CHAPTER 3

CEMENT PASTES

Cement paste primarily comes from hydration reaction between cement and water. It normally acts as a binder in concrete material. It separates as well as holds aggregate particles together. The microstructure of cement paste is characterized by gel pores and air voids in the mass of hydration products, of which this is mainly calcium silicate hydrate (CSH). Both the porosity and the presence of CSH significantly influence the features of cement paste. Reduction of pore space embedded in the dense amorphous mass of CSH is beneficial to paste properties.

In fact, a higher strength of cement paste can be achieved by keeping water/cement ratio as low as possible. The difficulty for fully compaction due to low water content can be relieved by the application of a hi-tech superplasticizer. Nevertheless, using of a water/cement ratio less than a certain value prevents paste from complete hydration, causing retrograde strength. Augmentation of pozzolanic materials is another approach to raise strength. The appropriate percentage of their addition depends on the chemical composition.

In this chapter, the optimum water/cement ratio and additional percentage of pozzolanic materials for equilibrium reactions are determined based on microstructual point of view. Superplasticizer is concerned in providing flowability. The amount of CSH and porosity are, further, related to paste strength. Therefore, with the conventional practice, cement paste with the desired strength can be produced.

3.1 Factors Affecting Paste Strength

It is generally appreciated that behavior of any material is governed by its microstructure. In cement paste, the porosity accounts for the primary weakness. Because CSH occupies most of the volume of the hydration products, its presence also dominates paste behavior. As a fundamental, the influences of porosity and CSH on cement paste properties are here reviewed.

3.1.1 Porosity

The void space in hardened cement paste can be categorized into three groups, i.e., interlayer space in CSH, capillary pores, and air voids. The width of the interlayer space is too small to have an adverse affect on strength and permeability of paste. Capillary pores represent the space not filled by cement or hydration products. Its volume and size depend on the original distance between the anhydrous cement particles in the freshly mixed cement paste as well as the degree of cement hydration. Whereas capillary pores are irregular in shape, air voids are generally spherical. Air may be entrapped or purposely entrained during the mixing operation. Air voids are much bigger than capillary voids. However, both of them are capable of adversely affecting paste strength and impermeability. Their total volume is popularly known as porosity.

Several displacement fluids, for example, water, methanol, mercury, and helium, have been used in measuring the porosity of hydrated cement paste. Water absorption is very simple and inexpensive, but, because water rehydrates on exposure to dried hydrosilicates, the apparent measured porosity is higher than the actual value. While the other media generally give similar results for most w/c preparations. Nevertheless, each method has its own limitation.

It is well known that there is an inverse relationship between paste porosity and strength. From fracture mechanics, several expressions are either in the forms of eq. (3.1) or (3.2), i.e.,

$$S = S_o e^{-bp} \tag{3.1}$$

$$S = S_o(1-p)^b \tag{3.2}$$

where S and S_o are the strength of paste containing porosity p and zero porosity, respectively. And, b is a factor depending on size and shape of pores. Similar formulas have been used for the porosity dependence of elastic modulus.

3.1.2 Calcium Silicate Hydrate

The hydration of C_3S* and C_2S produces a family of calcium silicate hydrates (CSH), varied widely in C/S ratio and the content of chemically combined water. Nevertheless, providing that the structure is similar, the compositional differences among CSH have little effect

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* The abbreviation used here and throughout this dissertation follow the follow the conversations of standard cement chemistry notation: C=CaO, $H=H_2O$, $S=SiO_2$, $F=Fe_2O_3$, $A=Al_2O_3$ and $\overline{S}=SO_3$

on their characteristics. On complete hydration, the approximate composition of the material corresponds to $C_3S_2H_3$, and the stoichiometric reactions for fully hydrated C_3S and C_2S may be expressed as

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \tag{3.3}$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \tag{3.4}$$

C_2S hydrates much slowly than C_3S, because it is a less reactive compound. Therefore, C_2S contributes to strength at a later time.

Until now, the picture of CSH has been unclear. However, its amorphous microstructure with high specific surface area can be figured out. Two types of CSH can be discriminated. The outer product of CSH takes place in the water-filled space surrounding cement particles. On the other hand, the inner product comes from solid-state reactions, formed within the original boundaries of hydrating cement. The inner product is more compact and poorly crystalline. Densities of the outer and inner product when their pores are empty are about 1440 and 1750 kg/m^3, respectively (Jennings, 2000). The ratio of the low-density CSH to the total mass of CSH (M_r) was proposed by Tennis and Jennings (2000), as

$$M_r = 3.017(w/c)\alpha - 1.347\alpha + 0.538 \tag{3.5}$$

where w/c is water/cement ratio and α is degree of hydration.

The quantity of CSH is very difficult to measure directly due to the lack of its crystallinity and indefinite composition. Thus, indirect techniques, such as thermogravimetric analysis (TGA) and X-ray diffraction (XRD) of unreacted cement and calcium hydroxide, were arisen. However, to some extent, Olson and Jennings (2001) developed the estimation of CSH content directly by using water adsorption.

Chakpaisan (1996) and Suwankawin (1996) pointed out the linear relations between strength and amount of CSH of hardened cement pastes containing fly ash and silica fume, respectively.

3.1.3 Strategies to Improve Strength

Consideration will be given to the above factors in mechanistic arguments pertaining to high strength. The idea of optimizing such factors is mentioned.

3.1.3.1 Low Water/Cement Ratio

The reduction of water content decreases the water-filled space during the hydration process, causing less amount of capillary pores in hardened cement paste. Furthermore, it is a satisfactory condition for solid-state hydrating, which produces inner product of CSH. However, the water/cement ratio below a certain value prevents complete hydration.

In this section, the water/cement ratio required for the most effective hydration reaction is determined stoichiometrically. With that ratio, it is believed that there are no cement compounds and water left after complete hydration reaction, and yielding the maximum amount of CSH. Because of uncertainties in cement composition and chemical reactions in the hydration process, some assumptions are established. The procedure of calculation similar to that stated by Taylor (1997) is listed below.

(1) Estimate four main compounds in cement from its chemical composition by using the modified Bogue's equation, i.e.,

$$C_3S = 4.071C - 7.6000S - 6.718A - 1.430F - 2.852\bar{S} \quad (3.6a)$$

$$C_2S = 2.867S - 0.7544C_3S \quad (3.6b)$$

$$C_3A = 2.650A - 1.692F \quad (3.6c)$$

$$C_4AF = 3.043F \quad (3.6d)$$

(2) Assume that a part of C_3A reacts with gypsum ($C\bar{S}H_2$) rapidly and forms ettringite ($C_6A\bar{S}H_{32}$), which transforms later to be $C_4A\bar{S}H_{12}$. The rest C_3A combines with water to form hydogarnet (C_3AH_6). The chemical reactions involving C_3A are

$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}H_{32} \quad (3.7)$$

$$2C_3A + C_6A\bar{S}_3H_{32} + 4H \rightarrow 3C_4A\bar{S}H_{12} \quad (3.8)$$

$$C_3A + 6H \rightarrow C_3AH_6 \quad (3.9)$$

(3) Assume that all the C_4AF hydrate with water as

$$C_4AF + 13H \rightarrow C_4(A,F)H_{13} \quad (3.10)$$

(4) Assume that all the C_3S and C_2S hydrate independently in the manner of eq. (3.3) and (3.4), respectively.

The calculation of each reaction is based on the mass conservation. The molecular weight and density of each compound gathered literally are shown in Table 3.1.

The commonly available portland cement type I and III are used in the investigation. Their chemical compositions are shown in Table 3.2. The required water for 100 grams of cement to hydrate completely is 26.37 grams for type-I portland cement, and 25.21 grams for type-III portland cement. For each type, CSH occupies 47.14% and 48.62% by weight of the hydration products. The difference between the volume of the substances before hydrating and the products supposes to be the volume of capillary pores. The porosity at the balance hydration reaction is 8.03% and 7.59% for type-I and type-III portlancd cement, respectively.

3.1.3.2 Addition of Pozzolanic Materials

In cement chemistry, pozzolanic materials are poor-crystalline silicious materials, which by themselves possess little or no cementitious value, but will react with calcium hydroxide, produced by hydrating portland cement, to form CSH that have cementitious properties. With the presence of moisture, the pozzolanic reaction of silica may be expressed as

$$2S + 3CH \rightarrow C_3S_2H_3 \tag{3.11}$$

There are many kinds of pozzolanic materials, varied in their source, mineralogical composition, and characteristics. The degree of pozzolanic reactivity of each material depends on size, crystallinity, and percentage of silica.

Fly ash is the most extensively used material. It is employed in a wide variety of construction. The diameter of fly ash mostly lies in the range of 1 - 100 μm, and the specific surface area is usually between 250 and 600 m^2/kg. Silica fume is very reactive pozzolanic materials and normally used in the production of high-strength concrete. It is extremely fine in size and contains much proportion of pure noncrystalline silica.

The performance of cementitious materials containing pozzolanic materials is improved owing to two mechanisms. In the physical aspect, a smaller size of pozzolanic materials than cement particles makes the mixture denser. While the secondary CSH is occurred chemically. With eq. (3.11), the quantity of required pozzolanic materials for the balance pozzolanic reactions can be approximated. Such amount is 10.46% and 19.48% by weight of cement for the 46.20%-S fly ash and 86.00%-S silica fume added in the hydration of type-I portland cement, respectively.

3.2 Optimized Water/Cement Ratio

To determine the optimum water/cement ratio for the most effective hydration reactions experimentally, the microstructure study of hardened cement paste specimens is performed, including scanning electron microscope (SEM), thermogravimetric analysis (TGA), and total porosity measurement. Furthermore, the contribution of the microstructure to the mechanical properties is also studied.

3.2.1 Sample Preparation

The ordinary portland cement type I is combined with tap water to produce cement paste. The cement composition and its physical properties are shown in Table 3.2. The mix proportion of cement pastes is presented in Table 3.3. The water/cement ratio ranges from 0.12 to 0.40. If necessary, the polymer-based superplasticizer is implemented to guarantee constant flow.

Cement and about 60% of water is placed into a bowl and mixed by mechanical mixer on a slow speed (approximately 140±5 rpm) for 60 seconds. Then, the mixture is rested for 30 seconds before adding the rest of water. It is mixed at slow speed for 60 seconds, rested again for 30 seconds, and mixed at medium speed (approximately 285±10 rpm) for 120 seconds.

The mixture is tested for its flow value by using the flow table according to ASTM C230. The required flow value conforming ASTM C311 is 110% more or less by 5%. If such a flow can not be obtained, superplasticizer is added. The mixture is mixed again at slow speed for 30 seconds, then, rested for 30 seconds, and mixed at medium speed for 60 seconds. The flow test is performed again. This procedure is repeated until the flow value is at the limit. To avoid the initial setting, the overall mixing duration must not exceed 15 minutes.

One part of this fresh cement paste is tested for its unit weight and air content, while the remaining is placed in the brass molds. After 24 hours, the hardened cement paste is removed from the molds. All specimens are stored under tap water at normal atmosphere and room temperature until the day of testing.

3.2.2 Fresh-State Properties

The unit weight and air content of fresh cement paste are examined gravimetrically in the same way that concrete is tested following ASTM C138. Due to the lack of aggregate, the required volume of the sample is reduced. The measured unit weight and air void are tabulated in

Table 3.4. The unit weight varies from 1943 to 2292 kg/m^3, depending on the cement content. All of the mixes yield an air void less than 2.0%. It may be the result of providing constant flow. The relation between flow of cement paste and air void will be stated further in section 3.3, in which the effect of superplasticizer is discussed.

3.2.3 Microstructure Characteristics

3.2.3.1 Scanning Electron Microscope

An electron microscope is a technique to display the microstructure of elements. An SEM can view specimens that can not be seen with the naked eyes. The electron beam is generated in the gun of the SEM apparatus. When it strikes the conductive and smooth surface of the specimen in vacuum condition, it bounces to a detector. This forms an image of surface details of the object. Although it is a useful technology, the results of analysis are difficult to interpret and can not determine the quantities of the compounds.

In this study, ordinary cement paste samples only with only 28-day age are explored. Approximately 10x10x10-mm specimens are taken from the core of 50x50x50-mm samples. One surface of each specimen is polished by the abrasive agent no. 220, and then coated with a thin layer of gold. Both sample preparation and analysis are performed at the laboratories of Metallurgy and Materials Science Research Institute, Chulalongkorn University.

The results obtained from SEM are depicted in Fig. 3.1 to 3.4 for cement paste with water/cement ratio of 0.36, 0.24, 0.16, and 0.12, respectively. With 75x-100x magnification, the surfaces of all samples are not smooth and microcracks occur during preparation. Nevertheless, these imperfections reveal much important information. In general, the entrapped air voids with diameter around 30 μm can be observed randomly. These voids seem to decrease at a water/cement ratio of 0.16, while with 0.12-water/cement ratio, the voids are enlarged. There are crystals of calcium hydroxide precipitated in the void space. With higher magnification, the loose structure of CSH and calcium hydroxide is usually found at the area of high porosity. Such area is easily found in cement paste with 0.36-water/cement ratio. Most of the volume of cement paste is full of the clusters of amorphous CSH, which seem very dense at low water/cement ratio. However, the fibrous morphology of CSH also exists. This kind of CSH appears most at the boundaries of unhydrated cement grains. Other hydration products, such as ettringite and monosulfate hydrate are embedded randomly.

3.2.3.2 Thermogravimetric Analysis

Normally, TGA is an approach for determining the quantity of compounds in materials that can decompose at a certain range of temperature. In cement paste, all the water dehydrates at a temperature up to 400 °C. During a temperature of 400-550 °C (Ramachandran, 1979), calcium hydroxide becomes calcium oxide and water, i.e.,

$$Ca(OH)_2 \rightarrow CaO + H_2O \tag{3.12}$$

This water evaporates and is detected as the weight loss at such temperature. The amount of the decomposed calcium hydroxide can be calculated with the conservation of molecular weight. Although there are several techniques to evaluate the amount of calcium hydroxide, TGA is recognized for its good accuracy (Fordham and Smalley, 1985).

In this study, TGA is performed at Scientific and Technological Research Equipment Centre, Chulalongkorn University. All samples are tested at 28 days. The remaining cement paste from testing by SEM is ground by tungsten carbide ball mill for 15 minutes. 200 mg of well-ground samples passing ASTM sieve no. 200 are heated in chamber until the temperature of 1100 °C is reached at normal atmospheric pressure for 2 hours. The data of weight loss is detected throughout the experiment.

The estimated amount of calcium hydroxide and CSH is shown in Fig. 3.5. The quantity of CSH is calculated stoichiometrically by using eq. (3.3) and (3.4). It is about two times of that of calcium hydroxide. It is approximately 20% at water/cement ratio of 0.12, rises with increasing water/cement ratio, and reaches a peak up to 42% at water/cement ratio of 0.28. Afterwards, it gradually decreases owing to insufficient cement for hydrating. Combining with the finding from the hydration model in 3.1.3.1, it can be said that, from the chemical aspect, the optimum water/cement ratio for this type-I potland cement for the most effective hydration lies in between 0.26 and 0.28.

However, according to two-type CSH model of Tennis and Jennings (2000), the detected CSH can be categorized as low-density CSH and high-density CSH. With eq. (3.5), the amount of both type of CSH can be computed, as shown in Table 3.5. The degree of hydration of each cement paste mix is assumed to be the ratio of the amount of detected CSH from the experiment and calculated CSH from the hydration model. It can be seen that the amount of low-density CSH is the proportion to water/cement ratio. All CSH is high-density CSH when water/cement ratio is less than 0.20. Regarding the fact that density of high-density CSH is about 1.20 times that of the low-density one, the equivalent amount of CSH can be figured out. The highest equivalent amount of CSH is found at water/cement ratio of 0.20.

3.2.3.3 Total Porosity

The method chosen to determine the porosity is total water porosity measurement conforming to RILEM method CPC 11.3. This method is very simple and inexpensive. It also has the advantage that the test pieces are not disturbed by boiling or oven drying before their volume determination (Kolias, 1994.)

Briefly, cement paste specimens are put in a vacuum compartment, before soaking under water for 24 hours. Then, they are weighted in SSD condition and their volume is determined. Dry weight is determined after 24-hour drying in an oven at 105 °C.

The measured total porosity with various ages is plotted with water/cement ratio, as shown in Fig. 3.6. At 7 days, the total porosity is 18.21% in the cement paste with water/cement ratio of 0.40. It decreases with reducing water/cement ratio until the minimum of 14.83% is found at water/cement ratio of 0.20. Then, the total porosity increases afterwards. When cement paste ages, the porosity decreases. The total porosity is between 13.64% and 17.17% at 28 days and becomes less in later age, i.e., 16.78%-12.79% at 56 days, and 16.52%-12.33% at 91 days. Obviously, the optimum water/cement ratio for the least total porosity is 0.16.

3.2.4 Mechanical Properties

3.2.4.1 Compressive Strength

Compressive strength is the most extensive-used parameter to indicate the quality of concrete or even cement paste. In this study, the compressive strength of cement paste is tested by compressing 50x50x50-mm cubic specimen according to ASTM C109. The test results are shown in Fig. 3.7. The 7-day compressive strength of cement paste with water/cement ratio of 0.40 is 53.37 MPa. It raises up to 79.98 MPa at water/cement ratio of 0.16, followed by a small rebound. Compressive strength also increases with time. In later age, the similar trend of compressive strength with water/cement ratio can be revealed. The water/cement ratio of 0.16 still provides the highest values of compressive strength. In order, they are 103.87, 114.45 and 120.03 MPa, at 28, 56 and 91 days.

3.2.4.2 Tensile Strength

ASTM C190 is used for measuring the direct tensile strength of hardened cement paste. In this method, briquette specimens are used. Fig. 3.8 presents the relation between direct tensile strength and water/cement ratio. The same trend of strength development as that of compressive strength is observed. Direct tensile strength is about one-twentieth of compressive strength. It varies from 2.65 to 4.09 MPa at 7 days, from 2.93 to 4.69 MPa at 28 days, from 3.12 to 5.09 MPa at 56 days, and from 3.42 to 5.32 MPa at 91 days. The maximum is found at water/cement ratio of 0.20 at 7 days and 0.16 after that.

3.2.4.3 Elastic Modulus

Elastic modulus is tested by compressing a 25x25x250-mm prism specimen in longitudinal direction. To measure displacement, two strain gauges are attached in two opposite faces. They are parallel to load direction. The test results are depicted in Fig. 3.9. Its relation to water/cement ratio looks like that of either compressive strength or tensile strength. There is an increase in elastic modulus with decreasing water/cement ratio and a small rebound when water/cement ratio below 0.16. At 7 days, the elastic modulus ranges from 14.24 to 21.64 GPa, while it is in between 18.46 and 31.02 GPa at 28 days, 21.84 and 36.17 GPa at 56 days, and 23.42 and 38.11 at 91 days. With compressive strength, the ultimate strain of cement paste can be calculated. It is 0.0037, 0.0034, 0.0031 and 0.0032 at 7, 28, 56 and 91 days, respectively.

3.2.5 Contribution of Microstructure to Strength

From the experiment in section 3.2.2-3.2.4, it can be summarized that water/cement ratio in between 0.26 and 0.28 yields the balance of hydration reaction. It gives the highest amount of CSH in cement paste. Nevertheless, the equivalent amount of CSH is found to be the most at water/cement ratio of 0.20. From a physical and mechanical point of view, the optimum water/cement ratio should lies between 0.16 and 0.20. For all ages, such value of water/cement ratio provides the minimum total porosity and the most excellent in mechanical properties, including compressive strength, tensile strength and elastic modulus.

In general, the dependence of compressive strength on the equivalent amount of CSH and total porosity is shown in Fig. 3.10 and 3.11, respectively. There are tendencies for a rising strength of cement paste when the equivalent amount of CSH increases or the total porosity is reduced. To account the effect of both parameters, the non-linear regression of the experimental results is performed. For cement used in this study, the relation among cement paste compressive strength (S_p), the equivalent amount of CSH (CSH_e), and the total porosity (p) can be expressed, with the confidence level of 90%, as

$$S_p = (286.64 + 232.62 * CSH_e)(1 - p)^{9.69} \tag{3.13}$$

For a given type of cement, the equation like eq. (3.13) may be helpful to design a mix proportion of cement paste with desired strength based on its microstructure. The capability of cement to provide CSH and the method used for reducing porosity in paste govern the required water/cement ratio.

3.3 Effects of Superplasticizers

When the water/cement ratio is low, cement paste becomes viscous and can not flow easily. Some volume of cement paste may not fill up, causing internal voids. This additional porosity makes cement paste weaker. However, a high-range water reducing agent (HRWRA) or superplasticizer is useful to relieve this problem. The compatibility with cement enables it to facilitate flow of the mixture. To avoid unexpected side effects, the amount of superplasticizer should not exceed the recommendation of the manufacturer.

In this section, the ability of a commonly used superplasticizer to provide flow and its effects on porosity and compressive strength is investigated experimentally. Type-I Portland cement paste specimens with water/cement ratio varying from 0.12 to 0.40 are produced with the addition of superplasticizer by 0%, 4% and 8% by weight of cement. Table 3.10 shows the mix proportion. The same mixing procedure and specimen preparation as in section 3.2 is applied.

3.3.1 Fresh-State Properties

3.3.1.1 Flow Value

Flow value is measured by using flow table according to ASTM C230. The test results are shown in Fig. 3.12. It is obvious that the flow value decreases with reducing water/cement ratio. With water/cement ratio of 0.12, the flow value of cement paste is 71.6% when no superplasticizer presents. It becomes 93.2% and 113.2%, providing that superplasticizer is added by 4% and 8%, respectively.

3.3.1.2 Unit Weight and Air Voids

Fig. 3.13 presents the measured unit weight as a function of water/cement ratio, while that of air void is shown in Fig. 3.14. The density of superplasticizer is lower than that of cement; therefore, the unit weight of cement paste decreases when superplasticizer is added. However, the difference in unit weight becomes smaller when water/cement ratio is low. There is a high air content in low-water/cement ratio pastes containing 0% and 4% of superplasticizer. Insufficient amount of superplasticizer prevents cement paste from fully compacting. It can be observed that cement paste that posseses flow value lower than 100% yields the air content higher than 2%.

3.3.2 Total Porosity

The total porosity of cement pastes at 28 days is shown in Fig. 3.15. It can be seen that total porosity reduces due to the addition of superplasticizer. The optimum water/cement ratio for the minimum porosity shifts from 0.24 in cement pastes without superplasticizer to 0.20 when superplasticizer is added by 8%. The rebound of total porosity, when the water/cement ratio is less than the optimum, may be the result of the high volume of air bubbles embedded in fresh cement paste. They become air voids and make cement paste more porous, when it hardens.

3.3.3 Compressive Strength

Fig. 3.16 shows the plots of 28-day compressive strength. Compressive strength rises with the presence of superplasticizer. Without superplasticizer, the highest compressive strength is 91.16 MPa at water/cement ratio of 0.24. It becomes 107.55 MPa at water/cement ratio of 0.20, when superplasticizer is included by 8%. As shown in Fig. 3.17, compressive strength is an inverse function of total porosity. The line is calculated by using eq. (3.13) and assuming CSH_e = 51.33%, which is the average from the experiment in section 3.2.

Although superplasticizer does not enter into the hydration reaction directly, it is beneficial for strength development of cement paste. Superplasticizer yields flowability to the viscous cement paste mixtures containing low water content. It allows cement pastes to fill up specimens with fully compaction, causing a low value of porosity when they harden. Insufficient quantity of cement paste makes cement pastes weaker. Like in Fig. 3.12, the amount of superplasticizer can be determined regarding to its capability for providing flow. However, overdosage of superplasticizer delay to concrete setting.

3.4 Effects of Pozzolanic Materials

Inclusion of pozzolanic materials, such as silica fume or fly ash, is beneficial to cement paste quality. Thank to both filler effect and chemical effect, they make improve the microstructure of cement paste, raising strength as well as durability. While approximately 10% and 20% by cement weight of 46.20%-S fly ash and 86.00%-S silica fume, respectively, for balance, pozzolanic reaction were analyzed stoichiometrically in section 3.1.3.2. The optimum content of such materials regarding compression of cement paste is experimentally evaluated as following in this section.

Chemical composition, specific gravity and Blaine fineness of Type-I Portland cement, fly ash and silica fume are already shown in Table 3.2. Water/cement ratio varies from 0.12 to 0.40. Fly ash is added by 10%, 15%, 20%, and 25% by weight of cement, whereas silica fume is consumed by 5%, 10%, 15% by weight of cement. Superplasticizer is also used to maintain cement paste flow value of 110% ±5%. The mix proportion is tabulated in Table 3.13 and 3.14 for cement paste with fly ash and silica fume, respectively. The mixing process and specimen preparation are the same as in section 3.2.

3.4.1 Fresh-State Properties

Table 3.15 and 3.16 show unit weight and air content of fresh cement paste incorporating fly ash and silica fume, respectively. It can be seen that unit weight depends on cement content. When sufficient workability for placing is provided, the unit weight is up to 2715 kg/m^3 for cement paste with water/cement ratio of 0.12, of which the air content is about 2.0%. No significant systematic difference can be found in unit weight and air content between cement pastes containing fly ash and silica fume.

3.4.2 Calcium Silicate Hydrate

The results from thermogravimetric analysis are shown in Table 3.17 and 3.18 for 28-day cement paste with fly ash and silica fume, respectively. The amount of detected calcium hydroxide reduces with the addition of fly ash or silica fume. Regarding water/cement ratio, the highest volume of calcium hydroxide can be found in cement paste with water/cement ratio of 0.24. With the same amount of replacement, it is also observed that silica fume consumes more calcium hydroxide in pozzolanic reaction than fly ash.

The stoichiometrically calculated quantity of CSH is approximately in the range of 20% and 45% by weight of cement paste specimens. CSH decreases with decreasing water/cement ratio. The maximum CSH is found in cement paste with 20% addition of fly ash and 10% addition of silica fume. The amount of CSH in cement paste with fly ash is slightly less than that in cement paste with silica fume.

3.4.3 Total Porosity

The measured total porosity of cement pastes with fly ash and silica fume is shown in Table. 3.19 and 3.20, respectively. Only the values of total porosity at 28 days are plotted with water/cement ratio in Fig. 3.18 and 3.19. The 28-day total porosity is lies between 11% and 15%. Due to higher packing, the total porosity of cement paste with silica fume is more than that with fly ash. For both fly ash and silica fume, total porosity is obviously reduced with water/cement ratio until the optimum water/cement ratio of about 0.16-0.20 is reached, followed by a small rebound. Furthermore, the lowest total porosity is found in cement paste specimens with 20% addition of fly ash and 10% addition of silica fume.

3.4.4 Compressive Strength

For cement paste with fly ash, Table 3.21 shows the tested compressive strength for all ages, while Fig. 3.20 depicts relations between 28-day compressive strength and water/cement ratio. At 7 days, the compressive strength of cement paste of all percentage addition of fly ash is less than with the control cement paste. It decreases with increasing amounts of fly ash. Only cement paste with 20% added provides compressive strength higher than control after 28 days. It is up to 124.31 MPa at 91 days. A water/cement ratio between 0.16 and 0.20 is an optimum for the highest compressive strength.

Those of cement paste containing silica fume are shown in Table 3.22 and Fig. 3.21. The highest compressive strength is 85.17 MPa at 7 days for cement paste with water/cement ratio of 0.16 and 10% addition of silica fume, and becomes 115.66, 126.49 and 137.96 MPa at 28, 56 and 91 days, respectively. A water/cement ratio between 0.16 and 0.20 is also an optimum for the highest compressive strength of cement paste containing silica fume.

The pozzolanic reaction of fly ash and silica fume is a primary reason for an increase in compressive strength of cement paste. By regression analysis, the ratio of compressive strength containing pozzolanic material ($f'_{p,w/FA}$ or $f'_{p,w/SF}$) to compressive strength of cement paste without any pozzolanic material ($f'_{p,w/o}$) is a function of the ratio between CSH in cement paste containing pozzolanic material ($\mathrm{CSH}_{w/FA}$ or $\mathrm{CSH}_{w/SF}$) and cement paste without pozzolanic material ($\mathrm{CSH}_{w/o}$), as following

$$f'_{p,w/FA} / f'_{p,w/o} = 1.2501\left(\mathrm{CSH}_{w/FA} / \mathrm{CSH}_{w/o}\right) - 0.2082 \qquad (3.14)$$

$$f'_{p,w/SF} / f'_{p,w/o} = 1.8381\left(\mathrm{CSH}_{w/SF} / \mathrm{CSH}_{w/o}\right) - 0.8333 \qquad (3.15)$$

Table 3.1 Molecular weight and density of compounds involving in hydration calculation

Cement Chemistry Notation	Molecular Weight (kg/mol)	Density * (kg/m^3)
C_3S	0.228	3150
C_2S	0.172	3280
C_3A	0.270	3030
C_4AF	0.486	3730
$C\bar{S}H_2$	0.172	2320
H	0.018	1000
$C_3S_2H_3$	0.342	1590
CH	0.074	2240
$C_6A\bar{S}H_{32}$	1.254	1750
$C_4A\bar{S}H_{12}$	0.622	1990
C_3AH_6	0.378	2050
$C_4(A,F)H_{13}$	0.589	2670

* from Tennis and Jennings (2000)

Table 3.2 Chemical compositions and physical features of materials

Properties	Portland Cement		Fly Ash	Silica Fume
	Type I	Type III		
Chemical Composition (%)				
- CaO	65.41	65.20	13.60	0.40
- SiO_2	20.90	21.36	46.20	86.00
- Al_2O_3	4.76	3.44	23.90	1.30
- Fe_2O_3	3.41	2.85	11.30	7.20
- MgO	1.25	2.06	2.10	1.60
- Na_2O	0.24	0.59	0.06	0.02
- K_2O	0.35	0.44	0.80	0.05
- SO_3	2.71	2.63	1.30	2.10
- LOI	0.96	1.42	0.40	0.20
Specific Gravity	3.14	3.12	2.36	2.29
Blaine Fineness (m^2/kg)	328	420	540	2100

Table 3.3 Mix proportion of cement pastes

Designation	W/C Ratio	Cement (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
P40	0.40	1394	558	0
P36	0.36	1476	531	0
P32	0.32	1569	502	0
P28	0.28	1674	469	0
P24	0.24	1794	431	9
P20	0.20	1933	387	39
P16	0.16	2094	335	105
P12	0.12	2286	274	206

Table 3.4 Fresh-state properties of cement pastes

Designation	Unit Weight (kg/m^3)	Air Void (%)
P40	1944	0.39
P36	1993	0.74
P32	2048	1.09
P28	2108	1.61
P24	2180	1.53
P20	2228	1.87
P16	2248	1.99
P12	2256	1.65

Table 3.5 Amount of CSH in cement pastes

Designation	Amount of CH (%)	Amount of CSH (%)	Degree of Hydration (%)	Amount of LD CSH (%)	Amount of HD CSH (%)	Equivalent Amount of CSH
P40	18.91	37.60	80.68	14.59	19.74	44.20
P36	19.73	39.23	82.10	11.65	24.32	48.12
P32	20.14	40.05	81.50	8.35	28.43	51.00
P28	20.97	41.68	82.54	4.74	33.67	55.25
P24	20.56	40.87	85.99	0.09	37.51	56.35
P20	18.09	35.96	95.52	0.00	37.60	56.40
P16	15.21	30.24	97.06	0.00	35.96	53.94
P12	10.69	21.25	87.80	0.00	30.24	45.36

Table 3.6 Total porosity of cement pastes

Designation	Total Porosity (%)			
	7 days	28 days	56 days	91 days
P40	18.21	17.17	16.78	16.52
P36	17.34	16.01	15.52	15.17
P32	16.65	15.20	14.49	14.26
P28	15.63	14.38	13.86	13.42
P24	15.22	13.93	13.21	12.98
P20	14.83	13.78	12.91	12.51
P16	14.94	13.64	12.74	12.33
P12	16.23	13.92	13.07	12.75

Table 3.7 Compressive strength of cement pastes

Designation	Compressive Strength (MPa)			
	7 days	28 days	56 days	91 days
P40	53.37	64.37	69.55	76.14
P36	59.74	72.68	80.34	84.26
P32	65.73	82.27	88.52	95.02
P28	68.54	90.31	98.71	104.52
P24	73.66	93.92	105.50	113.16
P20	77.88	101.29	111.94	118.96
P16	79.98	103.87	114.45	120.03
P12	65.26	90.12	101.39	108.51

Table 3.8 Tensile strength of cement pastes

Designation	Tensile Strength (MPa)			
	7 days	28 days	56 days	91 days
P40	2.65	2.93	3.12	3.42
P36	3.13	3.51	3.73	4.07
P32	3.51	3.83	4.18	4.51
P28	3.70	4.09	4.46	4.83
P24	3.94	4.44	4.81	5.12
P20	4.09	4.61	4.97	5.20
P16	4.05	4.69	5.09	5.32
P12	3.41	3.94	4.26	4.42

Table 3.9 Elastic modulus of cement pastes

Designation	Elastic Modulus (GPa)			
	7 days	28 days	56 days	91 days
P40	14.24	18.46	21.84	23.42
P36	16.44	20.75	25.13	26.19
P32	17.95	23.76	28.48	30.17
P28	18.49	26.89	30.11	32.45
P24	20.12	28.11	33.19	35.62
P20	21.24	30.48	35.84	38.29
P16	21.64	31.02	36.17	38.11
P12	17.66	27.44	33.48	34.51

Table 3.10 Mix proportion of cement pastes containing superplasticizer

Designation	W/C Ratio	Cement (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
P40-SP00	0.40	1394	558	0
P36-SP00	0.36	1476	531	0
P32-SP00	0.32	1569	502	0
P28-SP00	0.28	1674	469	0
P24-SP00	0.24	1794	431	0
P20-SP00	0.20	1933	387	0
P16-SP00	0.16	2094	335	0
P12-SP00	0.12	2286	274	0
P40-SP04	0.40	1394	558	56
P36-SP04	0.36	1476	531	59
P32-SP04	0.32	1569	502	63
P28-SP04	0.28	1674	469	67
P24-SP04	0.24	1794	431	72
P20-SP04	0.20	1933	387	77
P16-SP04	0.16	2094	335	84
P12-SP04	0.12	2286	274	91
P40-SP08	0.40	1394	558	112
P36-SP08	0.36	1476	531	118
P32-SP08	0.32	1569	502	125
P28-SP08	0.28	1674	469	134
P24-SP08	0.24	1794	431	144
P20-SP08	0.20	1933	387	155
P16-SP08	0.16	2094	335	168
P12-SP08	0.12	2286	274	183

Table 3.11 Fresh-state properties of cement pastes containing superplasticizer

Designation	Flow Value (%)	Unit Weight (kg/m^3)	Air Void (%)
P40-SP00	150.0	1944	0.39
P36-SP00	147.5	1993	0.74
P32-SP00	139.8	2048	1.09
P28-SP00	124.6	2108	1.61
P24-SP00	113.2	2184	1.80
P20-SP00	99.5	2264	2.39
P16-SP00	88.3	2294	5.57
P12-SP00	71.6	2312	9.71
P40-SP04	> 150.0	1894	0.37
P36-SP04	>150.0	1938	0.71
P32-SP04	148.3	1992	0.77
P28-SP04	135.3	2049	1.06
P24-SP04	129.3	2113	1.37
P20-SP04	123.4	2199	1.15
P16-SP04	108.3	2274	1.94
P12-SP04	93.2	2326	4.26
P40-SP08	> 150.0	1847	0.46
P36-SP08	>150.0	1889	0.63
P32-SP08	> 150.0	1941	0.52
P28-SP08	148.0	1989	0.94
P24-SP08	142.2	2054	0.81
P20-SP08	133.4	2121	1.02
P16-SP08	121.2	2198	1.17
P12-SP08	113.2	2292	1.19

Table 3.12 Hardened-state properties of cement pastes containing superplasticizer

Designation	Total Porosity (%)	Compressive Strength (MPa)
P40-SP00	17.17	64.37
P36-SP00	16.01	72.68
P32-SP00	15.10	82.27
P28-SP00	14.38	90.31
P24-SP00	14.03	91.16
P20-SP00	14.31	87.44
P16-SP00	14.51	85.51
P12-SP00	15.04	79.83
P40-SP04	17.30	67.52
P36-SP04	15.83	77.93
P32-SP04	14.86	85.19
P28-SP04	14.27	93.60
P24-SP04	13.72	99.43
P20-SP04	13.58	95.12
P16-SP04	13.92	94.66
P12-SP04	14.27	88.51
P40-SP08	17.62	65.18
P36-SP08	15.94	70.54
P32-SP08	14.91	86.80
P28-SP08	14.14	95.74
P24-SP08	13.59	103.96
P20-SP08	13.22	107.55
P16-SP08	13.37	101.12
P12-SP08	13.96	90.43

Table 3.13 *Mix proportion of cement pastes containing fly ash*

Designation	Cement (kg/m³)	Water (kg/m³)	Fly Ash (kg/m³)	Superplasticizer (kg/m³)
P40-FA10	1316	525	132	0
P36-FA10	1389	500	139	0
P32-FA10	1471	471	147	0
P28-FA10	1563	438	156	0
P24-FA10	1667	400	167	0
P20-FA10	1786	357	179	18
P16-FA10	1924	398	192	48
P12-FA10	2084	250	208	104
P40-FA15	1280	512	192	0
P36-FA15	1349	486	202	0
P32-FA15	1426	456	214	0
P28-FA15	1513	424	227	0
P24-FA15	1610	386	242	0
P20-FA15	1721	344	258	9
P16-FA15	1848	296	277	37
P12-FA15	1996	240	299	80
P40-FA20	1247	499	249	0
P36-FA20	1312	472	262	0
P32-FA20	1385	443	277	0
P28-FA20	1466	410	293	0
P24-FA20	1557	374	311	0
P20-FA20	1661	332	332	0
P16-FA20	1779	285	356	27
P12-FA20	1915	230	383	77
P40-FA25	1214	486	304	0
P36-FA25	1277	460	319	0
P32-FA25	1345	430	336	0
P28-FA25	1422	398	356	0
P24-FA25	1507	362	377	0
P20-FA25	1604	321	401	8
P16-FA25	1714	274	429	34
P12-FA25	1840	221	460	92

Table 3.14 Mix proportion of cement pastes containing silica fume

Designation	Cement (kg/m^3)	Water (kg/m^3)	Silica Fume (kg/m^3)	Superplasticizer (kg/m^3)
P40-SF05	1353	541	68	0
P36-SF05	1430	515	72	0
P32-SF05	1517	485	76	0
P28-SF05	1615	452	81	8
P24-SF05	1726	414	86	17
P20-SF05	1854	371	93	56
P16-SF05	2003	320	100	120
P12-SF05	2177	261	109	196
P40-SF10	1314	526	131	0
P36-SF10	1387	499	139	0
P32-SF10	1468	470	147	0
P28-SF10	1560	437	156	16
P24-SF10	1664	399	166	42
P20-SF10	1782	356	178	71
P16-SF10	1918	307	192	144
P12-SF10	2078	249	208	218
P40-SF15	1277	511	192	0
P36-SF15	1346	485	202	0
P32-SF15	1423	455	213	14
P28-SF15	1508	422	226	30
P24-SF15	1605	385	241	64
P20-SF15	1715	343	257	111
P16-SF15	1842	295	276	193
P12-SF15	1988	239	298	258

Table 3.15 Fresh-state properties of cement pastes containing fly ash

Designation	Unit Weight (kg/m^3)	Air Void (%)
P40-FA10	1951	1.10
P36-FA10	2010	0.88
P32-FA10	2063	1.25
P28-FA10	2129	1.31
P24-FA10	2214	0.88
P20-FA10	2314	1.09
P16-FA10	2527	1.39
P12-FA10	2593	2.03
P40-FA15	1962	1.11
P36-FA15	2005	1.59
P32-FA15	2070	1.24
P28-FA15	2143	0.97
P24-FA15	2205	1.45
P20-FA15	2293	1.66
P16-FA15	2413	1.84
P12-FA15	2578	1.42
P40-FA20	1964	1.57
P36-FA20	2016	1.49
P32-FA20	2082	1.09
P28-FA20	2144	1.16
P24-FA20	2207	1.58
P20-FA20	2295	1.30
P16-FA20	2408	1.57
P12-FA20	2562	1.64
P40-FA25	1983	1.02
P36-FA25	2031	1.23
P32-FA25	2079	1.53
P28-FA25	2155	0.94
P24-FA25	2218	1.24
P20-FA25	2306	1.20
P16-FA25	2418	1.34
P12-FA25	2560	2.03

Table 3.16 Fresh-state properties of cement pastes containing silica fume

Designation	Unit Weight (kg/m^3)	Air Void (%)
P40-SF05	1947	0.75
P36-SF05	1998	0.92
P32-SF05	2051	1.29
P28-SF05	2135	0.97
P24-SF05	2230	0.60
P20-SF05	2343	1.28
P16-SF05	2509	1.35
P12-SF05	2692	1.85
P40-SF10	1958	0.68
P36-SF10	2003	1.07
P32-SF10	2064	1.00
P28-SF10	2158	0.49
P24-SF10	2253	0.79
P20-SF10	2365	0.94
P16-SF10	2529	1.24
P12-SF10	2701	1.89
P40-SF15	1961	0.94
P36-SF15	2008	1.22
P32-SF15	2073	1.55
P28-SF15	2169	0.79
P24-SF15	2274	0.91
P20-SF15	2393	1.39
P16-SF15	2588	0.72
P12-SF15	2715	2.47

Table 3.17 Amount of CSH in cement pastes containing fly ash

Designation	Detected CH (%)	CH from Hydration (%)	CSH from Hydration (%)	CSH from Pozzolanic (%)	Total CSH (%)
P28-FA10	12.91	18.06	31.17	7.94	39.11
P24-FA10	13.46	18.50	31.93	7.77	39.70
P20-FA10	12.69	16.28	28.09	5.53	33.63
P16-FA10	11.22	13.69	23.62	3.80	27.43
P12-FA10	7.15	9.62	16.60	3.81	20.41
P28-FA15	9.58	17.06	29.44	11.52	40.96
P24-FA15	10.30	17.48	30.16	11.05	41.21
P20-FA15	9.87	15.38	26.53	8.48	35.02
P16-FA15	8.86	12.93	22.31	6.27	28.58
P12-FA15	5.62	9.09	15.68	5.34	21.02
P28-FA20	5.28	16.06	27.71	16.60	44.31
P24-FA20	6.35	16.45	28.38	15.56	43.94
P20-FA20	6.43	14.47	24.97	12.39	37.36
P16-FA20	6.00	12.17	21.00	9.50	30.50
P12-FA20	4.37	8.55	14.76	6.44	21.20
P28-FA25	3.56	15.05	25.97	17.70	43.68
P24-FA25	4.84	15.42	26.61	16.30	42.91
P20-FA25	4.81	13.57	23.41	13.49	36.90
P16-FA25	4.95	11.41	19.68	9.95	29.63
P12-FA25	3.69	8.02	13.83	6.67	20.50

Table 3.18 Amount of CSH in cement pastes containing silica fume

Designation	Detected CH (%)	CH from Hydration (%)	CSH from Hydration (%)	CSH from Pozzolanic (%)	Total CSH (%)
P28-SF05	9.82	18.06	31.17	12.70	43.87
P24-SF05	11.15	18.50	31.93	11.33	43.26
P20-SF05	10.44	16.28	28.09	9.00	37.09
P16-SF05	8.80	13.69	23.62	7.53	31.15
P12-SF05	6.03	9.62	16.60	5.53	22.13
P28-SF10	7.01	17.06	29.44	15.48	44.92
P24-SF10	8.14	17.48	30.16	14.38	44.54
P20-SF10	7.80	15.38	26.53	11.67	38.21
P16-SF10	6.62	12.93	22.31	9.72	32.03
P12-SF10	4.41	9.09	15.68	7.20	22.88
P28-SF15	5.47	16.06	27.71	16.31	44.01
P24-SF15	6.36	16.45	28.38	15.54	43.92
P20-SF15	6.30	14.47	24.97	12.59	37.56
P16-SF15	5.24	12.17	21.00	10.67	31.67
P12-SF15	3.61	8.55	14.76	7.61	22.37

Table 3.19 Total porosity of cement pastes containing fly ash

Designation	Total Porosity (%)			
	7 days	28 days	56 days	91 days
P40-FA10	16.06	14.93	14.58	14.32
P36-FA10	15.82	14.19	13.92	13.77
P32-FA10	15.33	14.04	13.64	13.51
P28-FA10	14.62	13.38	12.86	12.57
P24-FA10	13.98	13.17	12.69	12.44
P20-FA10	13.16	12.54	12.36	12.15
P16-FA10	13.47	12.68	12.43	12.04
P12-FA10	14.02	12.95	12.89	12.65
P40-FA15	15.72	14.48	14.02	13.75
P36-FA15	15.45	13.73	13.59	13.36
P32-FA15	14.90	13.42	13.21	12.97
P28-FA15	14.26	13.29	12.56	12.20
P24-FA15	13.87	12.74	12.14	11.89
P20-FA15	13.08	12.19	11.89	11.56
P16-FA15	13.26	12.28	12.04	11.63
P12-FA15	14.53	12.76	12.48	12.39
P40-FA20	15.30	14.16	13.85	13.61
P36-FA20	15.07	13.55	13.32	13.04
P32-FA20	14.64	13.08	12.74	12.58
P28-FA20	13.87	12.84	12.50	11.95
P24-FA20	13.42	12.42	12.28	11.73
P20-FA20	12.92	12.06	11.73	11.60
P16-FA20	12.86	12.08	11.98	11.52
P12-FA20	14.29	12.88	12.59	12.18
P40-FA25	15.44	14.30	13.76	13.58
P36-FA25	14.97	13.67	13.46	13.11
P32-FA25	14.71	13.31	13.05	12.36
P28-FA25	14.13	13.05	12.69	12.24
P24-FA25	13.52	12.66	12.32	11.99
P20-FA25	13.13	12.25	12.21	11.77
P16-FA25	13.04	12.47	12.18	11.83
P12-FA25	14.53	13.58	13.09	12.78

Table 3.20 *Total porosity of cement pastes containing silica fume*

Designation	Total Porosity (%)			
	7 days	28 days	56 days	91 days
P40-SF05	15.20	14.08	13.72	13.56
P36-SF05	14.79	13.65	13.34	13.10
P32-SF05	14.43	13.28	12.93	12.61
P28-SF05	13.86	12.93	12.35	12.19
P24-SF05	13.37	12.06	11.82	11.63
P20-SF05	12.75	11.84	11.48	11.12
P16-SF05	12.63	11.73	11.39	10.95
P12-SF05	13.58	12.64	12.15	12.03
P40-SF10	14.65	13.76	13.38	13.06
P36-SF10	14.22	13.08	12.67	12.39
P32-SF10	14.09	12.74	12.35	11.94
P28-SF10	13.45	12.29	12.01	11.53
P24-SF10	12.82	11.65	11.48	11.09
P20-SF10	12.36	11.42	11.15	10.74
P16-SF10	12.20	11.19	10.84	10.55
P12-SF10	13.07	12.28	12.03	11.72
P40-SF15	14.82	13.88	13.51	13.39
P36-SF15	14.45	13.46	13.19	12.75
P32-SF15	14.18	12.95	12.78	12.26
P28-SF15	13.71	12.24	11.96	11.70
P24-SF15	13.08	11.75	11.42	11.19
P20-SF15	12.57	11.53	11.27	10.89
P16-SF15	12.31	11.60	11.19	10.84
P12-SF15	13.32	12.58	12.28	11.73

Table 3.21 Compressive strength of cement pastes containing fly ash

Designation	Compressive Strength (MPa)			
	7 days	28 days	56 days	91 days
P40-FA10	56.35	64.88	70.14	83.33
P36-FA10	59.12	74.13	84.05	90.12
P32-FA10	63.18	83.23	90.47	97.60
P28-FA10	65.49	87.11	97.36	101.54
P24-FA10	68.12	94.49	102.66	108.12
P20-FA10	69.88	97.28	104.45	109.69
P16-FA10	66.93	96.11	105.30	111.12
P12-FA10	60.60	89.43	92.23	99.12
P40-FA15	52.13	66.47	78.57	85.21
P36-FA15	54.59	72.22	82.62	86.87
P32-FA15	59.62	84.69	89.57	96.43
P28-FA15	62.30	92.13	98.45	103.11
P24-FA15	66.11	98.83	101.63	111.38
P20-FA15	65.63	102.21	108.10	113.21
P16-FA15	62.98	101.06	107.47	115.62
P12-FA15	57.37	92.68	95.57	97.40
P40-FA20	54.68	69.23	81.51	88.19
P36-FA20	56.32	79.13	89.26	100.43
P32-FA20	60.51	93.44	98.73	103.60
P28-FA20	62.93	101.20	105.22	108.57
P24-FA20	61.66	106.68	109.67	115.72
P20-FA20	59.32	110.44	116.31	120.76
P16-FA20	57.74	109.32	118.22	124.31
P12-FA20	52.62	93.64	101.20	107.47
P40-FA25	52.95	66.12	77.98	81.62
P36-FA25	54.66	77.63	84.71	89.14
P32-FA25	58.17	88.47	93.60	98.78
P28-FA25	60.73	95.49	100.29	105.65
P24-FA25	57.12	103.74	107.34	113.13
P20-FA25	58.86	106.82	111.69	116.67
P16-FA25	57.93	105.63	112.58	119.83
P12-FA25	51.12	89.93	99.79	105.43

Table 3.22 Compressive strength of cement pastes containing silica fume

Designation	Compressive Strength (MPa)			
	7 days	28 days	56 days	91 days
P40-SF05	56.08	73.32	87.65	96.27
P36-SF05	62.49	79.89	93.13	101.13
P32-SF05	68.11	91.16	102.28	110.40
P28-SF05	71.20	99.42	109.76	117.63
P24-SF05	75.83	104.55	114.87	122.57
P20-SF05	79.42	107.60	120.49	128.16
P16-SF05	77.65	110.13	123.63	131.04
P12-SF05	62.15	97.44	111.42	119.29
P40-SF10	59.24	80.88	93.63	102.28
P36-SF10	64.85	86.39	100.26	109.31
P32-SF10	69.02	95.42	108.11	118.94
P28-SF10	73.59	103.63	115.29	123.61
P24-SF10	78.26	109.84	122.45	130.36
P20-SF10	83.44	113.43	127.82	135.49
P16-SF10	85.17	115.66	126.49	137.96
P12-SF10	70.63	103.35	113.66	125.05
P40-SF15	57.43	78.16	94.12	99.39
P36-SF15	63.06	84.90	99.27	108.16
P32-SF15	67.43	93.25	106.63	115.54
P28-SF15	71.29	100.03	112.05	122.37
P24-SF15	79.65	107.26	119.42	128.83
P20-SF15	81.92	110.11	124.51	133.63
P16-SF15	82.51	113.46	125.63	134.45
P12-SF15	66.32	99.37	115.85	123.32

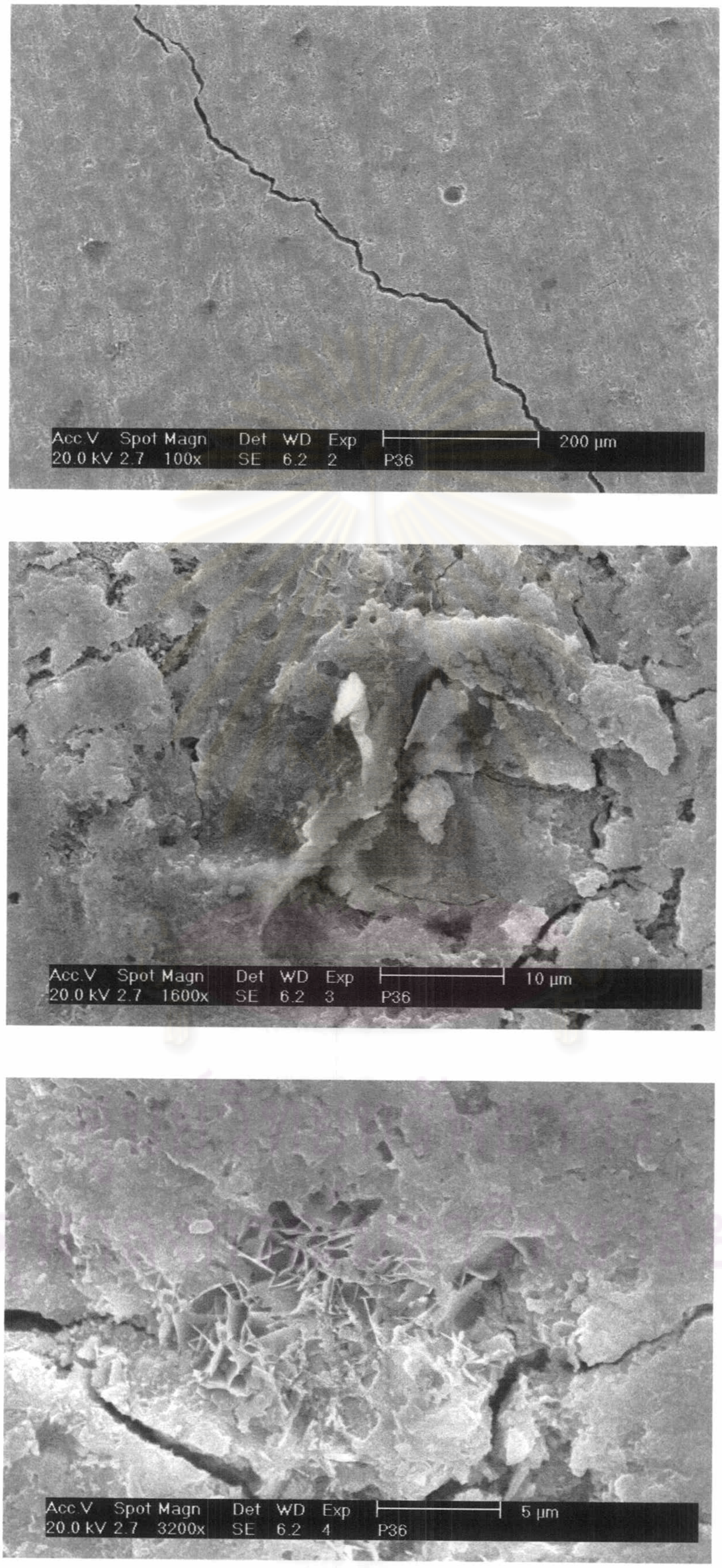

***Fig. 3.1** Microstructure of cement paste with water/cement ratio of 0.36*

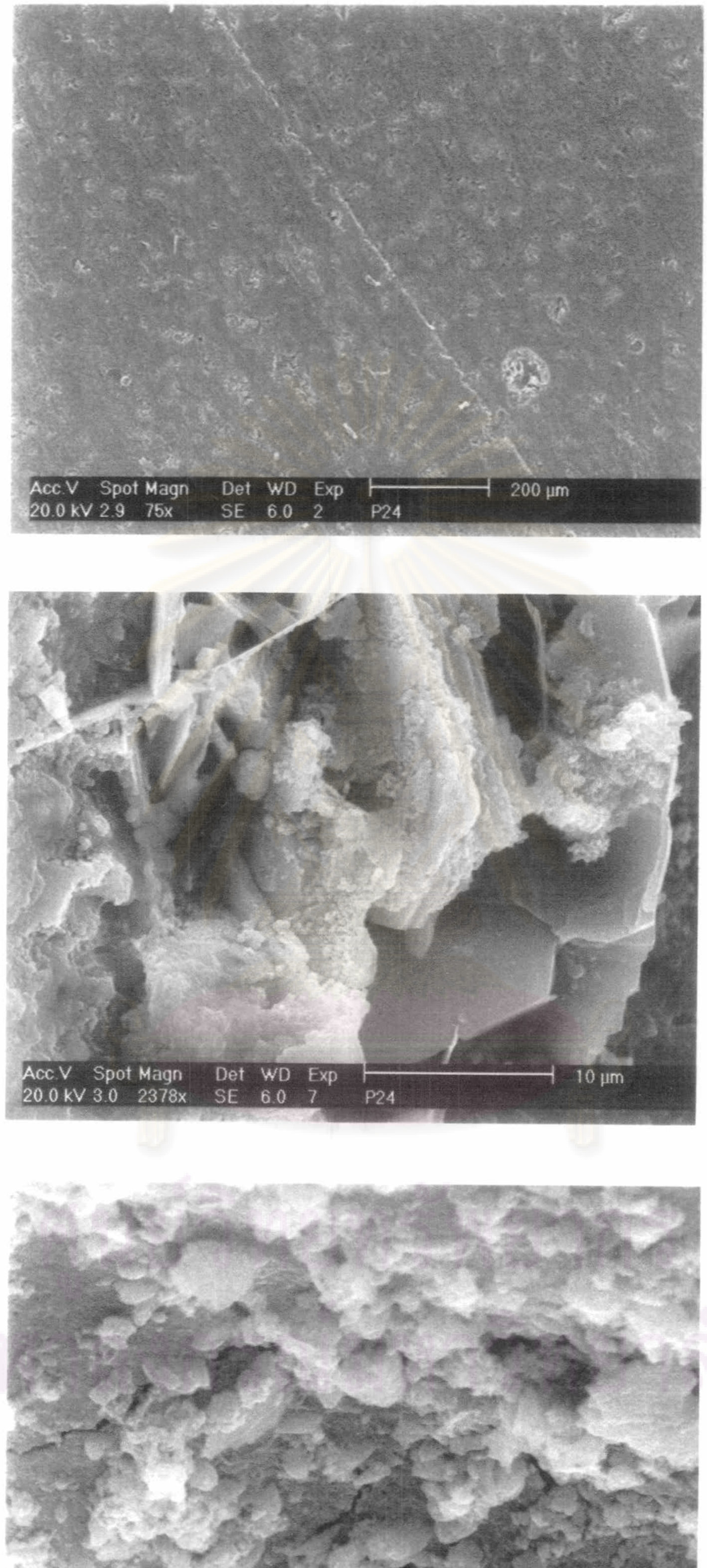

***Fig. 3.2** Microstructure of cement paste with water/cement ratio of 0.24*

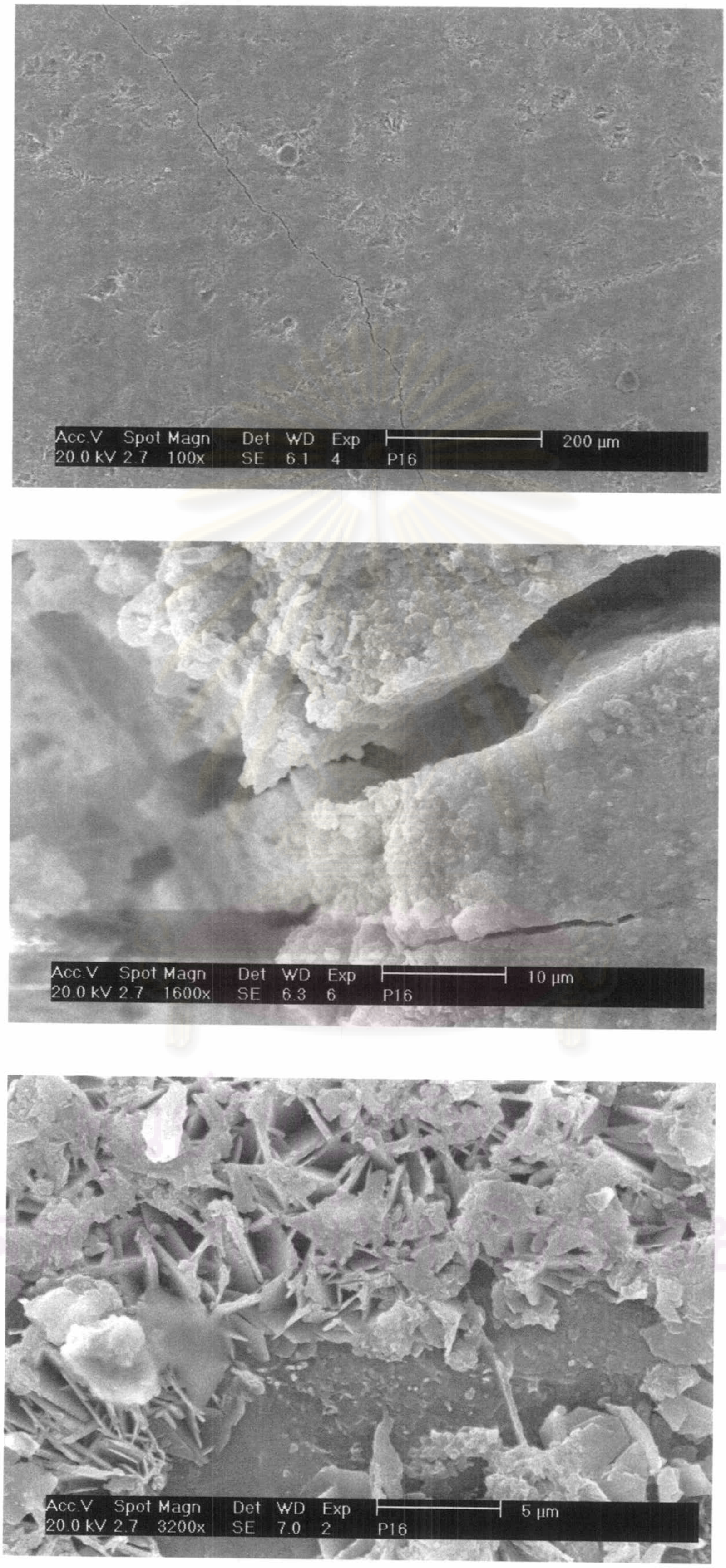

***Fig. 3.3** Microstructure of cement paste with water/cement ratio of 0.16*

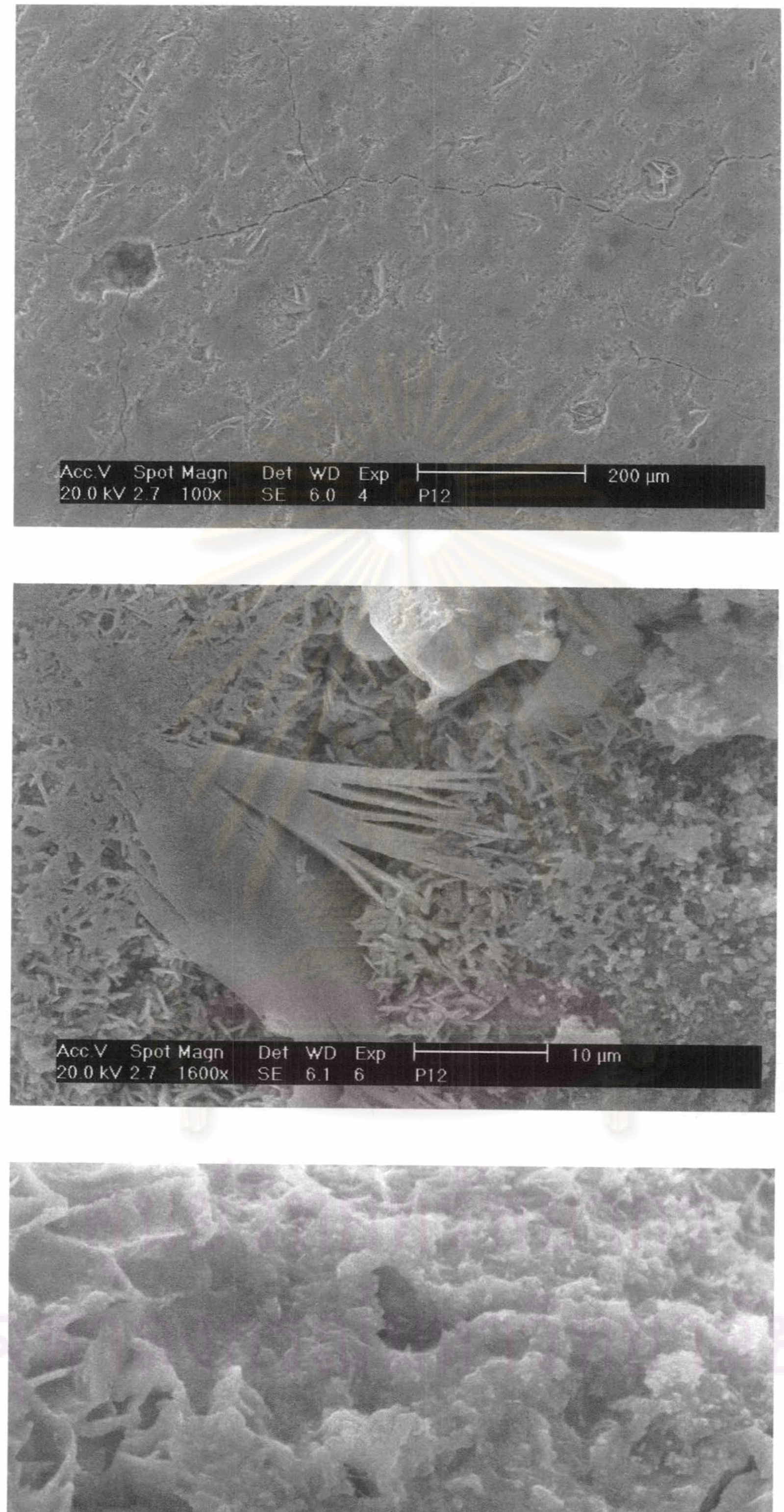

Fig. 3.4 *Microstructure of cement paste with water/cement ratio of 0.12*

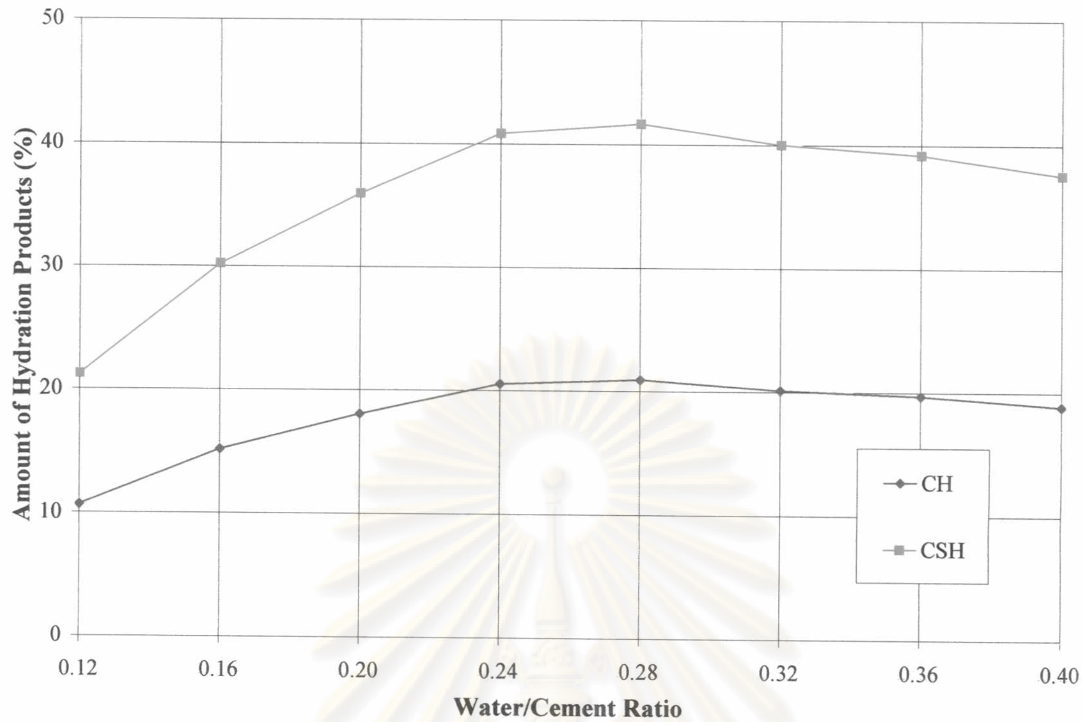

Fig. 3.5 *Amount of hydration products at 28 days against water/cement ratio*

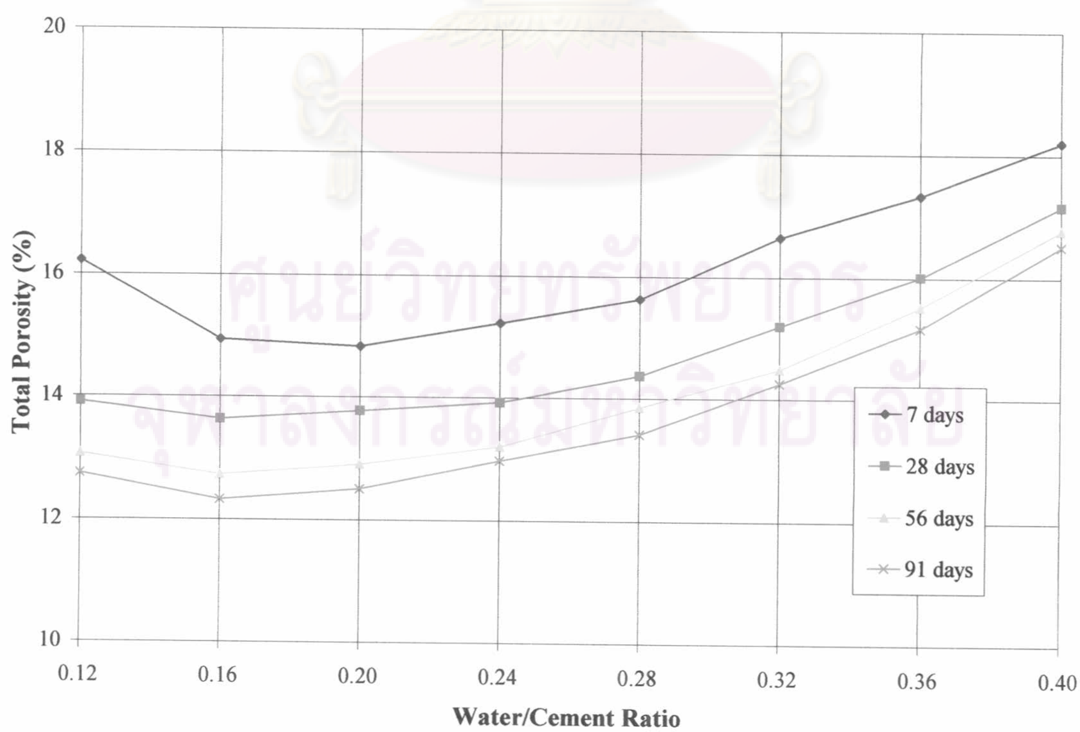

Fig. 3.6 *Total porosity against water/cement ratio*

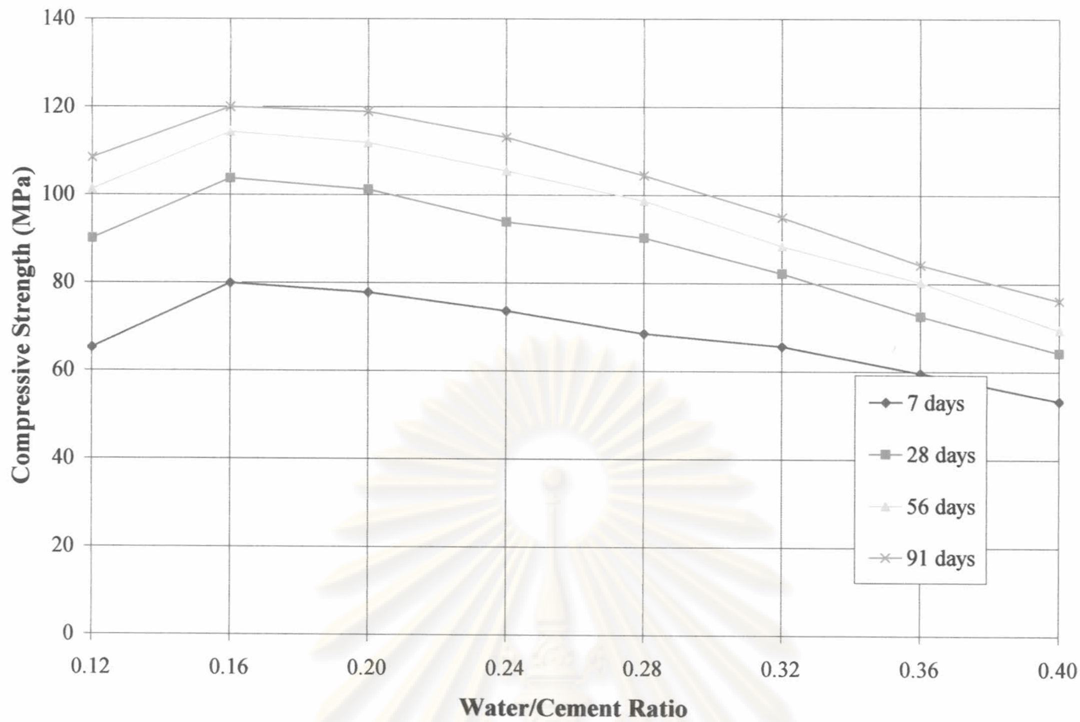

Fig. 3.7 Compressive strength against water/cement ratio

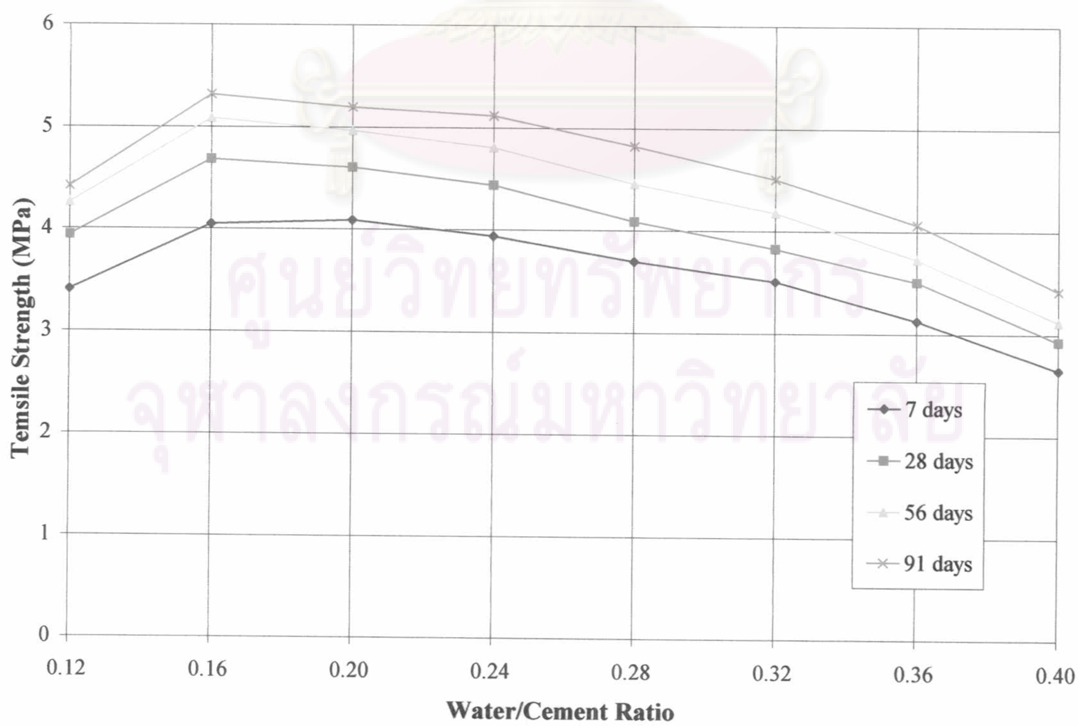

Fig. 3.8 Tensile strength against water/cement ratio

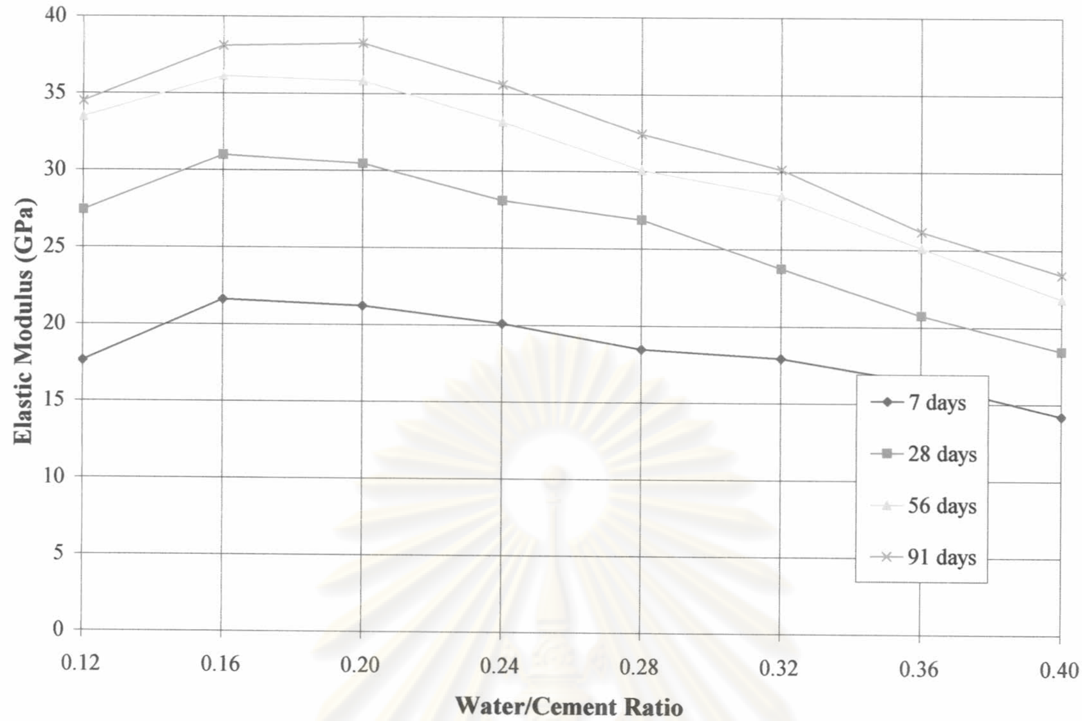

Fig. 3.9 *Elastic modulus against water/cement ratio*

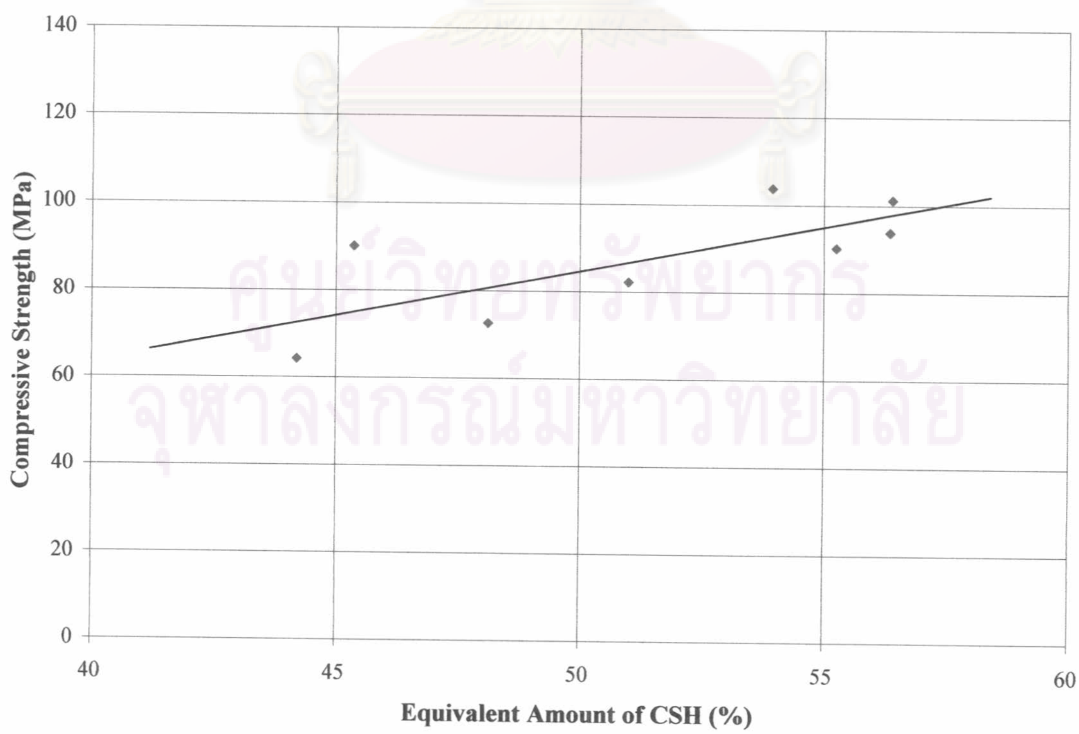

Fig. 3.10 *Compressive strength against equivalent amount of CSH at 28 days*

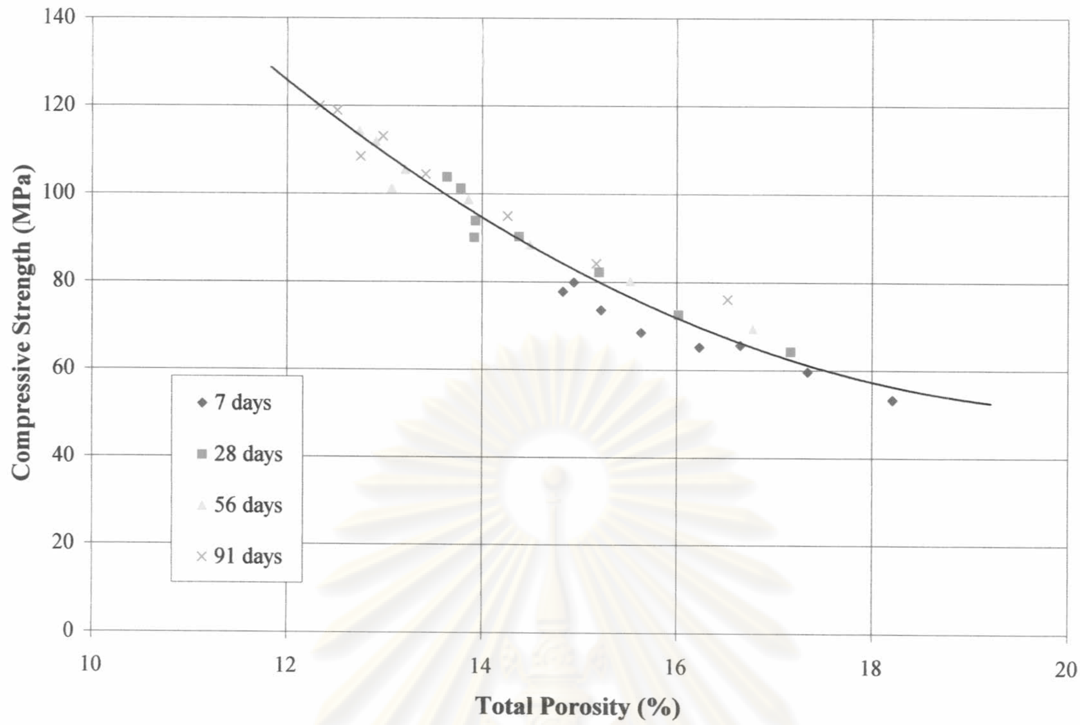

Fig. 3.11 *Compressive strength against total porosity*

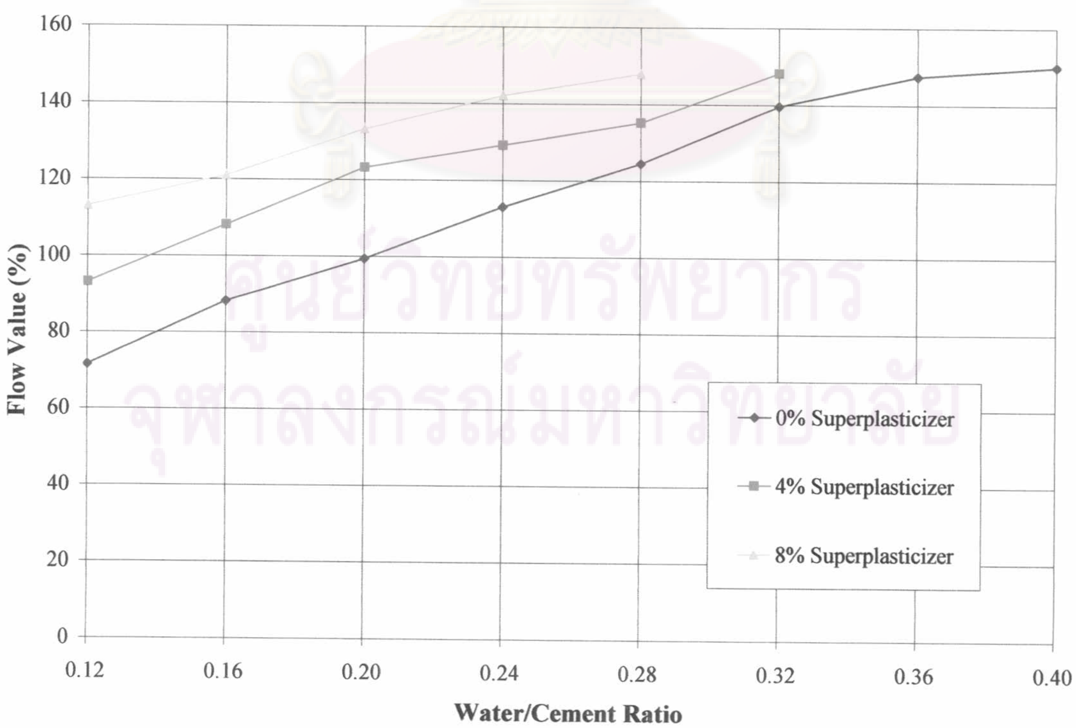

Fig. 3.12 *Flow value against water/cement ratio of pastes containing superplasticizer*

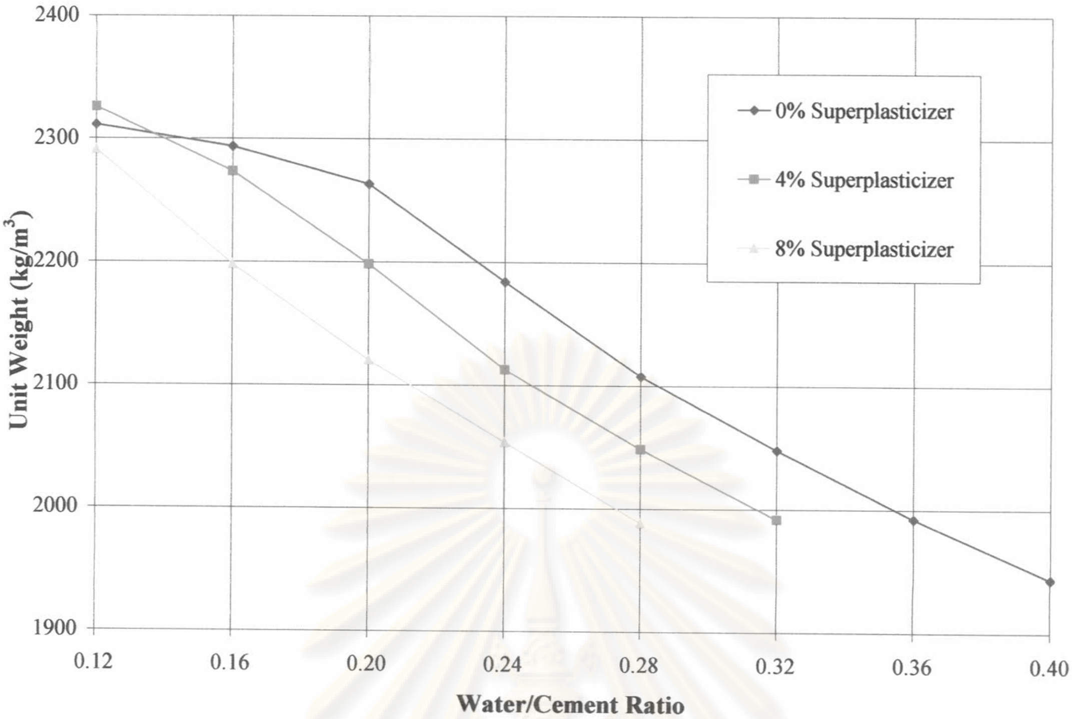

Fig. 3.13 Unit weight against water/cement ratio of pastes containing superplasticizer

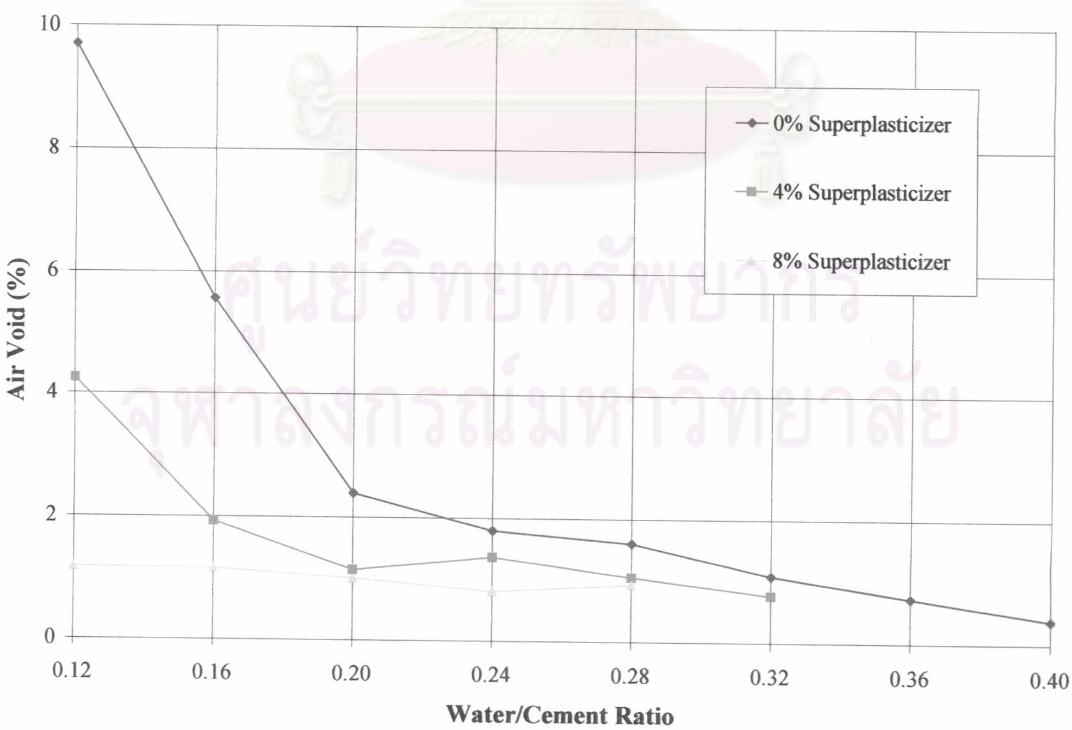

Fig. 3.14 Air void against water/cement ratio of pastes containing superplasticizer

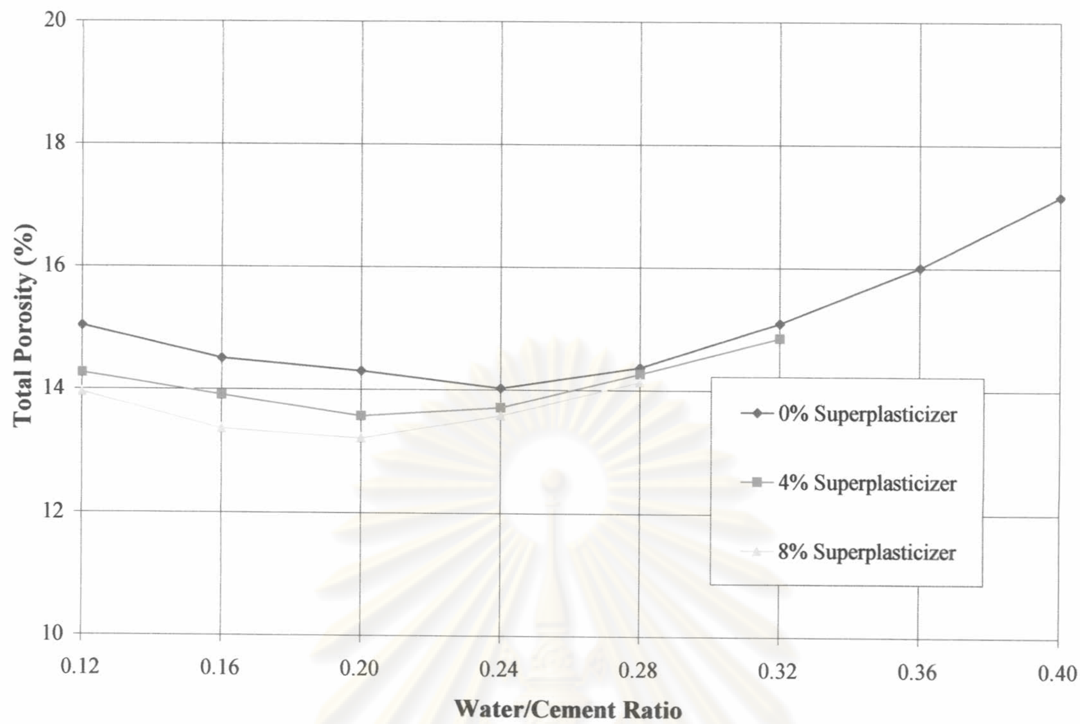

Fig. 3.15 *Total porosity against water/cement ratio of pastes containing superplasticizer*

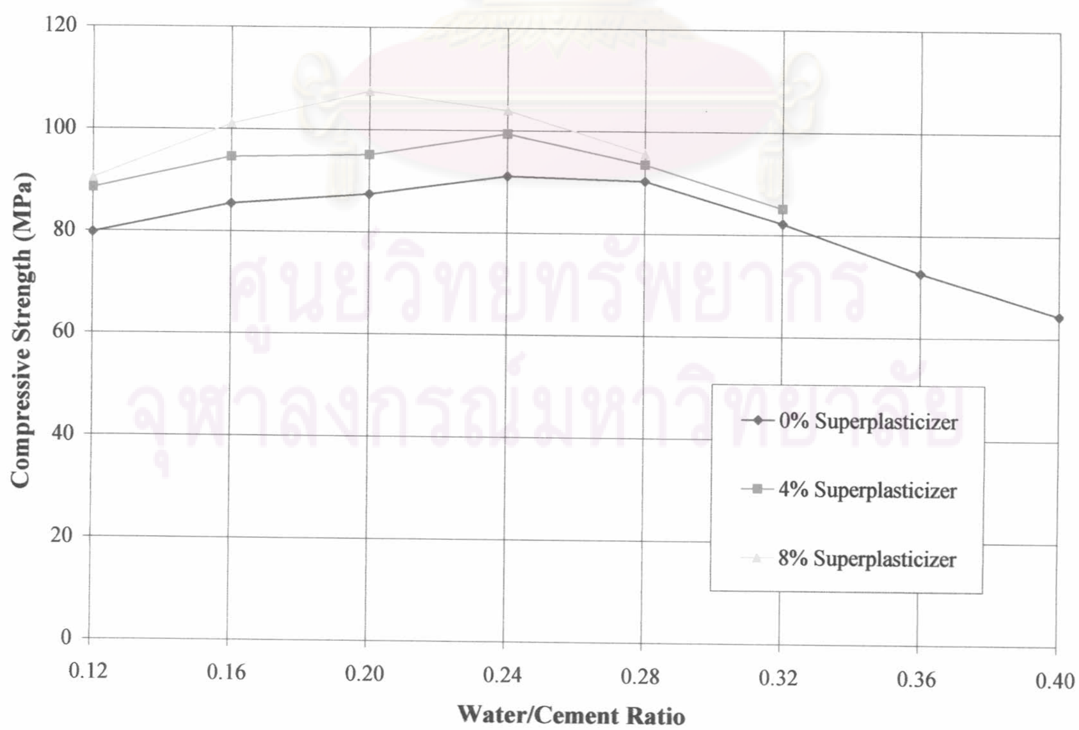

Fig. 3.16 *Compressive strength against water/cement ratio of pastes containing superplasticizer*

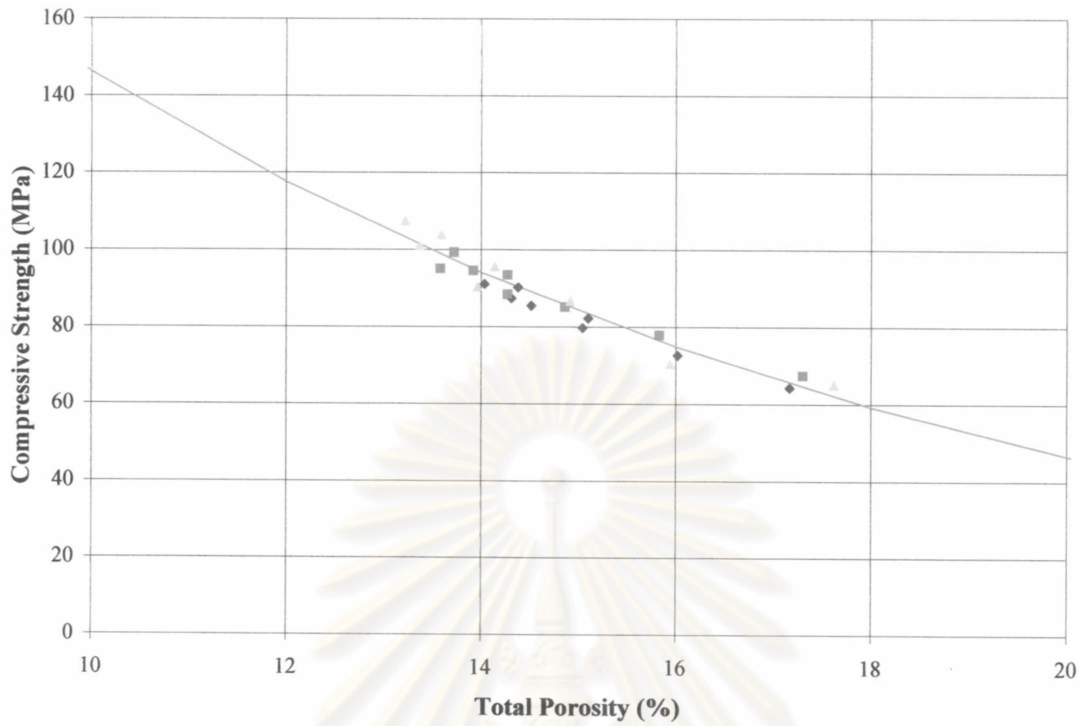

Fig. 3.17 *Compressive strength against total porosity of pastes containing superplasticizer*

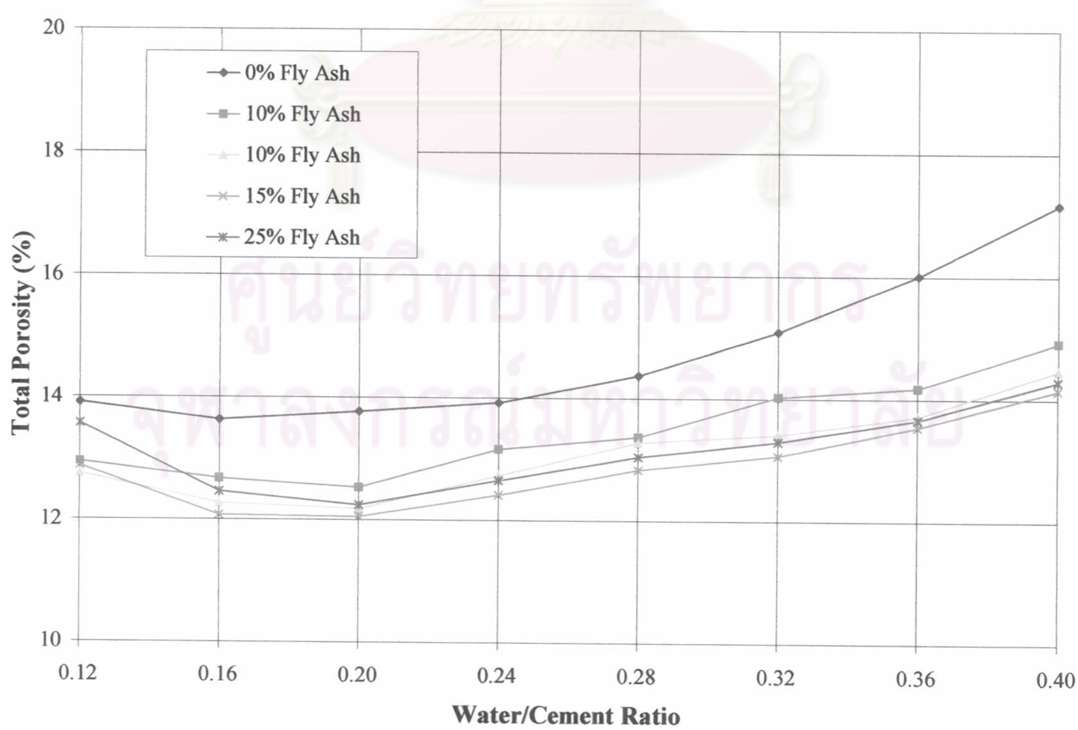

Fig. 3.18 *Total porosity against water/cement ratio of pastes containing fly ash at 28 days*

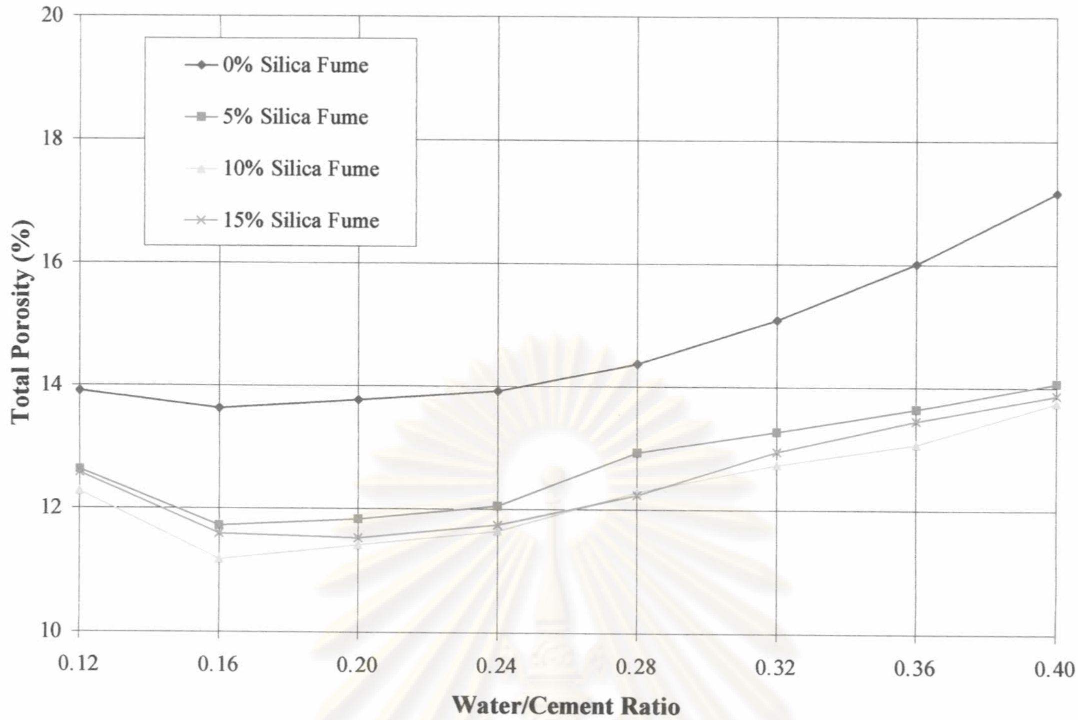

Fig. 3.19 *Total porosity against water/cement ratio of pastes containing silica fume at 28 days*

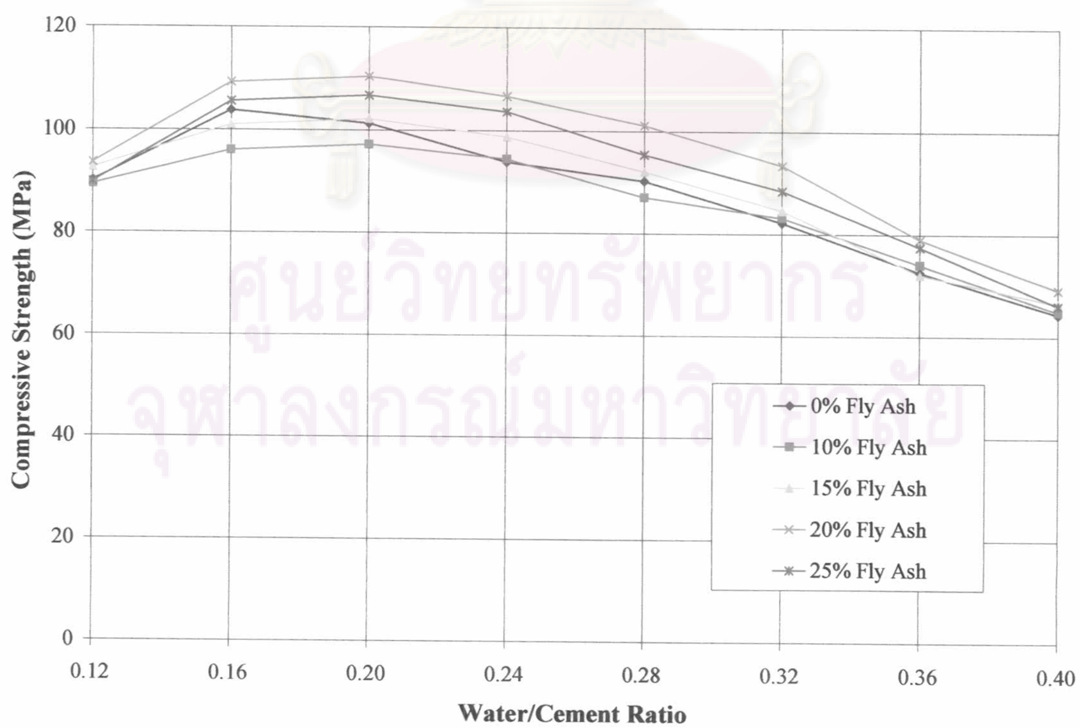

Fig. 3.20 *Compressive strength against water/cement ratio of pastes containing fly ash at 28 days*

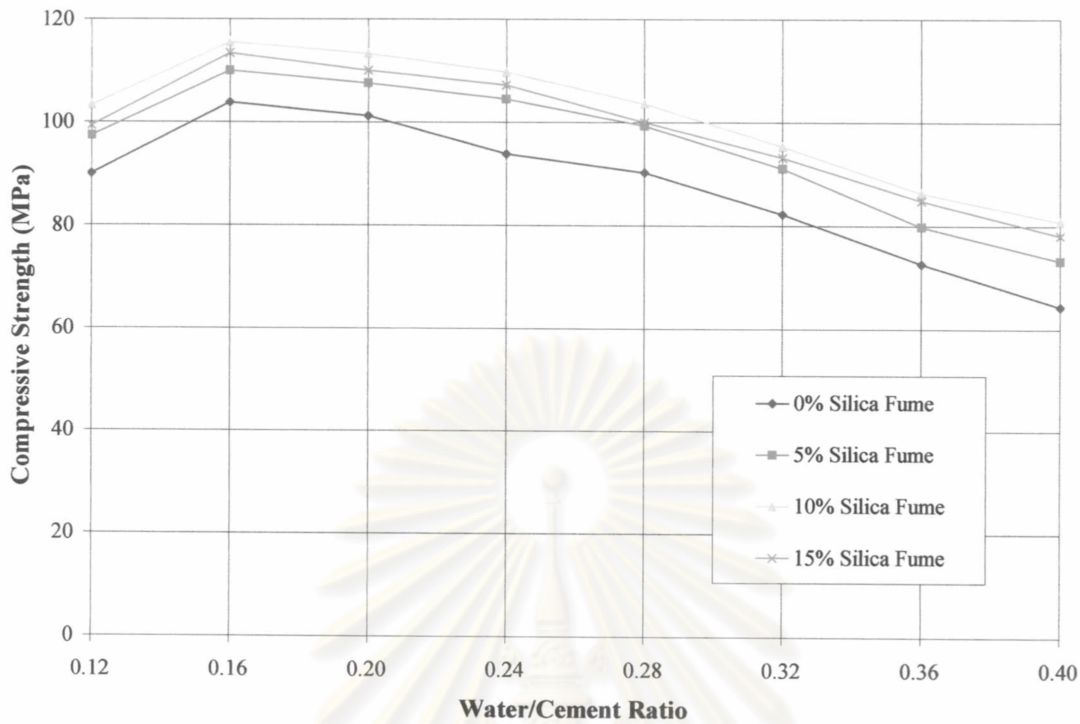

Fig. 3.21 *Compressive strength against water/cement ratio of pastes containing silica fume at 28 days*