08E+00	8.94E-02
106	3.46E-02	0.2332	1.09E+00	8.74E-02
107	3.34E-02	0.2346	1.10E+00	8.53E-02
108	3.23E-02	0.2359	1.12E+00	8.38E-02

Appendix Table 8 (Continued)

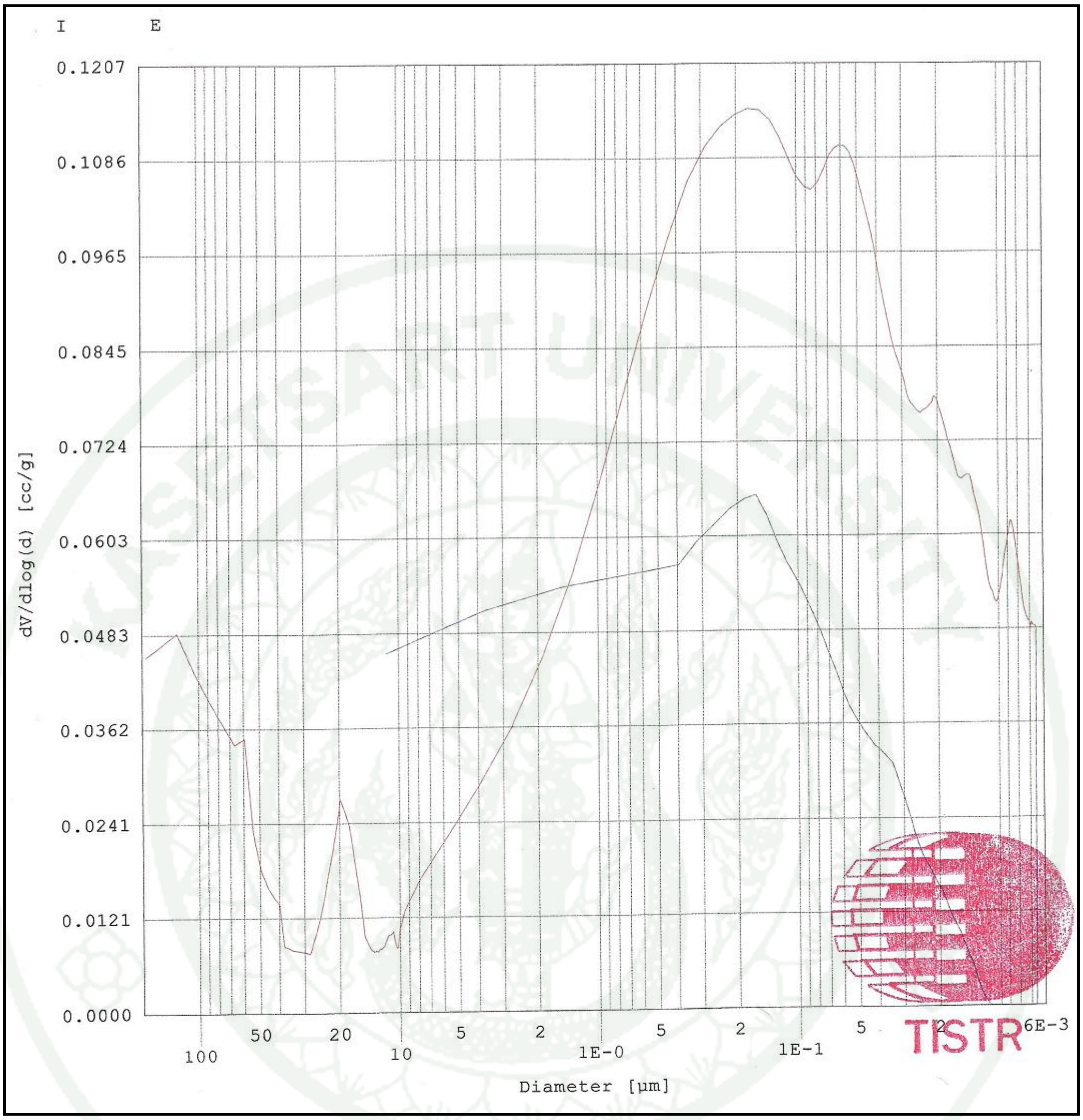
Data	Pore diameter (μm)	Volume Intruded (cc/g)	Dv (d) [cc/(μm-g)]	-dV / d (log d) (cc/g)
109	3.13E-02	0.2372	1.15E+00	8.27E-02
110	3.02E-02	0.2384	1.17E+00	8.16E-02
111	2.92E-02	0.2395	1.19E+00	8.02E-02
112	2.83E-02	0.2406	1.20E+00	7.85E-02
113	2.74E-02	0.2416	1.22E+00	7.74E-02
114	2.66E-02	0.2427	1.25E+00	7.70E-02
115	2.58E-02	0.2437	1.28E+00	7.66E-02
116	2.50E-02	0.2446	1.31E+00	7.62E-02
117	2.43E-02	0.2455	1.35E+00	7.60E-02
118	2.37E-02	0.2465	1.39E+00	7.62E-02
119	2.30E-02	0.2464	1.43E+00	7.64E-02
120	2.24E-02	0.2473	1.47E+00	7.66E-02
121	2.18E-02	0.2482	1.52E+00	7.70E-02
122	2.12E-02	0.2591	1.57E+00	7.73E-02
123	2.07E-02	0.2510	1.63E+00	7.81E-02
124	2.02E-02	0.2518	1.66E+00	7.77E-02
125	1.97E-02	0.2527	1.69E+00	7.65E-02
126	1.92E-02	0.2535	1.71E+00	7.60E-02
127	1.88E-02	0.2543	1.73E+00	7.50E-02
128	1.83E-02	0.2552	1.75E+00	7.41E-02
129	1.79E-02	0.2559	1.76E+00	7.28E-02
130	1.75E-02	0.2566	1.79E+00	7.20E-02
131	1.70E-02	0.2573	1.80E+00	7.10E-02
132	1.66E-02	0.2580	1.82E+00	7.00E-02
133	1.63E-02	0.2587	1.83E+00	6.89E-02
134	1.59E-02	0.2593	1.84E+00	6.79E-02
135	1.55E-02	0.2600	1.87E+00	6.76E-02
136	1.52E-02	0.2607	1.92E+00	6.75E-02
137	1.48E-02	0.2614	1.97E+00	6.78E-02
138	1.45E-02	0.2621	2.02E+00	6.79E-02
139	1.42E-02	0.2628	2.08E+00	6.80E-02
140	1.38E-02	0.2634	2.12E+00	6.79E-02
141	1.36E-02	0.2640	2.14E+00	6.70E-02
142	1.33E-02	0.2647	2.15E+00	6.58E-02
143	1.30E-02	0.2653	2.16E+00	6.47E-02
144	1.27E-02	0.2658	2.18E+00	6.40E-02

Appendix Table 9 (Continued)

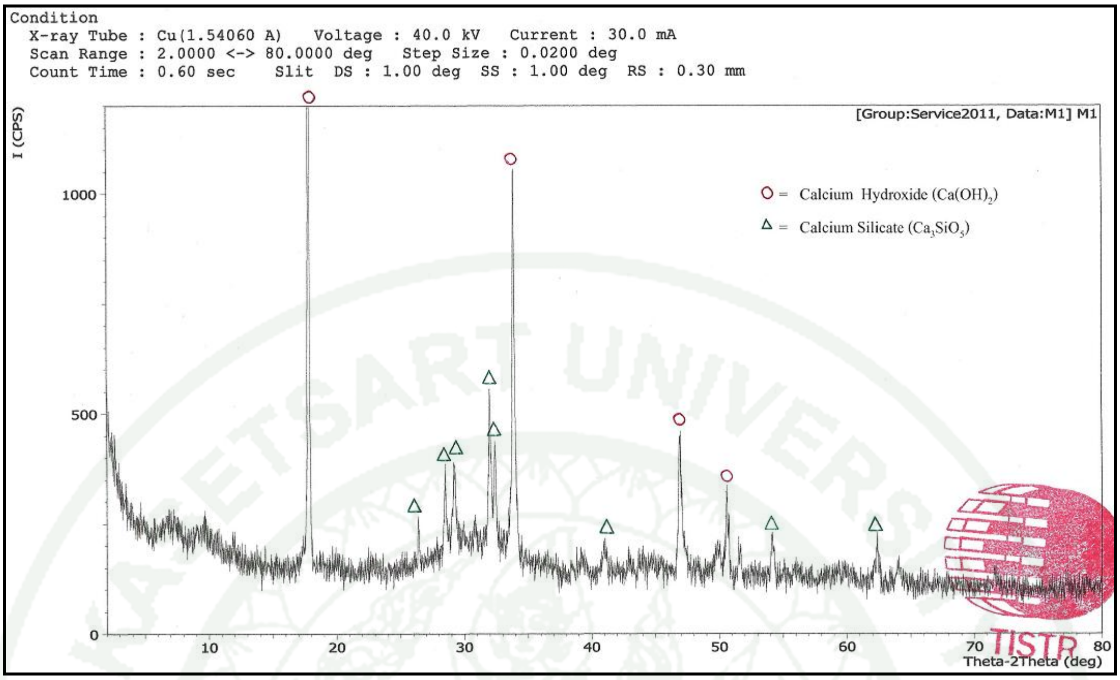
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
145	1.26E-02	0.2664	2.19E+00	6.30E-02
146	1.22E-02	0.2669	2.18E+00	6.18E-02
147	1.21E-02	0.2673	2.18E+00	6.04E-02
148	1.19E-02	0.2677	2.16E+00	5.89E-02
149	1.17E-02	0.2682	2.14E+00	5.74E-02
150	1.15E-02	0.2686	2.12E+00	5.59E-02
151	1.13E-02	0.2690	2.10E+00	5.46E-02
152	1.11E-02	0.2694	2.10E+00	5.37E-02
153	1.09E-02	0.2697	2.12E+00	5.33E-02
154	1.07E-02	0.2701	2.14E+00	5.30E-02
155	1.06E-02	0.2705	2.14E+00	5.22E-02
156	1.04E-02	0.2708	2.16E+00	5.18E-02
157	1.02E-02	0.2711	2.18E+00	5.17E-02
158	1.01E-02	0.2715	2.23E+00	5.21E-02
159	9.91E-03	0.2719	2.30E+00	5.29E-02
160	9.76E-03	0.2722	2.37E+00	5.38E-02
161	9.61E-03	0.2725	2.46E+00	5.49E-02
162	9.47E-03	0.2729	2.55E+00	5.61E-02
163	9.33E-03	0.2732	2.64E+00	5.73E-02
164	9.20E-03	0.2736	2.73E+00	5.84E-02
165	9.06E-03	0.2740	2.81E+00	5.91E-02
166	8.93E-03	0.2744	2.91E+00	6.03E-02
167	8.80E-03	0.2748	3.00E+00	6.13E-02
168	8.68E-03	0.2752	3.09E+00	6.21E-02
169	8.56E-03	0.2756	3.13E+00	6.19E-02
170	8.44E-03	0.2760	3.14E+00	6.12E-02
171	8.32E-03	0.2764	3.13E+00	6.01E-02
172	8.21E-03	0.2767	3.12E+00	5.92E-02
173	8.10E-03	0.2771	3.09E+00	5.77E-02
174	7.99E-03	0.2774	3.08E+00	5.67E-02
175	7.88E-03	0.2777	3.04E+00	5.53E-02
176	7.77E-03	0.2780	3.03E+00	5.44E-02
177	7.67E-03	0.2783	3.01E+00	5.32E-02
178	7.57E-03	0.2786	2.97E+00	5.20E-02
179	7.47E-03	0.2789	2.95E+00	5.09E-02
180	7.38E-03	0.2792	2.95E+00	5.03E-02

Appendix Table 9 (Continued)

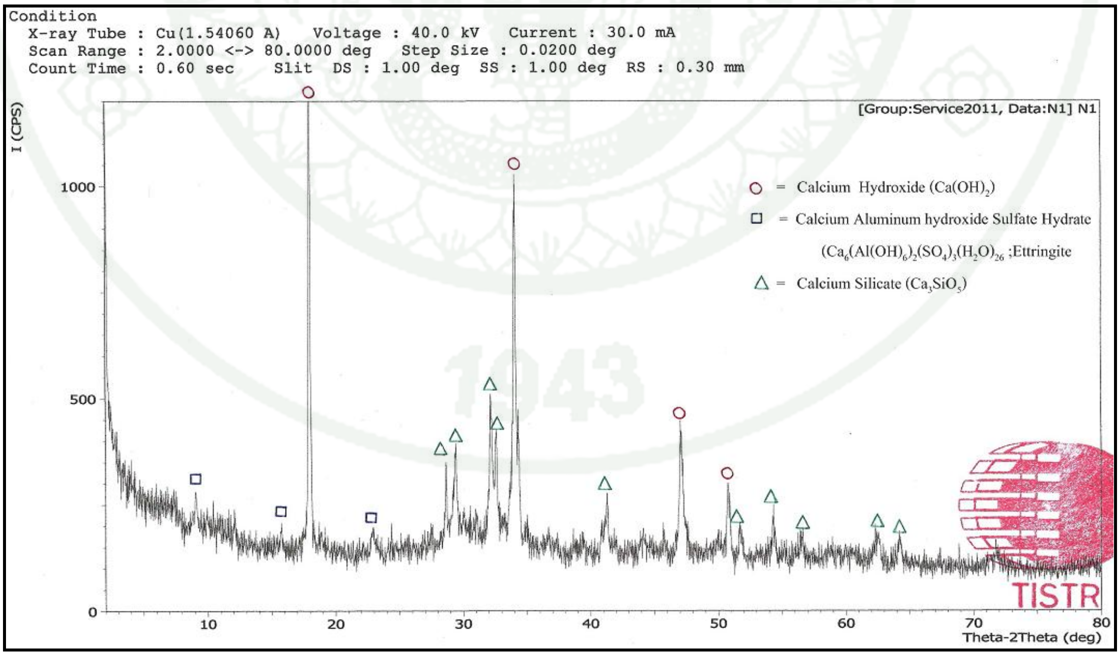
Data	Pore diameter (µm)	Volume Intruded (cc/g)	Dv (d) [cc/(µm-g)]	-dV / d (log d) (cc/g)
181	7.28E-03	0.2795	2.96E+00	4.98E-02
182	7.19E-03	0.2797	2.95E+00	4.96E-02
183	7.10E-03	0.2800	3.00E+00	4.92E-02
184	7.01E-03	0.2803	3.08E+00	4.93E-02
185	6.92E-03	0.2805	3.05E+00	4.94E-02
186	6.85E-03	0.2808	3.12E+00	4.90E-02
187	6.77E-03	0.2810	3.11E+00	4.88E-02
188	6.69E-03	0.2813	3.13E+00	4.86E-02
189	6.61E-03	0.2815	3.28E+00	4.86E-02
190	6.54E-03	0.2817	3.24E+00	4.85E-02
191	6.51E-03	0.2818	3.27E+00	4.83E-02



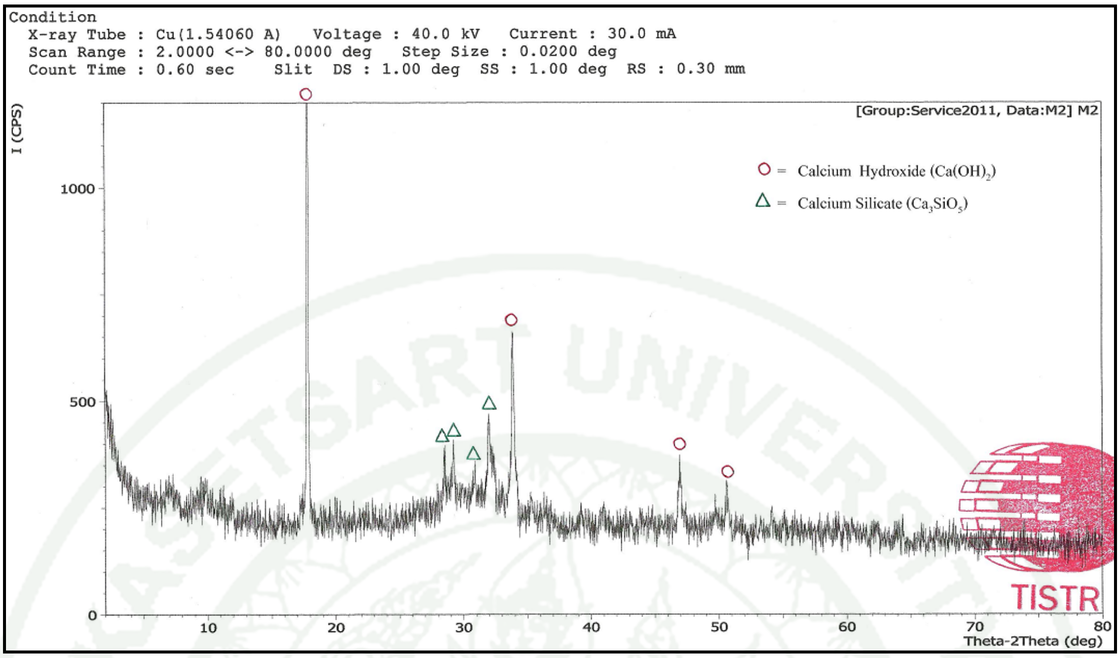
Appendix Figure 6 Porosity at 1 day of cement paste containing fly ash 50% with normal curing.



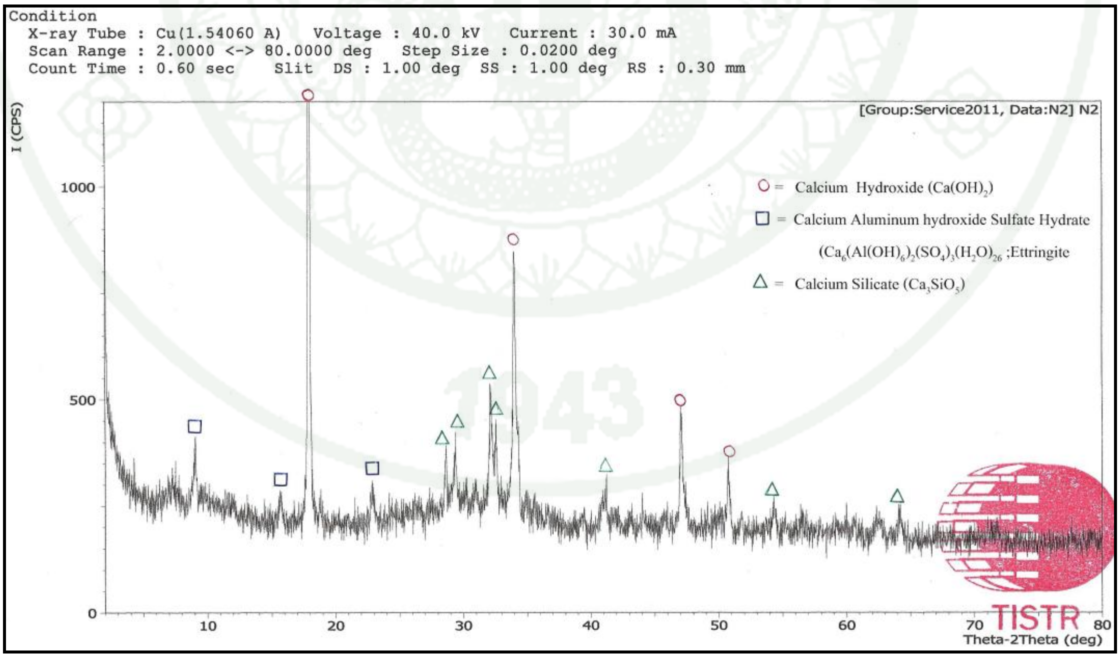
Appendix Figure 7 XRD pattern at 1 day of cement paste containing fly ash 0% with 7 hours of microwave curing.



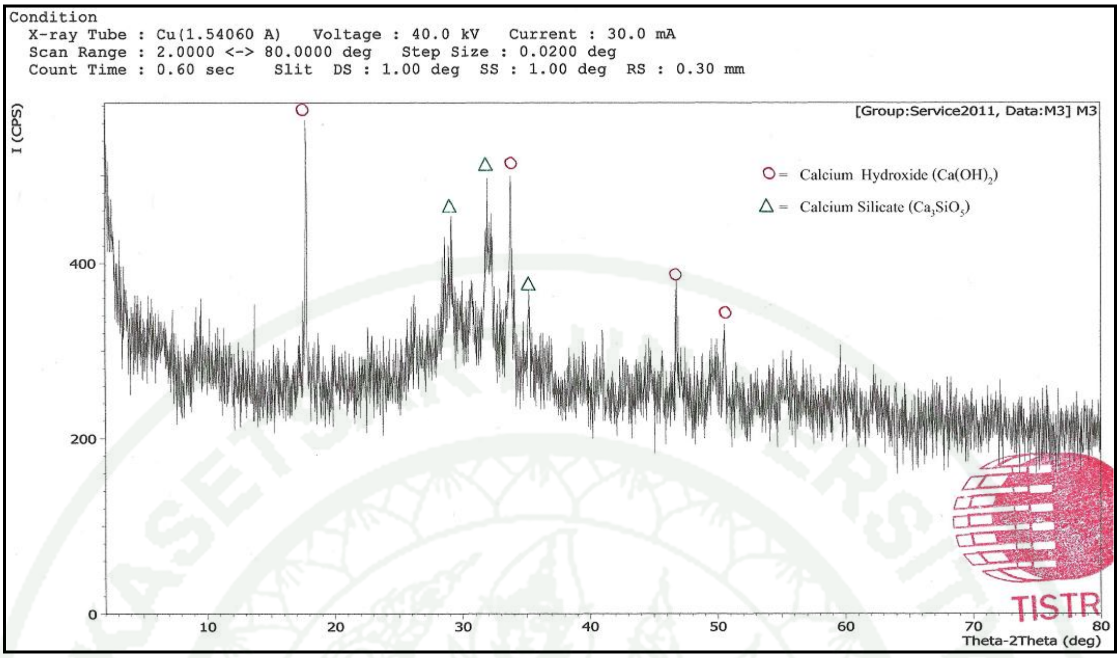
Appendix Figure 8 XRD pattern at 1 day of cement paste containing fly ash 0% with normal curing.



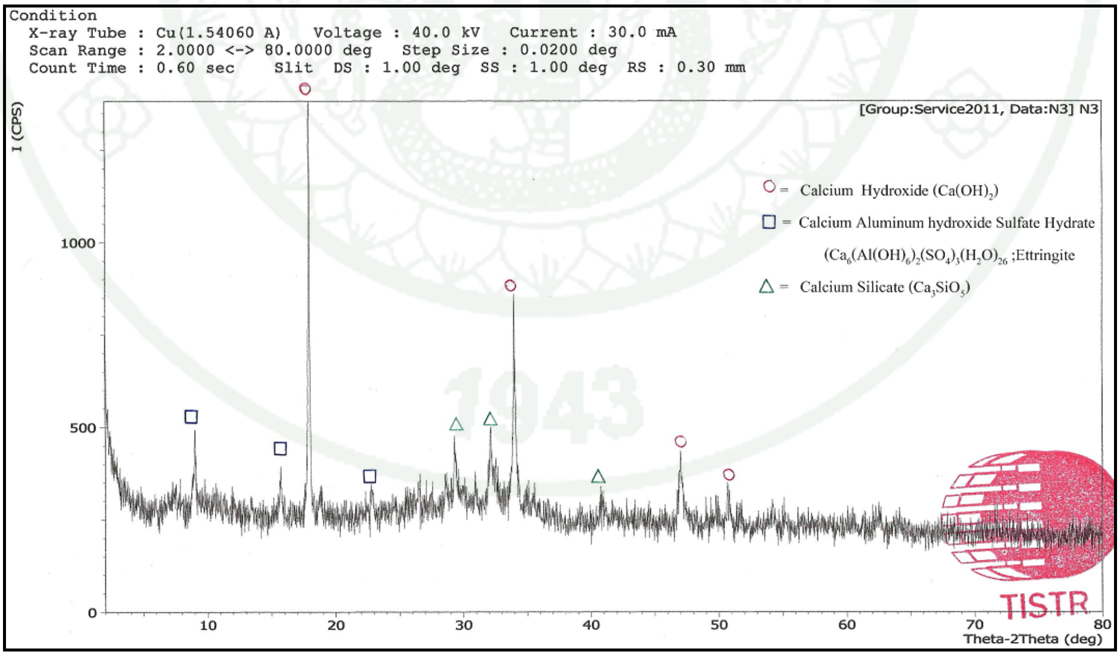
Appendix Figure 9 XRD pattern at 1 day of cement paste containing fly ash 30% with 7 hours of microwave curing.



Appendix Figure 10 XRD pattern at 1 day of cement paste containing fly ash 30% with normal curing.



Appendix Figure 11 XRD pattern at 1 day of cement paste containing fly ash 50% with 7 hours of microwave curing.



Appendix Figure 12 XRD pattern at 1 day of cement paste containing fly ash 50% with normal curing.

CURRICULUM VITAE

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