CHAPTER 6

MIX DESIGN FOR ULTRA-HIGH STRENGTH CONCRETE

In the previous chapters, the contribution of concrete components, i.e., cement paste, fine aggregate, and coarse aggregate, to the overall performance was investigated step by step via both experiments in laboratory and simulations of developed micro-mechanical model. The proportion of concrete-making materials providing ultra-high strength of concrete is analyzed chemically, physically as well as mechanically. Based on the optimized parameters of concrete mix, ultra-high strength concrete will be manufactured in this chapter. In addition, a mix design method for ultra-high strength concrete will be presented.

6.1 Keys to Achieve Ultra-High Strength

6.1.1 Coarse Aggregate

It is obvious that coarse aggregate occupies the major volume of concrete, and thus significantly influences concrete properties. An intimate examination is necessary for qualifying coarse aggregate. Not only must physical properties such as shape, texture and gradation be considered, but also load carrying capacity. Aggregate crushing value, aggregate impact value, modified Los Angeles abrasion, or point load strength index should be evaluated for the acceptance of qualified quarries.

It can be concluded in this research that, owing to its high strength, basalt crushed rock seems to be the most appropriate coarse aggregate for producing ultra-high strength concrete. Nevertheless, the selection of good-shape particle from quarries is necessary because there is a tendency of particles to be flat or elongated after crushing. The gradation of such coarse aggregate has to be composed in a way to attain high enough packing density. Smaller maximum aggregate size is tentative because it supplies more strength and surface area compared to the larger one. Both strength and packing should be considered when particle size distribution is specified.

The strength-based gradation (SBG) index is proved in the chapter 5 as a capable indicator of concrete strength. To raise concrete strength, high SBG index, i.e., large volume of dense and strong coarse aggregate, is desirable. For a given ratio of binder volume to void content of compacted aggregate (γ), the ratio of concrete to mortar strength is a proportion to SBG index (see Fig. 5.21). Furthermore, the optimum γ value for the highest ratio of strength increment decreases with increasing value of SBG index. With the linear regression analysis, the following equation between such optimum γ value (γ_o) and SBG index computed by using aggregate crushing value representing strength index can be extracted:

$$\gamma_o = 1.5508 - 1.2583\left(\text{SBG Index}_{\text{ACV}}\right) \tag{6.1}$$

And, the ratio of concrete to mortar strength accompanied to this γ_o is

$$f'_c / f'_m = 3.3611 - 1.9383\gamma_o \tag{6.2}$$

6.1.2 Fine Aggregate

Sand or fine aggregate should be clean and always free of impurities. Fine aggregate with the gradation according to ASTM C33 is beneficial for concrete workability. As illustrated in chapter 4, fine aggregate with low fineness modulus tends to increase mortar strength, but it trades off in flow value and water requirement. Therefore, the lowest porosity and highest compressive strength is found in the mortar with fineness modulus more or less 3.04.

Sand/cement ratio means the distance between fine aggregate particles. A less amount of fine aggregate reduces concrete strength, while a surplus induces porosity in microstructure. Simulation shows that the best sand/cement ratio regarding to mortar strength lies between 1.5 and 2.5. But, in practice, these values of sand/cement ratio provide a rather large amount of porosity in hardened mortar and is consequently harmful to strength. A strength reduction factor (S_r) scaling the experimented strength from the simulated one is a function of sand/cement ratio:

$$S_r = 1 - 0.007\left(s/c\right) + 0.006\left(s/c\right)^2 - 0.008\left(s/c\right)^3 \tag{6.3}$$

The optimum ratio of fine aggregate to coarse aggregate for minimum void content is not constant. It depends on gradation and packing density of both fine and coarse aggregate. In laboratory, sand/aggregate ratio varies from 0.4 to 0.6. Nevertheless, the sand/aggregate ratio can be approximately checked by using de Larrard's formula of packing density of n-class aggregate, i.e., Eq. (4.1).

6.1.3 Cement Paste

Cement paste acts as a binder in concrete material. Because it is weaker than aggregate, cement paste is usually considered the weakest link. However, the compressive strength of cement paste can be raised by improving its microstructure. The internal porosity can be reduced by adjusting water content as well as adding pozzolanic materials. Chapter 3 shows that the optimum water/cement ratio for the maximum strength and minimum porosity is in between 0.16 and 0.18. This value is a bit lower than the balance water/cement ratio for hydration reaction. When aggregate is present in concrete mix, such optimum water content is altered due to the water retaining of aggregate particles. The average change in water content is approximately 0.04.

Fly ash and silica fume have been popularly applied as pozzolanic materials in concrete. They react with calcium hydroxide, yielding additional CSH. The relations between additional CSH and increase in compressive strength of concrete can be found as following:

$$f'_{p,\text{w/ FA}} / f'_{p,\text{w/o}} = 1.2501\left(\text{CSH}_{\text{w/ FA}}/\text{CSH}_{\text{w/o}}\right) - 0.2082 \tag{6.4}$$

$$f'_{p,\text{w/ SF}} / f'_{p,\text{w/o}} = 1.8381\left(\text{CSH}_{\text{w/ SF}}/\text{CSH}_{\text{w/o}}\right) - 0.8333 \tag{6.5}$$

where $f'_{p,\text{w/ FA}}$, $f'_{p,\text{w/ SF}}$ and $f'_{p,\text{w/o}}$ are the compressive strength of cement paste containing fly ash, silica fume, and without any pozzolanic materials, respectively. While, in order, $\text{CSH}_{\text{w/ FA}}$, $\text{CSH}_{\text{w/ SF}}$ and $\text{CSH}_{\text{w/o}}$ are the amount of calcium silicate hydrate in cement paste containing fly ash, silica fume, and without any pozzolanic materials. Because of their sizes, the filling effect of silica fume is more significant to concrete strength than that of fly ash. Then, the coefficients in eq. (6.4) are higher than that in eq. (6.5). It is also revealed that the optimum adding percent of fly ash and silica fume is 20% and 10%, respectively.

6.2 Recommended Mix Design

With the findings, observations and experience in the earlier studies, a mix proportioning procedure for ultra-high strength concrete can be established. Fig. 6.1 shows the 8 steps of the suggested procedure. Details of each step are described in the following:

Step 1: *Check for fine and coarse aggregate properties*

Firstly, both physical and mechanical properties of fine and coarse aggregate must be determined. Fine and coarse aggregate must be classified regarding to their size by using the standard sieves. Each group of aggregate should be tested physically for specific gravity, unit weight, water absorption, as well as packing density. Especially for coarse aggregate, the mechanical properties, for example, aggregate crushing value, aggregate impact value, modified Los Angeles, or point-load strength index should be evaluated. Besides use as a parameter in mix proportioning, these properties can reflect the possibility of coarse aggregate in each quarry for producing ultra-high strength concrete.

Step 2: *Estimate recommended s/a and corresponding void content of aggregate mixture*

By using the properties of fine and coarse aggregate evaluated in step 1, the optimum sand/aggregate ratio for the highest packing density (or the lowest void content) of aggregate mixture can be computed. De Larrard's equation for implicitly calculating packing density (ϕ) may be written as

$$K = (s/a)\sum_{i=1}^{m}\frac{y_i/\beta_i}{\frac{1}{\phi}-\frac{1}{\gamma_i}} + (1-s/a)\sum_{j=1}^{n}\frac{y_j/\beta_j}{\frac{1}{\phi}-\frac{1}{\gamma_j}} \quad (6.6)$$

The former term is for m-group of fine aggregate, whereas the latter is dedicated to n-class of coarse aggregate. The compaction factor (K) can be used as 4.5 for rod-sticking compaction that usually used in the measurement of void content. Explanation of the other variables is available in section 4.1.1.

Step 3: *Specify ratio of paste volume to void content of dry and compacted aggregate mixture (γ)*

The ratio of paste volume to void content of dry and compacted aggregate mixture (γ) has to be chosen. Like that shown in Fig. 6.2, the interaction diagram among SBG index, γ value and ratio of mortar to concrete strength is very helpful. With the known SBG index, the optimum γ value for the highest ratio of mortar to concrete strength is easily obtained. When the γ value is attainable, the volume of required cement paste can be determined.

Step 4: *Specify w/c ratio and percent addition of pozzolanic materials*

Water/cement ratio and percent addition of pozzolanic materials are two important parameters governing concrete performance. They influence the occurrence of calcium silicate hydrate from hydration and pozzolanic reaction. Fig. 6.3 shows the relation between water/cement ratio and compressive strength of cement paste. The compressive strength of concrete may be about 1.2-1.6 times of paste strength depending on the other ingredients. An increase in compressive strength due to additional CSH from pozzolanic reaction of fly ash and silica fume can be approximated by using eq. (6.4) and (6.5), respectively.

Step 5: *Calculate s/c ratio and estimate additional water content due to the existence of aggregate*

When the packing density (ϕ), γ value, sand/aggregate ratio and water cement ratio are specified, proportion of each concrete-making component can be calculated, i.e.,

$$\text{cement} = \frac{1000\gamma\phi}{(w/c) + \dfrac{1}{SG_c}} \tag{6.7}$$

$$\text{water} = \frac{(w/c)1000\gamma\phi}{(w/c) + \dfrac{1}{SG_c}} \tag{6.8}$$

$$\text{fine agg.} = \frac{1000(1-\gamma\phi)}{\dfrac{1}{SG_f} + \dfrac{(1/(s/a)-1)}{SG_{ca}}} \tag{6.9}$$

$$\text{coarse agg.} = \left(\frac{1}{s/a} - 1\right)\frac{1000(1-\gamma\phi)}{\dfrac{1}{SG_f} + \dfrac{(1/(s/a)-1)}{SG_{ca}}} \tag{6.10}$$

Unit in the eq. (6.7)-(6.10) is kg/m^3. Then the additional water content compensating the retaining of coarse and fine aggregate can be evaluated by using free water concept;

$$\text{water}_{\text{add}} = \beta_f M_f + \beta_{ca} M_{ca} \tag{6.11}$$

where M_f and M_{ca} are masses of fine and coarse aggregate, respectively. While, in order, β_f and β_{ca} are the coefficients of retaining of fine and coarse aggregate, which can be calculated as a term of specific surface (SS). That is,

$$\beta = \left(2\times10^{-6}\right) SS^{0.92} \tag{6.12}$$

Step 6: *Estimate compressive strength of concrete*

With sand/cement ratio, the ratio of mortar to paste strength can be obtained by using a chart like the one shown in Fig. 6.4. It comes from the simulation of mortar specimen with specific gradation. But, if a fine aggregate conforms to the recommended of ASTM C33, the variation can be omitted. The strength reduction factor due to imperfection of aggregate arrangement is expressed in eq. (6.3). Therefore, the compressive strength of concrete can be computed from the ratio of concrete to mortar strength, the ratio of mortar to cement paste strength, and estimated cement paste compressive strength. If the calculated compressive strength of concrete is significantly less than the expected one, water/cement ratio and percent addition of pozzolanic materials should be re-specified.

Step 7: *Estimate percent addition of superplasticizer*

The amount of superplasticizer added to provide flowability of concrete may be approximated from the suggestions of the manufacturer. A trial mix of cement paste with the same water/cement ratio and percent addition of pozzolanic materials may be helpful.

Step 8: *Trial concrete mix and adjust mix proportion*

If the moisture content of fine and coarse aggregate is not in saturated surface dry condition, then the material weight should be corrected. Furthermore, a trial mix of concrete should be produced. Concrete flowability must be checked, and the amount of superplasticizer must be corrected. If concrete flow is difficult to adjust, a new ratio of paste volume to void content of aggregate mixture (γ) should be assigned.

6.3 Production of UHSC

To verify the proposed mix proportioning procedure, three concrete mixes are produced and tested for their compressive strength in this section. Their expected intervals of 28-day compressive strength are 50-100 MPa, 100-150 MPa, and 150-200 MPa so that all level of concrete strength is included. Furthermore, tensile strength, elastic modulus, and Poisson's ratio of such concrete are also evaluated.

6.3.1 Materials and sample preparation

Ordinary river sand with fineness modulus of 3.04 is applied as fine aggregate. Its gradation meets the requirement of ASTM C33. The physical properties of each size of fine aggregate are shown in Table 6.1. Two types of coarse aggregate are used, i.e., limestone and basalt. Limestone aggregate is the common-used coarse aggregate in Bangkok area, while basalt aggregate is appreciated for its high strength. The average aggregate crushing value for all size is 27.09% and 20.07% for limestone and basalt, respectively. Table 6.2 shows both physical and mechanical properties for them. While ordinary portland cement type-I in addition to fly ash or silica fume are served as cementitious materials. Their chemical composition and some physical properties are tabulated in Table 6.3. The polymer-based superplasticizer is also utilized here.

The procedure for mixing concrete is shown in Fig. 6.5. It derived from the author's experience in high-strength concrete works. Firstly, cement and pozzolanic material are mixed in dry condition by hand until their uniformity can be observed by the naked eye. Then, they are placed in the mixer before fine aggregate is added and blended for a few minutes. About 20% of water is poured later and mixed for 2 1/2 minutes prior to the coarse aggregate being added and mixed further for 2 1/2 minutes. Consequently, about 40% of water is added and mixed for 5 minutes. The mixture is rested for 5 minutes and mixed again for 5 minutes. The rest of the water and superplastcizer are poured, mixed for 10 minutes, rested for 10 minutes. The mixture is mixed further for 10 minutes and rested again for 10 minutes. It is mixed for more 10 minutes before measuring flow value and placing in molds. If the consistency of concrete is not satisfactory, the additional superplasticizer is added in the last mixing step. The overall duration of mixing process after adding of water is approximately 70 minutes.

To acquire a smooth surface for compressive testing, 150x150-mm pieces of glass are placed over the cylindrical molds with some pressure. The concrete specimens are demolded after approximately 24 hours. They are stored under water until the time of testing.

6.3.2 Mix Proportioning

The details of calculation following the procedure in section 6.2 are shown below. The amount of concrete ingredients of all three mixes is summarized in Table 6.4.

a.) High-strength concrete with compressive strength of 50-100 MPa

Step 1: In the first mix, limestone crushed rock is used as a coarse aggregate. Its properties of each size are tabulated in Table 6.2. By running all possibilities through computer programming, the limestone coarse aggregate with 48% of 1/2"-MSA and 52% of 3/8"-MSA provides the highest SBG index computed from aggregate crushing value. The SBG index is 0.3017. While gradation and properties of fine aggregate are shown in Table 6.1.

Step 2: With the coarse and fine aggregate obtained in the first step, the relation between sand/aggregate ratio and void content around aggregate particles can be predicted by using eq. (6.6). It is shown in Fig. 6.6, which the optimum sand/aggregate ratio for minimum void content, i.e. about 28.72%, is 0.45.

Step 3: For coarse aggregate with SBG index computed from aggregate crushing value equals to 0.3017, the optimum ratio of paste volume to void content of dry and compacted aggregate mixture calculated from eq. (6.1) is 1.17. And, the predicted ratio of concrete strength to mortar strength computed from eq. (6.2) is approximately 1.09.

Step 4: Try water/cement ratio equal to 0.40. The expected compressive strength of cement paste is about 62 MPa. No pozzolanic material is included in this mix.

Step 5: With eq. (6.7) – (6.10), the amount of each concrete-making ingredient can be obtained. That is, 468.35 kg/m^3 of cement, 187.34 kg/m^3 of water, 1024.67 kg/m^3 of coarse aggregate, and 838.37 kg/m^3 of fine aggregate. Therefore, the additional water/cement ratio due to the retaining of aggregate is 0.036. The quantity of cement and water are then changed to 445.97 kg/m^3 and 194.44 kg/m^3, respectively. The ratio of sand to cement becomes 1.88.

Step 6: With sand/cement ratio of 1.88, the ratio of mortar strength to cement paste strength from simulation is 1.30, but the strength reduction factor is 0.95. Then, the predicted compressive strength of concrete is 83.46 MPa.

Step 7: 1% by cement weight of superplasticizer is added to guarantee flowability of concrete (4.68 kg/m^3).

Step 8: The moisture at the surface of coarse and fine aggregate are 1.5% and 3.8%, respectively. Then, the weight of coarse aggregate, fine aggregate and water become 1040.04 kg/m^3, 870.23 kg/m^3 and 147.21 kg/m^3, respectively.

b.) Very-high strength concrete with compressive strength of 100-150 MPa

Step 1: Basalt crushed rock is used as coarse aggregate for the second concrete mix. The properties of each size are tabulated in Table 6.2. The maximum size of coarse aggregate mixture is 1". The amount of each size of coarse aggregate is the same, i.e. 25%. The SBG index computed from aggregate crushing value is 0.3550. The gradation and properties of fine aggregate are shown in Table 6.1.

Step 2: The relation between sand/aggregate ratio and void content around aggregate particles is shown in Fig. 6.7. The minimum void content is 27.82%, and the optimum sand/aggregate ratio for is 0.39.

Step 3: For coarse aggregate with SBG index computed from aggregate crushing value equals to 0.3550, the optimum ratio of paste volume to void content of dry and compacted aggregate mixture calculated from eq. (6.1) is 1.10. And the predicted ratio of concrete strength to mortar strength computed from eq. (6.2) is approximately 1.22.

Step 4: Try water/cement ratio equal to 0.30. The expected compressive strength of cement paste is about 85 MPa. Fly ash is also included with 10% by weight of cement. By using total hydration analysis described in chapter 3, 41.71 grams of CSH due to hydration reaction and 17.95 grams of CSH due to pozzolanic reation per 100 grams of cement can be calculated. Then, the strength-enlarging coefficient of 1.11 can be evaluated by using eq. (6.5).

Step 5: The proportion of each concrete-making ingredient can be obtained as following; cement 463.01 kg/m^3, water 138.90 kg/m^3, fly ash 46.30 kg/m^3, coarse aggregate 1168.88 kg/m^3, and fine aggregate 747.32 kg/m^3. The additional water/cement ratio due to the retaining of aggregate is 0.036. The quantity of cement, water, and fly ash are then shifted to 439.09 kg/m^3, 147.53 kg/m^3, and 43.91 kg/m^3, respectively. Then, sand/cement ratio is 1.70.

Step 6: With sand/cement ratio of 1.70, the ratio of mortar strength to cement paste strength from simulation is 1.27, but the strength reduction factor is 0.96. Then the predicted compressive strength of concrete becomes 140.34 MPa.

Step 7: 2% by cement weight of superplasticizer is added to guarantee flowability of concrete (8.78 kg/m^3).

Step 8: The moisture at the surface of coarse and fine aggregate are 1.5% and 3.8%, respectively. Then, the weight of coarse aggregate, fine aggregate and water become 1186.41 kg/m^3, 775.72 kg/m^3 and 101.60 kg/m^3, respectively.

c.) Ultra-high strength concrete with compressive strength of 150-200 MPa

Step 1: Basalt crushed rock is also used as coarse aggregate for this mix. The properties of each size of basalt coarse aggregate are tabulated in Table 6.2. By running all possibilities through computer programming, the basalt coarse aggregate mixture with maximum size of 3/8" provides the highest SBG index computed from aggregate crushing value, i.e. 0.4155. The gradation and properties of fine aggregate are similar to the former and already shown in Table 6.1.

Step 2: The relation between sand/aggregate ratio and void content around aggregate particles is shown in Fig. 6.8. The minimum void content is 30.06%, and the optimum sand/aggregate ratio for is 0.53.

Step 3: For coarse aggregate with SBG index computed from aggregate crushing value equals 0.4155, the optimum ratio of paste volume to void content of dry and compacted aggregate mixture calculated from eq. (6.1) is 1.03. And, the predicted ratio of concrete strength to mortar strength computed from eq. (6.2) is approximately 1.36.

Step 4: Try water/cement ratio equal to 0.20. The expected compressive strength of cement paste is about 100 MPa. Silica fume is used as pozzolanic material with 10% addition by weight of cement. By using total hydration analysis described in chapter 3, 47.66 grams of CSH due to hydration reaction and 41.03 grams of CSH due to pozzolanic reation per 100 grams of cement can be calculated. Then the strength-enlarging coefficient of 1.17 can be evaluated by using eq. (6.4).

Step 5: The proportion of each concrete-making ingredient can be obtained as following; cement 551.96 kg/m^3, water 110.39 kg/m^3, fly ash 55.20 kg/m^3, coarse aggregate 881.36 kg/m^3, and fine aggregate 993.87 kg/m^3. The additional water/cement ratio due to the retaining of aggregate is 0.037. The quantity of cement, water, and fly ash are then shifted to 517.81 kg/m^3, 122.72 kg/m^3, and 51.78 kg/m^3, respectively. Then the final sand/cement ratio is 1.92.

Step 6: With sand/cement ratio of 1.92, the ratio of mortar strength to cement paste strength from simulation is 1.30, but the strength reduction factor is 0.95. Then the predicted compressive strength of concrete becomes 196.50 MPa.

Step 7: 4% by cement weight of superplasticizer is added to guarantee flowability of concrete (22.08 kg/m^3).

Step 8: The moisture at the surface of coarse and fine aggregate are 1.5% and 3.8%, respectively. Then, the weight of coarse aggregate, fine aggregate and water become 894.58 kg/m^3, 1031.64 kg/m^3 and 71.73 kg/m^3, respectively.

6.3.3 Test Results

6.3.3.1 Fresh-State Properties

The fresh-state properties including flow value, slump, unit weight, and air content of the concrete mixtures are tabulated in Table 6.5. Of all three mixes, flow value is higher than 110% and slump is at least 40 mm. Obviously, all concretes can be placed and compacted in molds with little effort. The unit weight of these concretes is more or less 2500 kg/m^3. The higher unit weight than ordinary may raise hardened concrete strength. Whereas, the percentage of air content in the fresh mixes is little. It is up to only 1.77%.

6.3.3.2 Mechanical Properties

The average compressive strength of hardened concretes is tabulated in Table 6.6 and plotted with its age in Fig. 6.9. At 7 days, the compressive strength of each mix is 53.82 MPa, 91.06 MPa, and 125.17 MPa. They become 85.43 MPa, 135.74 MPa, and 188.30 MPa, respectively, at 28 days. The difference from prediction is up to only 4.55% in the third concrete mix. This can prove the validity of the proposed mix design procedure in the production of concrete with a different degree of compressive strength. Furthermore, the concrete strength can develop exceeding 200 MPa after 91 days.

Table 6.7 shows the average tensile strength of concrete at various ages. At 28 days, they are 6.94 MPa, 9.55 MPa, and 12.12 MPa. Tensile strength is about 7% of compressive strength, as shown in Fig. 6.10. The elastic modulus of each concrete is tabulated in Table 6.8. The relation with compressive strength can be expressed readily as follow;

$$E = 4.54\sqrt{f_c'} \tag{6.13}$$

While Poisson's ratio of concrete seems constant approximately 0.197. The average measured Poisson's ratio is shown in Table 6.9.

Table 6.1 Gradation and physical properties of fine aggregate for the example mixes

Passing Seive		Percert Retained	Specific Gravity	Water Absorption (%)	Unit Weight (kg/m³)	Packing Density
No.	Max. Diam. (mm)					
3/8"	9.50	0.79	2.61	0.65	1581	0.5676
4	4.75	7.73	2.60	0.50	1586	0.5686
8	2.36	21.70	2.60	0.40	1616	0.5796
16	1.18	33.74	2.61	0.45	1627	0.5824
30	0.60	28.71	2.61	0.35	1640	0.5864
50	0.30	5.98	2.61	0.30	1656	0.5944
100	0.15	1.35	2.62	0.35	1662	0.5940

Table 6.2 Physical and mechanical properties of coarse aggregates for the example mixes

Limestone						
Passing Seive		Specific Gravity	Water Absorption (%)	Unit Weight (kg/m³)	Packing Density	Aggregate Crushing Value (%)
No.	Max. Diam. (mm)					
1"	25.40	2.74	0.61	1611	0.5873	33.72
3/4"	19.07	2.76	0.88	1604	0.5817	27.82
1/2"	12.70	2.77	1.08	1587	0.5736	24.25
3/8"	9.50	2.77	1.23	1564	0.5643	22.56

Basalt						
Passing Seive		Specific Gravity	Water Absorption (%)	Unit Weight (kg/m³)	Packing Density	Aggregate Crushing Value (%)
No.	Max. Diam. (mm)					
1"	25.40	2.89	1.18	1663	0.5759	28.00
3/4"	19.07	2.88	1.13	1622	0.5636	23.85
1/2"	12.70	2.86	1.05	1601	0.5602	17.85
3/8"	9.50	2.85	1.15	1571	0.5515	10.59

Table 6.3 Chemical and physical of cementitious materials

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

Table 6.4 Mix proportion and design strength of concrete with different degree of strength

Proportion	Mix No. 1	Mix No. 2	Mix No. 3
Cement	445.97	439.09	517.81
Water	194.44	147.53	122.72
Coarse Aggregate	1024.67	1168.88	881.36
Fine Aggregate	838.37	747.32	993.87
Fly Ash	-	46.30	-
Silica Fume	-	-	51.78
Superplasticizer	4.68	8.78	22.08
Design Str. (MPa)	83.46	140.34	196.50

Table 6.5 Fresh-state properties of concrete with different degree of strength

Concrete Mix	Flow Value (%)	Slump (mm)	Unit Weight (kg/m3)	Air Content (%)
Mix No. 1	132.50	95	2472	1.43
Mix No. 2	121.84	60	2513	1.77
Mix No. 3	115.67	40	2544	1.75

Table 6.6 Compressive strength of concrete with different degree of strength

Concrete Mix	Compressive Strength (MPa)			
	7 days	28 days	56 days	91 days
Mix No.1	53.82	85.43	98.60	105.32
Mix No. 2	91.06	135.74	147.22	156.98
Mix No. 3	125.17	188.30	195.64	203.48

Table 6.7 Tensile strength of concrete with different degree of strength

Concrete Mix	Tensile Strength (MPa)			
	7 days	28 days	56 days	91 days
Mix No.1	4.82	6.94	7.63	8.25
Mix No. 2	6.84	9.55	10.64	11.48
Mix No. 3	9.63	12.12	13.78	14.33

Table 6.8 Elastic modulus of concrete with different degree of strength

Concrete Mix	Elastic Modulus (GPa)			
	7 days	28 days	56 days	91 days
Mix No.1	32.55	45.83	50.12	51.63
Mix No. 2	46.12	57.82	59.42	61.31
Mix No. 3	53.11	65.29	67.90	65.42

Table 6.9 Poisson's ratio of concrete with different degree of strength

Concrete Mix	Poisson's Ratio			
	7 days	28 days	56 days	91 days
Mix No.1	0.22	0.20	0.19	0.19
Mix No. 2	0.21	0.20	0.18	0.18
Mix No. 3	0.21	0.21	0.19	0.18

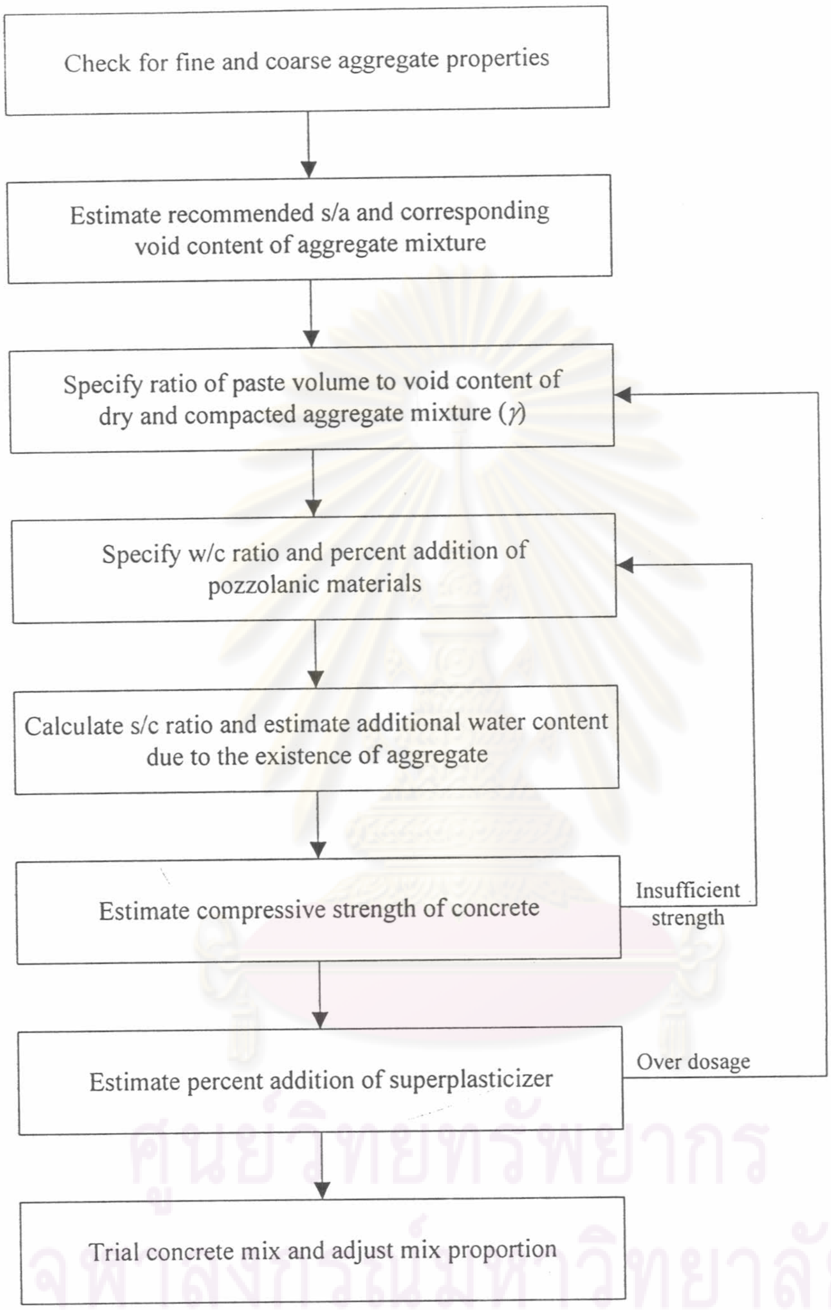

Fig. 6.1 Mix proportioning procedure for ultra-high strength concrete

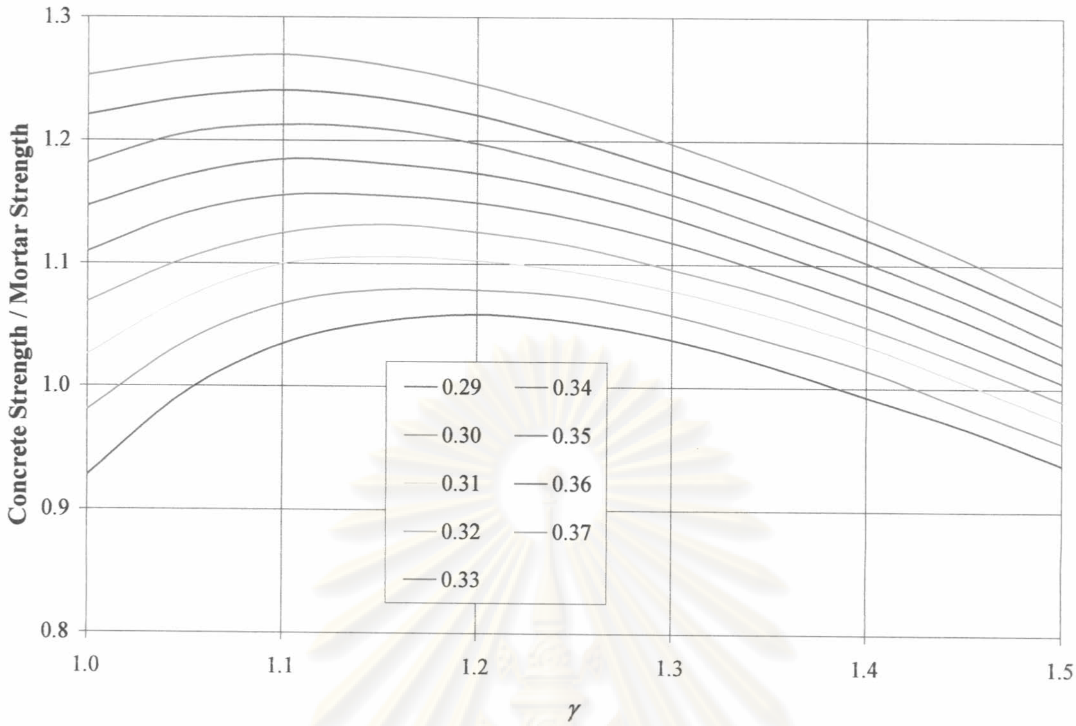

Fig. 6.2 *Ratio of concrete to mortar strength against γ value of concrete with various SBG index*

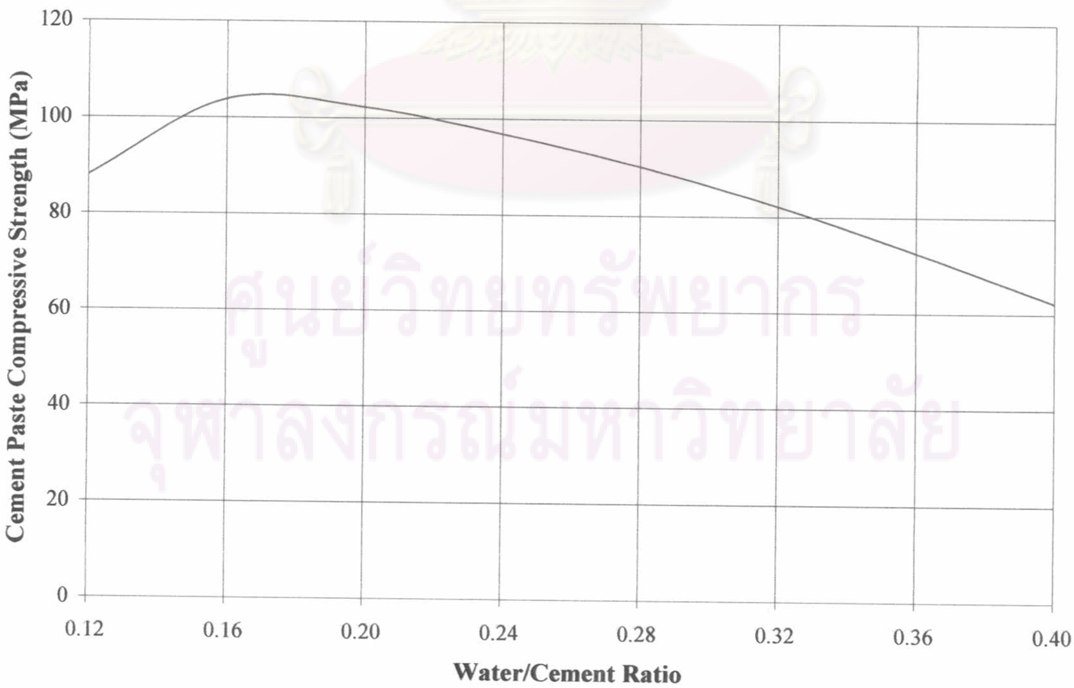

Fig. 6.3 *Compressive strength of cement paste against water/cement ratio*

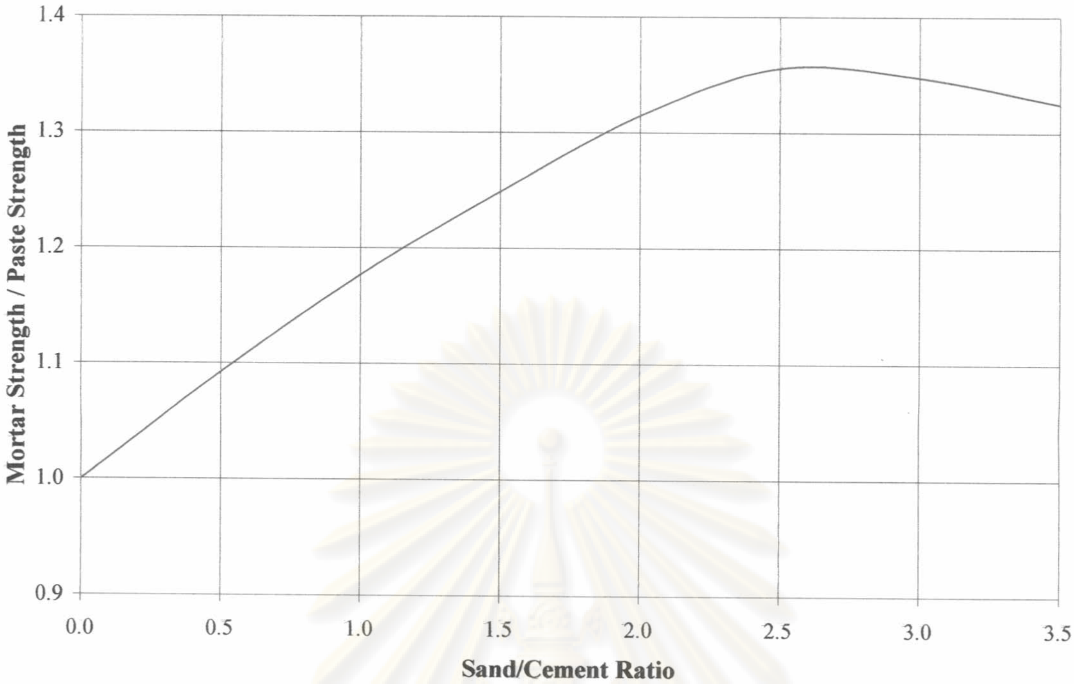

Fig. 6.4 *Ratio of mortar to paste strength against sand/cement ratio*

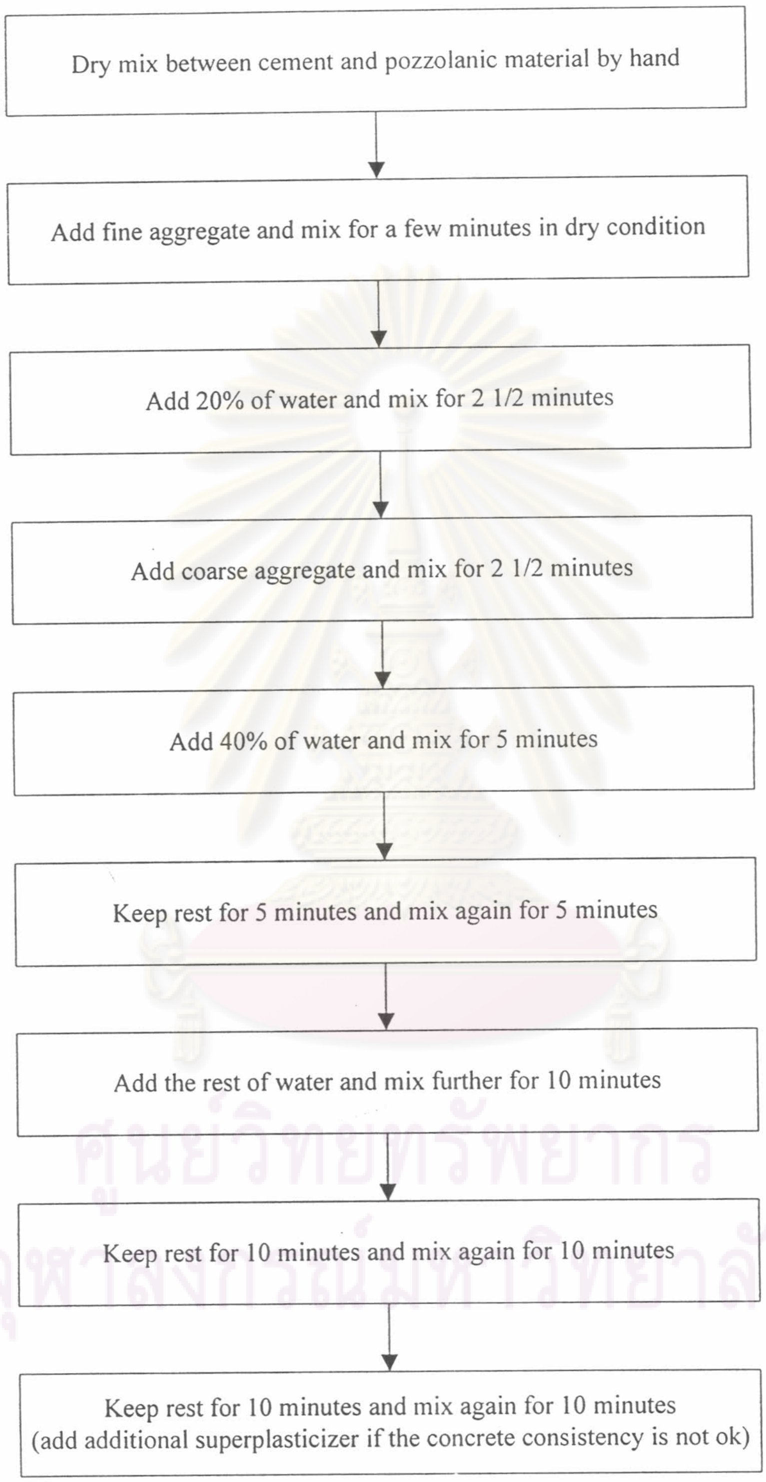

Fig. 6.5 Mixing procedure for concrete in this study

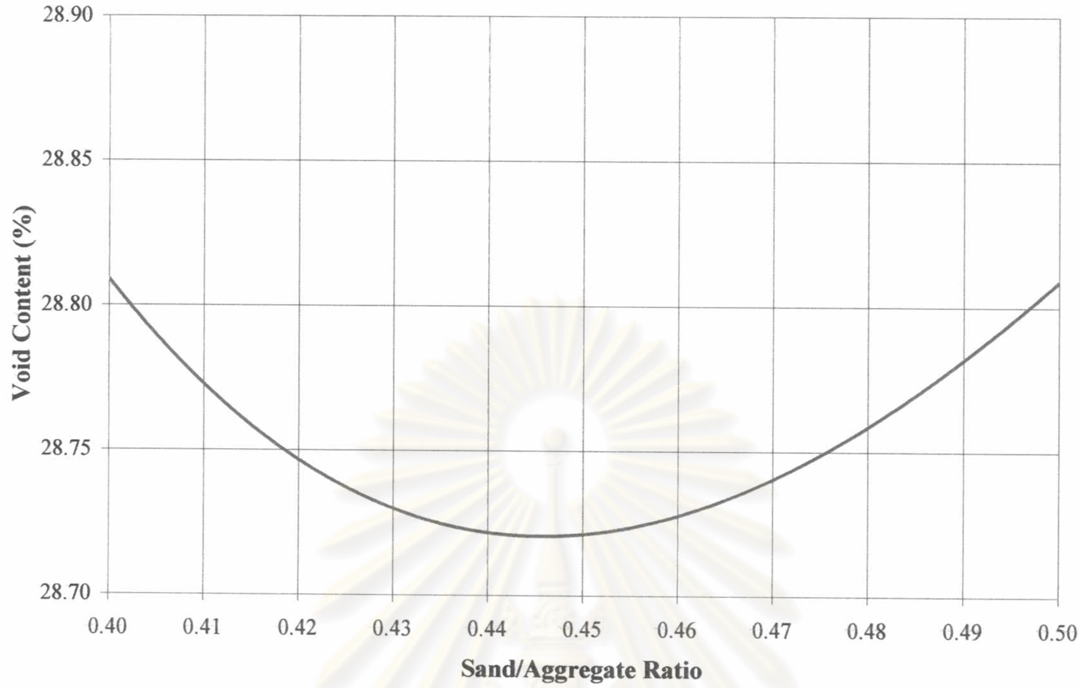

Fig. 6.6 *Void content against sand/cement ratio of concrete mix no. 1*

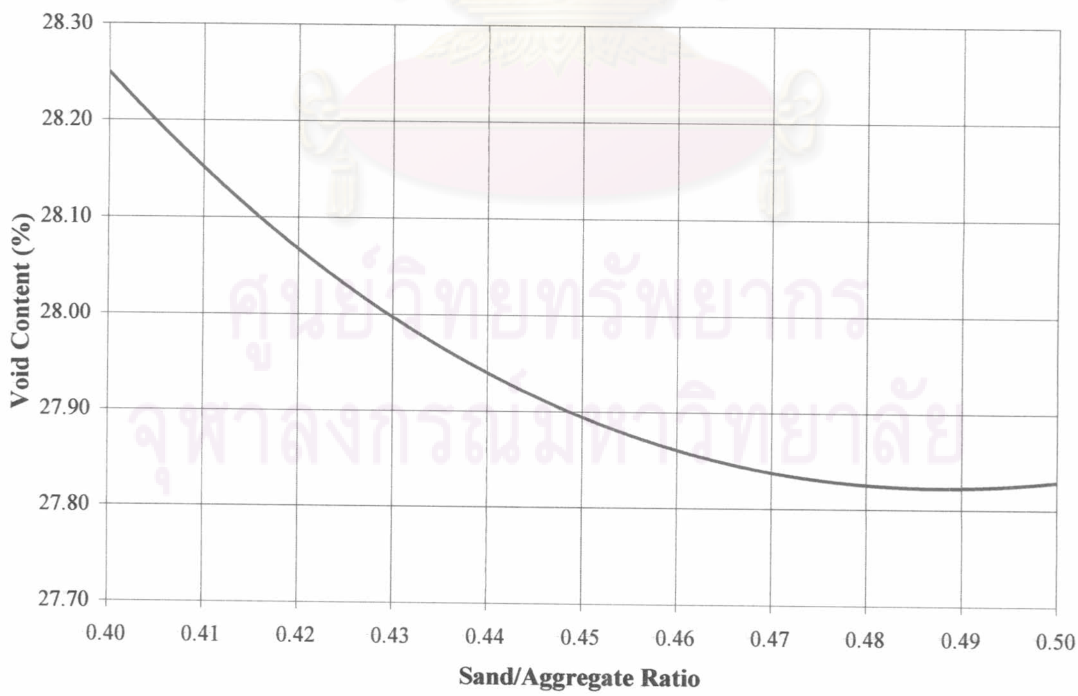

Fig. 6.7 *Void content against sand/cement ratio of concrete mix no. 2*

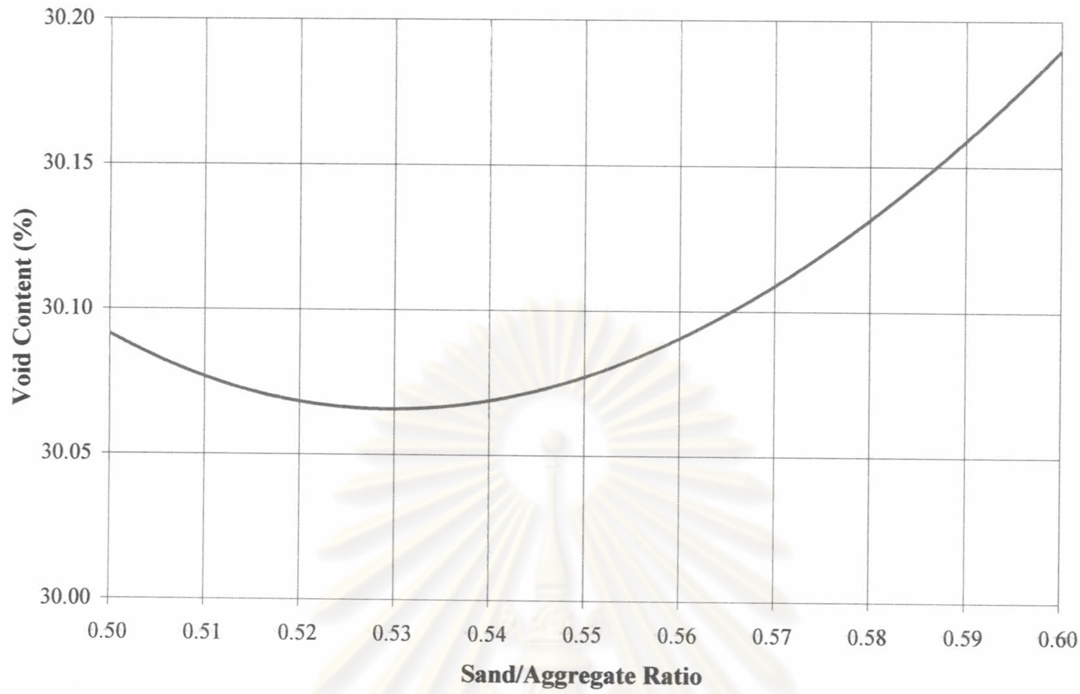

Fig. 6.8 *Void content against sand/cement ratio of concrete mix no. 3*

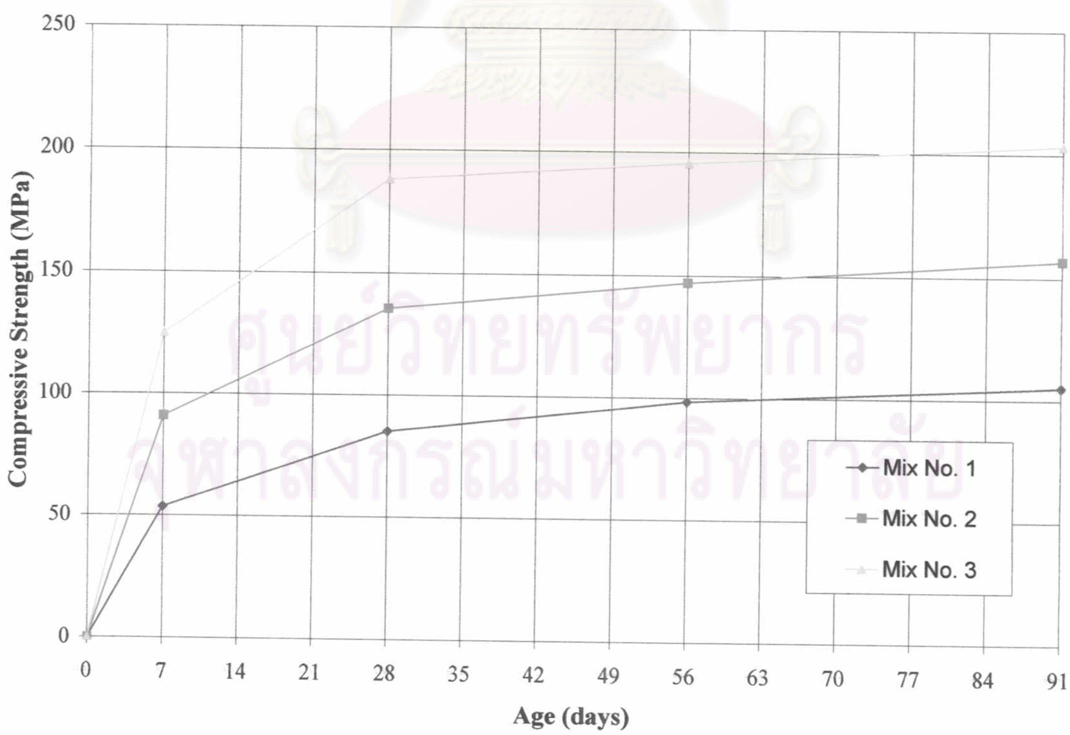

Fig. 6.9 *Compressive strength against age of concrete with different degree of strength*

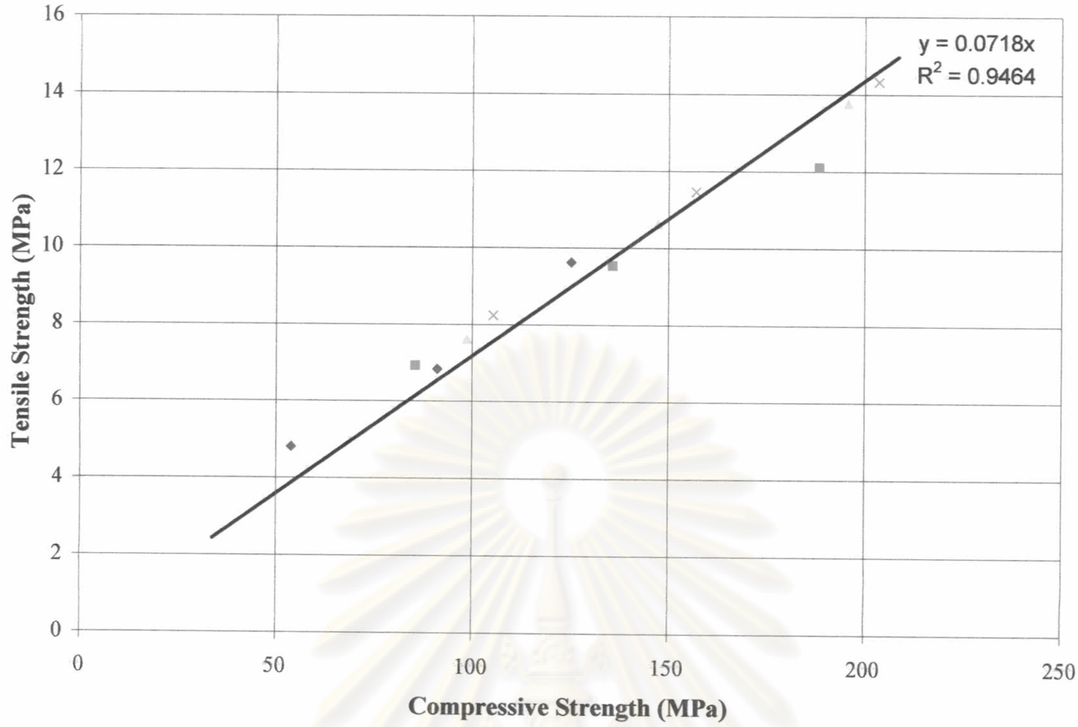

Fig. 6.10 *Compressive strength against tensile strength of concrete*

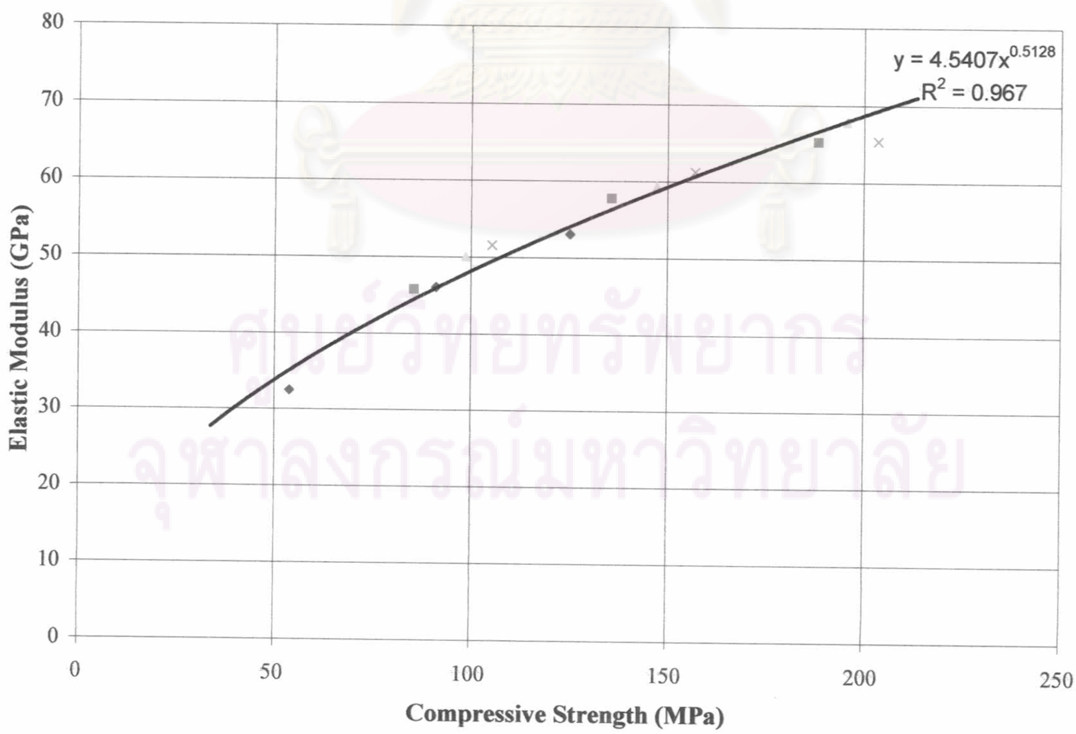

Fig. 6.11 *Compressive strength against elastic modulus of concrete*