INFLUENCE OF FLY ASH ON FLOWABILITY OF FRESH MORTAR

Chalermchai Wattanalamlerd

A dissertation submitted to
Kochi University of Technology
in partial fulfillment of the requirements for
The Degree of Master of Engineering

Supervisor
Associate Professor Masahiro Ouchi

Department of Infrastructure Systems Engineering
Kochi University of Technology
Kochi, Japan

January 2003

ACKNOWLEDGEMENT

The author would like to express my deepest gratitude to my advisor Assoc. Prof. Masahiro Ouchi for his kind encouragement and valuable advice throughout the course of this study. I express my profound gratitude to Prof. Hajime Okamura for his guidance especially on the current problem of self-compacting concrete and his encouragement during the course of this study. My grateful appreciations extended to Prof. Hiroshi Shima for his suggestions. It has been an honor and privilege to work with them for their outstanding example of science dedication in their fields.

ABSTRACT

Self-compacting concrete is a concrete that can be compacted into every corner of formwork, purely by means of its own weight and without the need for vibrating compaction. It requires co-existing of high flowability and no segregation simultaneously. In order to satisfy those requirements, concrete must has limitation of aggregate content, high amount of powder and using superplasticizer. Both of cement powder and superplasticizer are the most expensive ingredients in concrete. Pozzolanic material was introduced to replace amount of cement in order to reduce the cost and improve durability of concrete. Fly ash, one of the most widely used pozzolans, was believed to capable the minimization of SP dosage and maintains moderate flowability due to its physical characteristics. It is well known that flowability of fresh concrete is mainly affected by the flowability of the fresh mortar. Flowability of fresh mortar containing Ordinary Portland cement and polycarboxylate based was measured for several combinations of fly ash replacement ratio, SP dosage and water–powder ratio. The influence of fly ash on flowability was evaluated by functions of flow area and funnel speed. The relationship among SP dosage, fly ash replacement ratio and water-powder ratio was investigated. Within 75% fly ash replacement ratio, the relationship between fly ash replacement ratio and both of index represent amount of free water (A) and index represent SP dispersing effect (B) were clarified. From those relationships, the method to predict the flowability of mortar which used any fly ash replacement ratio was developed by interpolation of the index represent free water of pure cement mortar and binary mixes, and interpolation of the index of SP dispersing effect of those. Totally 4 mixes have to be mixed in order to predict the flowability of fresh mortar, 2 mixes of pure cement mortar and 2 of binary mixture. After that the chart represents the flowability of those cement and fly ash will able to be constructed. With using that chart the flowability of considered mix can be estimated. On other hand, the proper SP dosage and water-powder ratio are also able to be predicted according to any fly ash replacement ratio.

TABLE OF CONTENT

CHAPTER 1
INTRODUCTION

1.1 Concept of Flowability

Self-compacting concrete (SCC) is the concrete that can fill formwork by itself without aggregate segregation and consolidation. It was first developed on 1988 by Okamura et al. in order to solve the problem of lack of skilled workers. Due to its self-compactability, conventional test for workability, slump test, became not appropriate. Flow area was introduced to be used as index to represent workability for self compacting concrete rather than slump. Flow area test use the same flow cone (name of apparatus) as in slump test, the only different between these two tests is: after remove the flow cone, change of concrete in vertical direction is measured in slump test but change of concrete in horizontal direction is measured in flow area test. In order to achieve self-compactability, developers have employed the following methods:

1. limited aggregate content and higher powder content
2. co-exist of high deformability and high viscosity

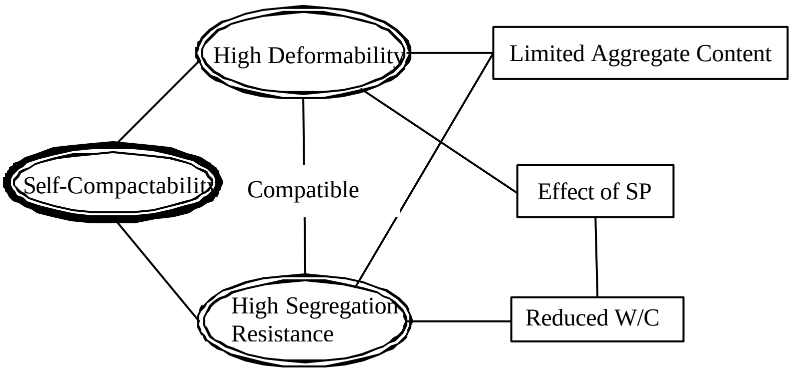


Fig. 1.1 Methods for achieving self-compactability

The frequency of collision and contact between aggregate particles can increase as the relative distance between the particles decreases and then the internal stress can increase when concrete is deformed, particularly near obstacles. It has been revealed that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal proportions is effective in avoiding this kind of blockage.

Viscosity of the paste is also required to avoid the blockage of coarse aggregate when concrete flows though obstacles. When concrete is deformed, paste with high viscosity also prevents localized increases in the internal stress due to the approach of coarse aggregate particles. Co-exist of high deformability and high viscosity can be achieved only by the employment of superplasticizer, which results in low water-powder ratio of the paste.

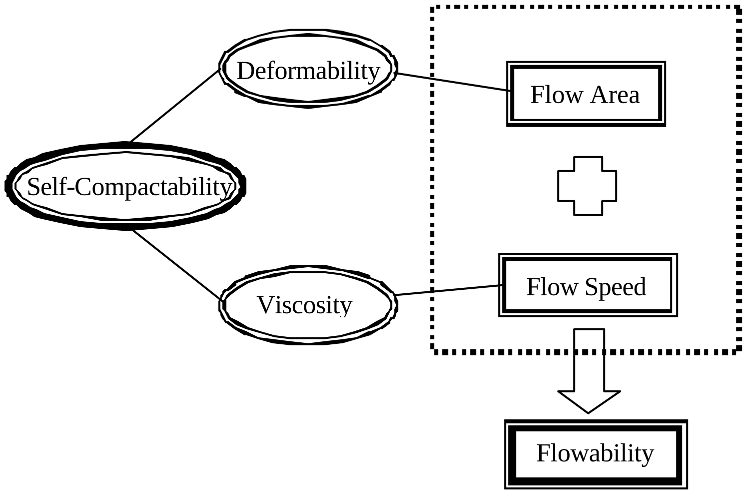


Fig. 1.2 Concept of Flowability

Either superplasticizer or water can increase the deformability of concrete, represent by flow area, in different manners which results as several of viscosity concrete but all them can provide same flow area. Only certain combination of deformation and viscosity of concrete can provide self-compactability, so only flow area is not enough to define how workability of concrete is. Flow speed was introduced to represent the viscosity of concrete. Flow speed is measured from how long the concrete take time to flow out of the apparatus, which has specified volume and shape. Then the term "flowability" refers to both of flow area, which represent deformability, and flow speed, which represent viscosity. Flowability of normal concrete and self compacting concrete are shown here.

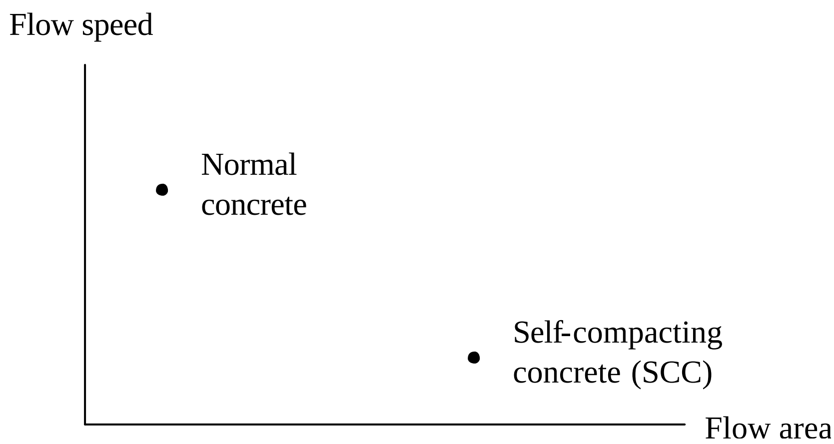


Fig. 1.3 Comparison between flowability of normal concrete and SCC

1.2 Superplasticizer (SP)

(1) Types of super plasticizer

Super plasticizers used in self-compacting concrete are of two types – high range water reducing agent and high range AE water reducing agent. High range water reducing agent is mainly used in self-compacting concrete at secondary product plants. On the other hand, high range AE water reducing agent has the functions of enhancing the slump retention ability in addition to the slump retention components. Moreover, the AE agent also retains the air in the concrete at a constant level, and this concrete is being used in applications of ready mixed concrete that requires time for transportation or placement.

Until now, naphthalene sulfonate or melamine sulfonate-based agents were mainly used, but polycarboxylate-based agents with improved water-reducing ability are being developed. As shown in Fig. 1.4, currently used superplasticizer includes naphthalene sulfonate, polycarboxylate, melamine sulfonate, and amino sulfonate-based agents.

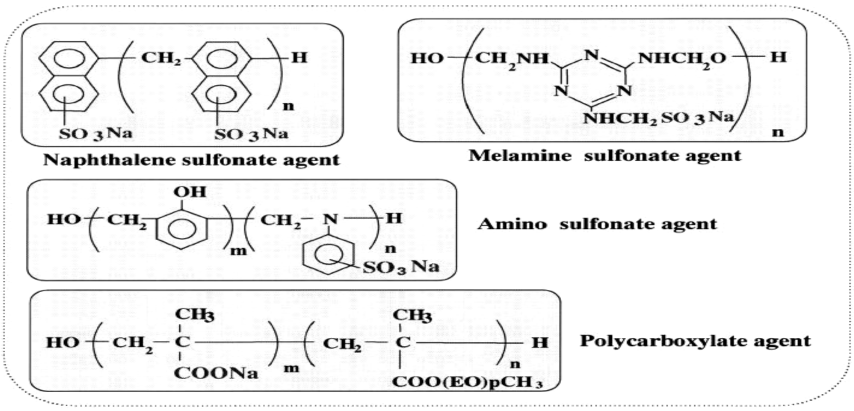


Fig. 1.4 Classification of superplasticizers.

(2) Dispersion mechanism

Dispersion mechanisms of cement particles by superplasticizers may be broadly divided into two types: 1) those based on electrostatic repulsion; 2) those based on steric repulsion. Superplasticizers based on electrostatic repulsion include naphthalene sulfonate, melamine sulfonate and amino sulfonate based agents, all of which include the sulfonic group in the molecule. The ion dissociating ability of the sulfonic group is stronger compared to that of the carboxyl group, therefore it gives a negative charge to cement particles in even materials such as concrete, which has a high ion concentration, and stabilizes the dispersion.

On the other hand, dispersion mechanisms based on steric repulsion include polycarboxylate-based agents. All these superplasticizers are graft polymers having ethylene oxide chains (EO chains) with strong salt resistance in the molecules of the side chains. The EO chains have a strong ability to hold water (water-retention abilities strong), due to which a bulky and thick adsorption layer is formed on the cement surface. This thick adsorption layer generates high steric repulsion.

1.3 Fly Ash (FA)

Self-compacting concrete proposed until now, may be broadly classified into three types mentioned below, according to the method of preventing ingredient segregation, that is, by the method of increasing the plastic viscosity of paste:

1. Powder-based self-compacting concrete in which large amount of powder is added
2. Viscosity agent-based self-compacting concrete in which viscosity agent is added
3. Combined-type self-compacting concrete where the two substances above are combined

Powder-based self-compacting concrete, which requires large amount of powder, might have very high cost if only cement powder is used as powder-base due to the cost of cement powder. Pozzolanic material is usually used to replace cement in order to improve durability of concrete, reduce the cost of concrete that cause from cement powder, and reduce the gross volume of pozzolan itself in the owner country (most of pozzolan is waste material which also require proper management).

Fly ash, a by-product obtained when burning pulverized coal in a power plant, has been used in a large number of structures, mainly civil engineering structures such as dams. Since good quality fly ash is in particulate or spherical form, the flowability of concrete is enhanced by its "ball-bearing" effect. Consequently, fly ash is frequently used in self-compacting concrete.

The usage of fly ash is mostly depended on its chemical composition. Fly ash can be classified into 2 classes according to its chemical compositions: high calcium-oxide content fly ash and high silica-oxide content fly ash

High calcium content fly ash has high possibility to produce hydration reaction, which is the reaction of hardening of concrete or formation of calcium silicate hydrate, by fly ash itself due to the existing of calcium-oxide. Then the high calcium fly ash usually has been used at high replacement ratio (even more than 75% of volume of cement still be possible in some cases) to minimize the total cost of concrete and provide enough compressive strength for structure. By nature, high calcium fly ash always contains low silica content.

High silica content fly ash is used at lower replacement ratio than that of high calcium content fly ash. In case of high silica content fly ash, fly ash can produce pozzolanic reaction, the reaction between by-product from hydration reaction and silica in fly ash which results as increasing of calcium silicate hydrate. Pozzolanic reaction needs by-product from hydration reaction, then high silica content fly ash must be used at low replacement ratio which is usually lower than 50%.

Anyway, not only compressive strength receives direct influence from the type and replacement ratio of fly ash but also other properties of concrete. In order to use fly ash, the environmental conditions of the structure have to be considered carefully.

According to quality control of power plants in Japan, only high-silica content fly ash is available. Then Japanese use their own standard, Japanese Industrial Standard [JIS A 6201] to classify types of fly ash in Japan as shown here.

Table 1.1 Classification of fly ash according to JIS A 6201

		Class			
		1	2	3	4
Silicon dioxide		=45.0			
Moisture content		=1.0			
Ignition loss		=3.0	=5.0	=8.0	=5.0
Density (g/cm3)		=1.95			
Fineness	Specific surface area (cm2/g)	=5000	=2500	=2500	=1500
Percent flow		=105	=95	=85	=75
Activity Index	28 days	=90	=80	=80	=60
	91 days	=100	=90	=90	=70

Fly ash class 1 is treated as special high fineness fly ash, only few companies produce it. Fly ash class 2 has bigger size than fly ash class 1 ash, most of fly ash in this world has this size. Fly ash class 3 is almost same as class 2 except the content of ignition loss (LOI). This ignition loss is not good for concrete therefore fly ash class 3 is treated as low quality fly ash. Fly ash class 4 has the biggest size when compare to all them. It is treated as the one type of fine aggregate. So, fly ash class 1 and class 2 are the most widely used in Japan.

1.4 Objectives of this research

It was known that flowability of concrete is mainly effort from flowability of mortar. When fresh mortar that has adequate flowability combines together with coarse aggregate that satisfied some criteria will result as self-compacting concrete.

If superplasticizer does not exist in mortar, flowability of fresh mortar mainly depends on the physical characteristics of powder material in use and amount of free water in mortar. The existing of superplasticizer induces difficulty to the mix-proportion design due to chemical reaction between superplasticizer and cement powder. Either superplasticizer or water can increase the deformability of fresh mortar. Increasing the water-powder ratio (Vw/Vp) can result in a decrease in the viscosity due to a decrease in the number of solid particle. On the other hand, increasing superplasticizer dosage (SP/P) cannot decrease the viscosity as much as water can, because superplasticizer does not decrease the number of the solid particles but increase the dispersing force between solid particles.

The mix design becomes more difficult when fly ash is used to replace some volume of cement powder in mortar. Fly ash itself can not react with superplasticizer as same as cement but due to its spherical shape fly ash may act as lubricant material in mortar. *This research is conducted in order to find out the new mix design method for mortar that use blended powder between fly ash and cement as powder material.*

CHAPTER 2
LITERATURE REVIEW

2.1 Basic Equations of Mortar Flow

Relative mortar flow area (Eq.(2.1)) is given by the basic equation Eq.(2.2), and for a particular powder is determined by the volumetric water-powder ratio, the volumetric ratio of sand in the mortar, and the water-retaining factor and flow factor representing sand properties (Fig.2.1). The value of mortar flow (Eq.(2.1)) in the absence of vibration was measured according to "An experimental method of quality control of cement on fresh mortar properties in high-performance concrete ".

$$\Gamma_m = \left(\frac{F_m}{100}\right)^2 - 1 \tag{2.1}$$

$$\frac{V_w}{V_p} = E_m \Gamma_m + \beta_m \tag{2.2}$$

$$E_m = \left(E_p + E_s \frac{V_s}{V_p}\right) \frac{1 - V_s}{1 - V_s(1 + \beta_s)} \tag{2.3}$$

$$\beta_m = \frac{\beta_p(1 - V_s) + \beta_s V_s}{1 - V_s(1 - \beta_s)} \tag{2.4}$$

where Γ_m is the relative flow area of the mortar, F_m is the value of the mortar flow (mm) in the absence of vibration, β_m is the water-retaining factor of the mortar, E_m is the flow factor of the mortar, V_w is the volumetric ratio of water in the mortar, V_p is the volumetric ratio of powder in the mortar, V_s is the volumetric ratio of sand in the mortar, β_p is the water-retaining factor of the powder, E_p is the flow factor of the powder, β_s is the water-retaining factor of the sand, and E_s is the flow factor of the sand.

When blended of cement and admixture is used as the powder material, water-retaining factor and flow factor of powder are obtained from linear interpolation between those of cement and admixture (Eq.(2.5) and Eq.(2.6)).

$$\beta_p = \beta_c + (\beta_{ad} - \beta_c) * \gamma_{ad} \tag{2.5}$$

$$E_p = E_c + (E_{ad} - E_c) * \gamma_{ad} \tag{2.6}$$

where β_p is the water-retaining factor of blended powder, βc is the water-retaining factor of cement, bad is the water-retaining factor of the admixture, Ep is the flow factor of blended powder, Ec is the flow factor of cement, Ead is the flow factor of the admixture, and gad is the volumetric ratio of the admixture to blended powder.

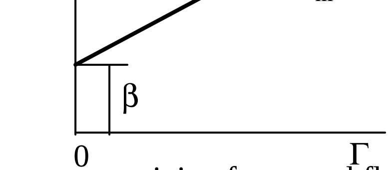


Fig. 2.1 Basic equation of mortar flow (V_s: constant)

The water-retaining factor and flow factor of the sand, which are formulated as a function of the volumetric ratio of sand in the mortar (V_s), are given by Eq.(2.7) and Eq.(2.10)

$$\beta_s = \beta_{s0} + \beta_{sv} \quad (2.7)$$

$$\beta_{sv} = A.\left\{\frac{V_s(1+\beta_p)}{1+V_s.(\beta_p - \beta_s)} - \frac{V_{si}(1+\beta_p)}{1+V_{si}.(\beta_p - \beta_{s0})}\right\}^{1.5} \quad (2.8)$$

$$V_{si} = \frac{\gamma_{si}}{1+\beta_p - \gamma_{si}(\beta_p - \beta_{s0})} \quad (2.9)$$

$$E_s = E_{s0} + E_{sv} \quad (2.10)$$

$$E_{sv} = B\left(\frac{1}{V_{sr} - V_s} - \frac{1}{V_{sr} - V_{si}}\right) \quad (2.11)$$

where β_{s0} is the absolute water-retaining factor of the sand, β_{sv} is the apparent water-retaining factor resulting from interactions of sand particles, V_{si} is the volumetric ratio at the start of sand particle interaction, γ_{si} is the volumetric ratio of sand to solid particles at the start of sand particle interaction, A is a constant, E_{s0} is the absolute flow factor of the sand, E_{sv} is the apparent flow factor resulting from sand particle interaction, V_{sr} is the limit volumetric ratio of sand, and B is a constant.

2.2 Index for Effect of Superplasticizer and the Relationship with The Dosage

Ouchi et al. have defined the ratio Γ_m/R_m as the dispersing effect of powder particles by superplasticizer on the flowability of fresh mortar in self-compacting concrete. A larger Γ_m/R_m corresponds to a greater effect of superplasticizer. For example, a relationship between superplasticizer dosage (weight ratio of superplasticizer to powder weight) and Γ_m/R_m for mortar using moderate heat cement and a polycarboxylate type superplasticizer is shown (Fig.2.2). The Γ_m/R_m is almost 0, while the superplasticizer dosage (S_p/P), weight ratio of superplasticizer to powder, is less than 0.7%. On the other hand, the Γ_m/R_m is linear while Sp/P is more than 0.7%. That was the case with the mortar using other type of cement or superplasticizer. The authors simplified the relationship between Sp/P and Γ_m/R_m, in which the relationship can be described as the combination of the intercept and the inclination (Fig.2.3). The intercept "Restrained SP dosage" can be described as the minimum superplasticizer dosage for mortar to disperse the powder particles. The inclination "Unit dispersing SP dosage" can be described as the required dosage superplasticizer to increase the unit dispersing effect.

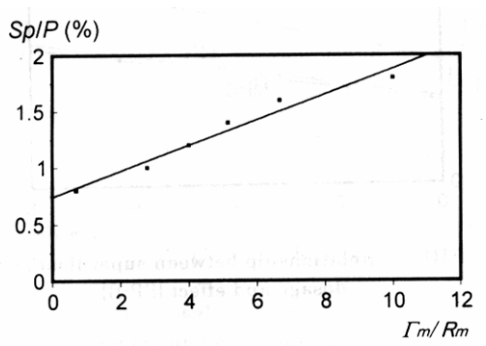


Fig. 2.2 Relationship between superplasticizer dosage and effect [MPC+SP-A, fine aggregate content 40%]

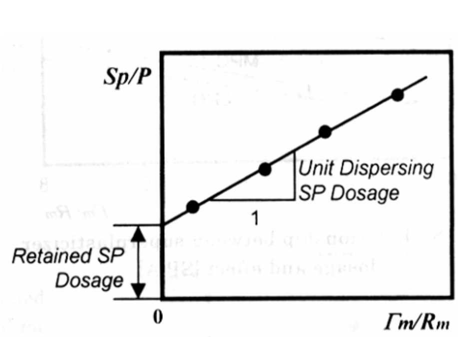


Fig. 2.3 Simplified relationship between superplasticizer dosage and dispersing effect

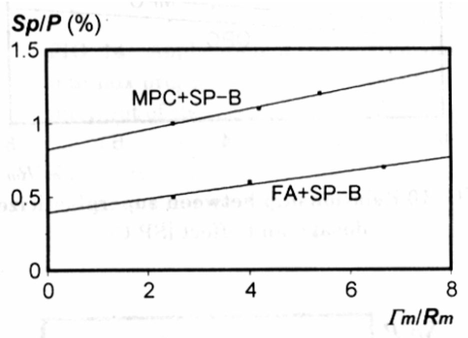


Fig. 2.4 Difference in the required superplasticizer dosage due to chemical characteristics of powder material in use in fresh mortar [Fine aggregate content 40%]

For example, both the retained SP dosage and the unit dispersing SP dosage for fresh mortar using fly ash only as a powder material were smaller than mortar using moderate heat cement as a powder material (Fig. 2.4). That can be due to the existence of the component in cement that absorbs superplasticizer, resulting in no dispersing effect of powder particles. Further investigations are required on the relationship between the chemical characteristics of powder material or superplasticizer and the retained SP dosage or the unit dispersing SP dosage.

It was found out that the relationship between the retained SP dosage and unit dispersing SP dosage for each type of superplasticizer can be plotted on the same line (Fig. 2.5– Fig. 2.8). That means that the minimum dosage of superplasticizer to disperse powder particles in mortar is proportional to the required dosage of superplasticizer to increase the unit dispersing effect of powder material despite of the type of cement on the condition that the type of superplasticizer is the same (Fig. 2.8). The ratio of the retained SP dosage to the unit dispersing SP dosage can be the own character value for the superplasticizer.

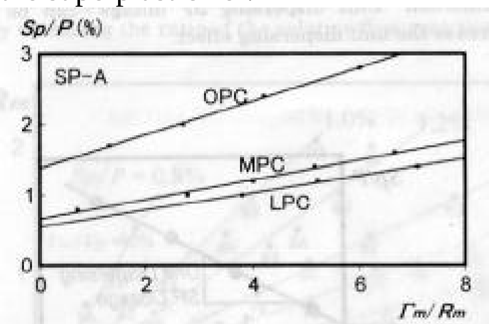


Fig. 2.5 Relationship between superplasticizer dosage and effect [SP-A]

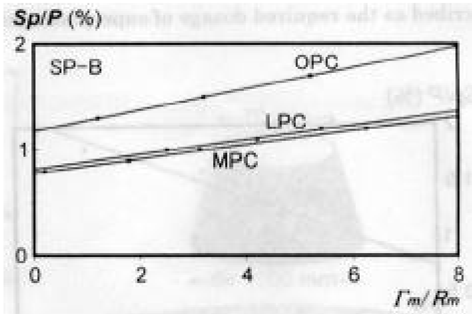


Fig. 2.6 Relationship between superplasticizer dosage and effect [SP-B]

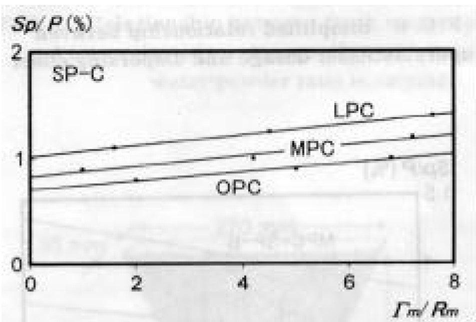


Fig. 2.7 Relationship between superplasticizer dosage and effect [SP-C]

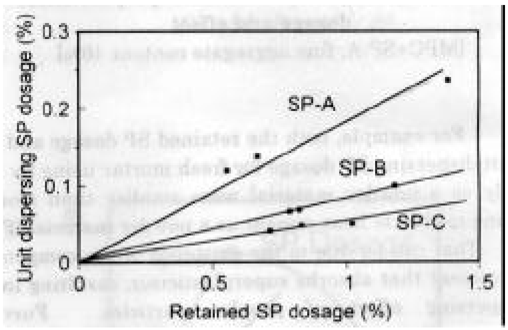


Fig. 2.8 Relationship between retained SP dosage and unit dispersing SP dosage for each type of superplasticizer

CHAPTER 3
METHODOLOGY

3.1 Method to analyze influence of fly ash on flowability

In order to understand the relationship of each material on mix design, the definitions and names of each parameter in use have to be clarified. Usually the materials ingredients in mortar are fine aggregate, powder (cement and pozzolan), superplasticizer, and water. Three parameters, which are fine aggregate content (S/M), water-powder ratio (Vw/Vp) and superplasticizer dosage (SP/P), are required for design the mix proportion of mortar using only one type of powder. In order to use fly ash to replace some volume of cement, another parameter called as fly ash replacement ratio (V_{FA}/Vp) is introduced.

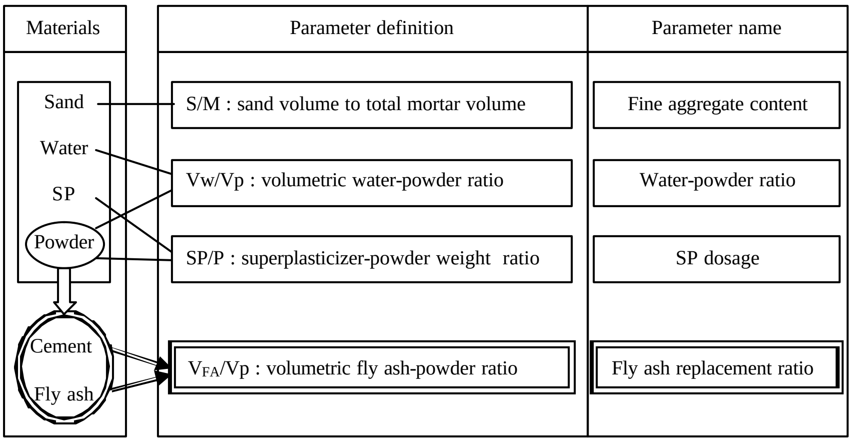


Fig. 3.1 materials and parameters in mortar mix proportion design

Ouchi et al. found that if the fine aggregate content (S/M) is equal to 0.4 and only one type of powder is used (pure cement or any other pozzolanic materials), the relationship between water-powder ratio (Vw/Vp) and flowability of mortar (Rm represent flow speed, Gm represent flow area) and the relationship between SP dosage (SP/P) and flowability of mortar can be considered independently to each other (Fig . 3.2).

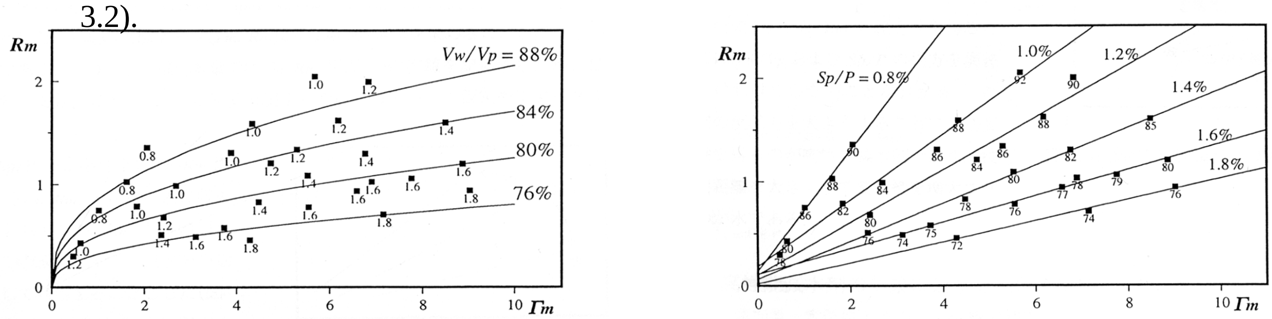


Fig. 3.2 Relationship between Vw/Vp, SP/P and Flowability of mortar (Rm vs. Γm) which use moderate heat Portland cement and fix fine aggregate content at 40%

Left : relationship between Vw/Vp and flowability of mortar

Right : relationship between SP/P and flowability of mortar

If blended powder of cement and fly ash is treated as another type of powder, it provides another set of "Rm vs. Γm" as shown below.

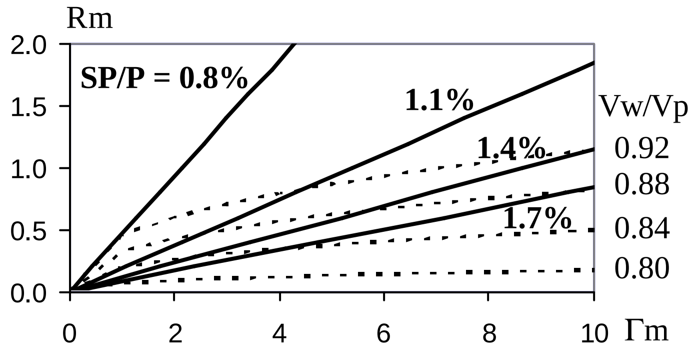


Fig. 3.3 Rm vs. Gm of cement only mortar
Fine aggregate content : 40%
Cement : OPC

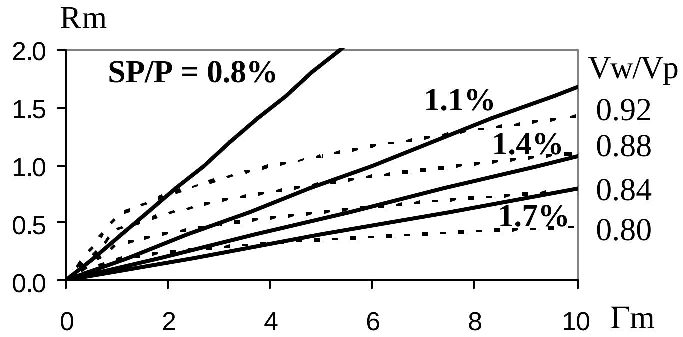


Fig. 3.4 Rm vs. Gm of cement + fly ash mortar
Fine aggregate content : 40%
Cement : OPC
Fly ash : JIS class 1
Fly ash replacement ratio : 0.25

Thick line is plotted along the data which use same SP dosage. Dot line is plotted along the data which use same Vw/Vp. When fly ash is used, the flowability chart (Rm vs. Γm) is changed. For example, the interception between thick line SP/P 1.1% and dot line Vw/Vp 0.92 (which refer to mortar that has SP dosage 1.1%, water-powder ratio 0.92 and fine aggregate content equal to 40%) in case of cement only represents the mortar that has flow area equal to 4.5 and flow speed equal to 0.8 change to be flow area equal to 7 and flow speed equal to 1.2 when fly ash is used to replace some volume of cement.

Then the influence of fly ash on flowability of mortar can be divided into 2 parts: influence of fly ash on relationship between Vw/Vp and flowability, and influence of fly ash on relationship between SP/P and flowability.

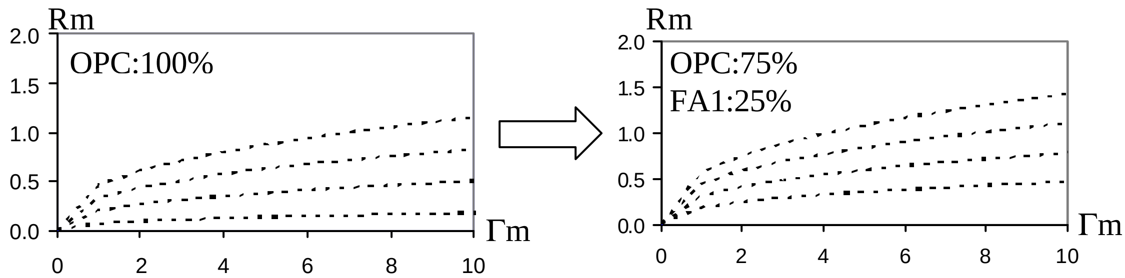


Fig. 3.5 Influence of fly ash on relationship between Vw/Vp and Flowability

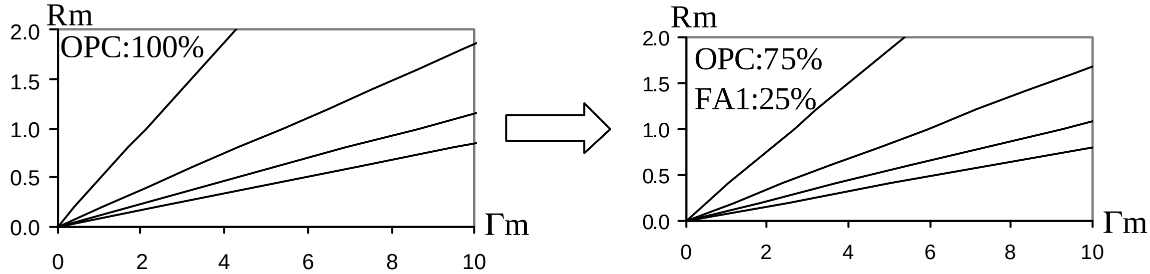


Fig. 3.6 Influence of fly ash on relationship between SP/P and Flowability

From this way of thinking, the flowability charts (Rm vs. Γm) of several fly ash replacement ratios have to be constructed in order to find out the effect of fly ash replacement ratio. The effect of type of fly ash can be obtained by repeat the whole process again but change the fly ash powder in use.

3.2 Materials in use

The scope of this research based on role of fly ash on fresh mortar properties. Then the information of fly ash in market has to be investigated. Fly ash was classified by Japanese Industrial Standard [JIS A 6201] into 4 classes as shown in table 3.1

Table 3.1 Properties of Fly ash in use

		Class				Used	
		1	2	3	4	FA1	FA2
Silicon dioxide		=45.0				53.8	53.8
Moisture content		=1.0				0.16	0.16
Ignition loss		=3.0	=5.0	=8.0	=5.0	2.0	2.0
Density (g/cm^3)		=1.95				2.40	2.20
Fineness	Specific surface area (cm^2/g)	=5000	=2500	=2500	=1500	5520	3000~4000
Percent flow		=105	=95	=85	=75	109	=100
Activity Index	28 days	=90	=80	=80	=60	92	=80
	91 days	=100	=90	=90	=70	106	=90

This research was conducted base on physical characteristic of fly ash, so the high LOI (Loss on Ignition) content fly ash was not considered here. Fly ash class 1 and class 2 (namely as FA1and FA2) were tested for this research. Two batches of fly ash, which produced from same resource and same raw materials, were used. They were believed to have different characteristic in fineness only.

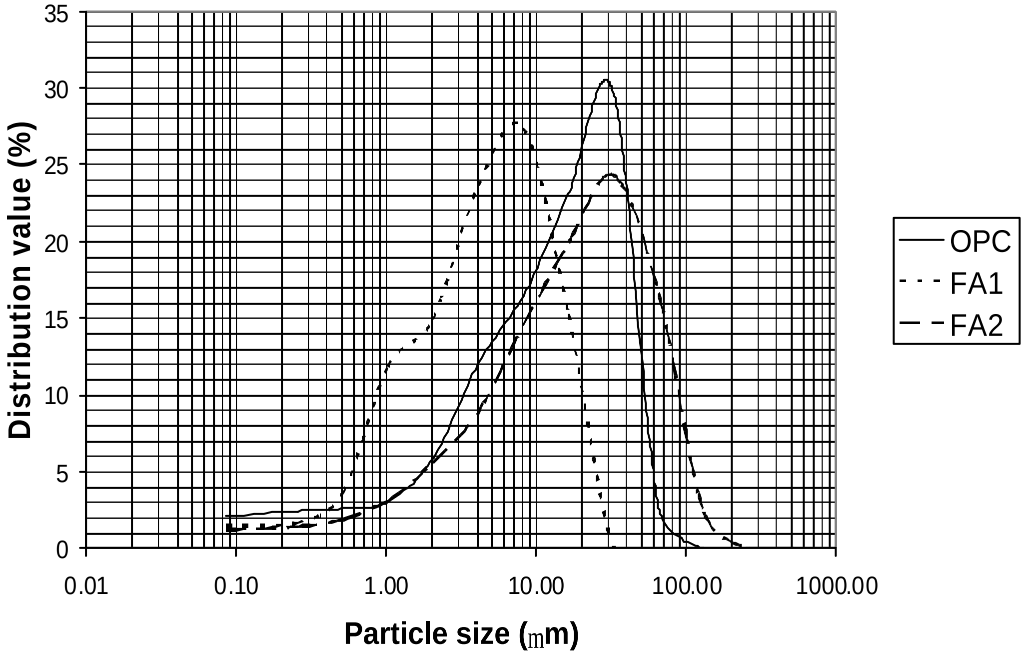


Fig. 3.7 Particle size distribution of fly ash and Ordinary Portland cement

Table 3.2 Properties of Ordinary Portland cement

		JIS R 5210	Used OPC
Density		-	3.15
specific surface area		2500	3430
initial setting		=60 min	2-02
final setting		=10 hrs	3-08
strength	3d	=12.5	31.9
	7d	=22.5	47.2
	28d	=42.5	64.20
MgO%		=3.0	1.74
SiO2%		=3.1	2.00
LOI%		=3.2	1.64
Alkali%		=3.3	0.48

Ordinary Portland cement and polycarboxylate based superplasticizer were treated as the main ingredients. Particle size distribution of each powder was shown in Fig. 3.7. Table 3.2 shows the properties of cement powder. Usually, the combination of crushed sand and sea sand was used as fine aggregate, but in this research in order to eliminate the influence of organic substance (impurity in sea sand) on the chemical reaction within mortar only crushed sand was used as fine aggregate.

All materials were kept and tested in the standard control-temperature room, the temperature of water that used in this experiment was also controlled to be 20°± 0.5°C. Properties of sand are shown in Fig. 3.8, Fig. 3.9, and table 3.3

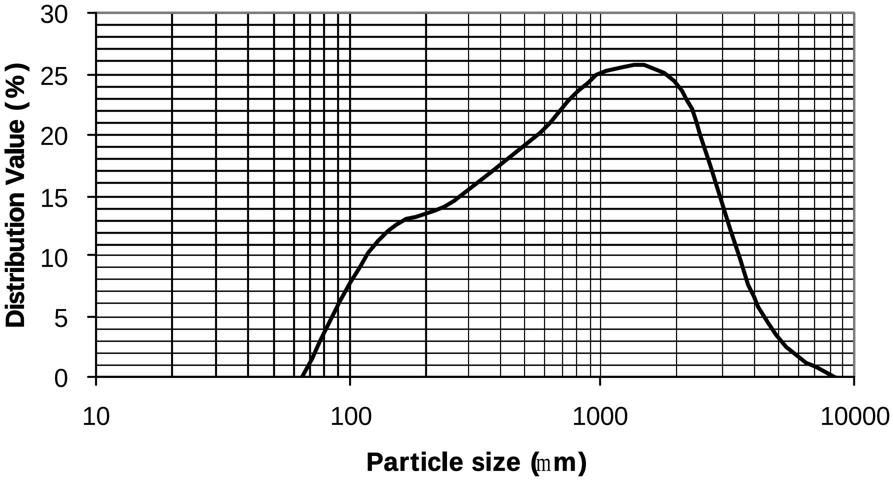


Fig. 3.8 Particle size distribution of crushed sand

Fig. 3.9 Shape of the crushed sand

Table 3.3 physical properties of the crushed sand

Type	Crushed sand
Source	Kochi,JAPAN
Specific gravity	2.58
Solid volume(%)	66.0
Absorption (vol.%)	1.69
Fineness Modulus (F.M.)	2.67

3.3 Experimental program

The parameters that considered in this research were fly ash replacement ratio(V_{FA}/Vp) superplasticizer dosage(SP/P), water-powder ratio(Vw/Vp). The fine aggregate content (S/M) was fixed to be 40% of total volume of mortar for all mixes. Then the change in combination of material can be treated as the change in paste properties. The selected value for each parameters are shown as follows

- Fly ash replacement ratio(V_{FA}/Vp): 0, 0.25, 0.5, 0.75, 1 by volume of powder
- SP dosage (SP/P) : 0%,0.8%,1.1%,1.4%,1.7%
- Water-powder ratio (Vw/Vp) : in the range of 0.7-1.7 by volume of powder

For each combination of V_{FA}/Vp and SP/P, trial mixes for 4 different values of Vw/Vp are required. The way to trial Vw/Vp is in order to obtain the test result value of flow area (Γm) between 5 to7 and flow speed of around 1.0, because these two values are preferable for the production of concrete that has a high self-compactability if it contains an adequate amount of coarse aggregate. The SP dosage was used in range of around 0.8%-1.7%, because it is the range of SP usage in practical work.

3.4 Measurement of flowability

All mixes have been tested for both flow cone test and funnel test(Fig 3.10). The value of relative flow area (Gm) expresses the degree of spread relative to the bottom area of the mortar flow cone express by

$$\Gamma m = ((r^2 - r_0^2)/r_0^2$$

where r is the average mortar flow value (mm) = (r_1+r_2)/2

r_0 is the bottom diameter of flow cone = 100 mm

The relative funnel speed (Rm) obtained from measure the time that mortar requires in order to completely flow out of this funnel. The greater value of Γm means the greater deformability of the mortar. The greater of the value of Rm means the lower viscosity.

Rm = 10/ t

where t is funnel discharging time (sec.)

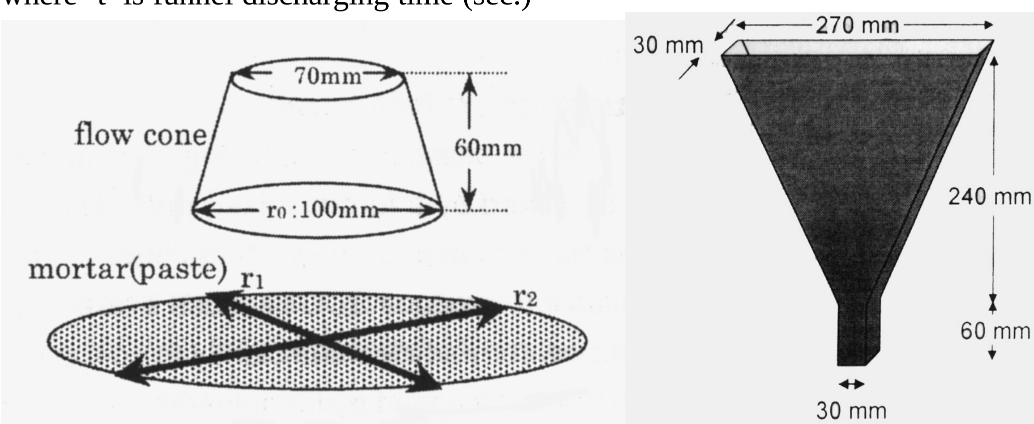


Fig.3.10 Flow test and funnel test of mortar

Since now, relative flow area (Gm) and relative funnel speed (Rm) will be used to refer to flow area and flow speed of mortar.

CHAPTER 4
EXPERIMENTAL RESULTS

4.1 Influence of Fly Ash on Relationship between Vw/Vp and Flowability of Mortar

The relationship between Vw/Vp and flowability of mortar can be considered independently to the SP dosage. The line represented the data that have same Vw/Vp can be plotted. Each line can be expressed by Eq.(4.1)

$$R_m = A \cdot \Gamma_m^{0.4} \tag{4.1}$$

where

Rm is the relative funnel speed of mortar, Γm is the relative flow area of mortar, and A is the coefficient that provides the curve of each Vw/Vp best fit to the test data.

Each Vw/Vp-line has its own corresponding coefficient A. Then the whole chart of relationship between Vw/Vp and flowability can be represented by only one line (Fig. 4.1). Each point in the graph between Vw/Vp and A does not mean only one mix proportion but means all mixes which use that Vw/Vp. One type of powder can be represented by one line. When the fly ash replacement ratio is changed, mortar can be treated as changing the powder type. Changing of fly ash replacement ratio results as changing of graph between Vw/Vp and A.

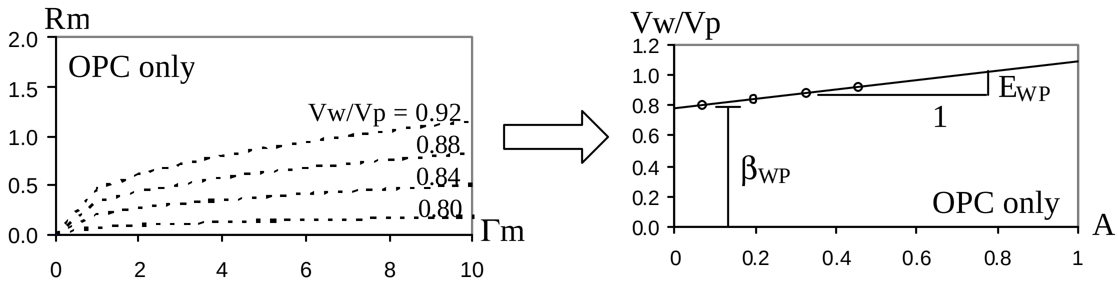
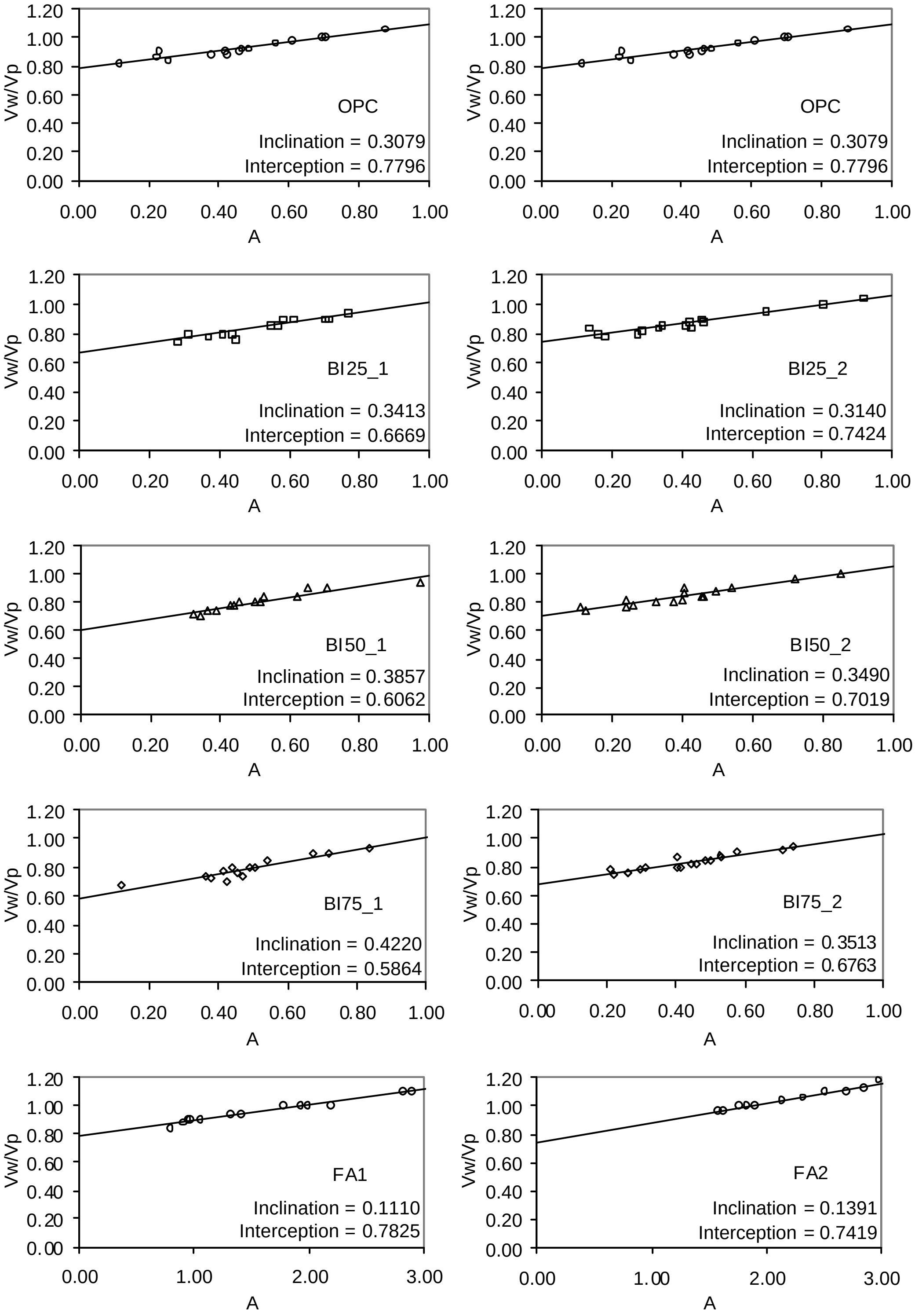


Fig. 4.1 Transform a flowability chart of OPC only mortar to be a line by using A

The water in mortar can be separated into 2 parts: retained water, which is the water that retained on the surface of solid particle in mortar, and free water, which is the water that excess the retainability of solid particle and cause the mortar flow.

From the graph between Vw/Vp and A, each line compose of inclination and Vw/Vp-axis interception. Considering flowability chart (Rm vs. Γm), when A equal to zero it place on Γm-axis which means the mortar has very high flow area but the flow speed is zero or means that mortar can not flow. Increasing Vw/Vp result as increasing the value of A, then flow speed (Rm) is increased. Then the Vw/Vp-axis interception means the minimum water-powder ratio that mortar required to flow or means the retained water on surface of solid particle in mortar. The inclination means the amount of water-powder ratio that required for increase one unit of the coefficient A or means unit free water.



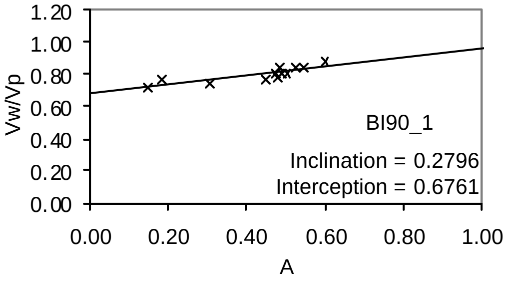


Fig. 4.2 Relationship between Vw/Vp and A when vary fly ash replacement ratio and Blaine fineness of fly ash
BIxx_y means binary mixture between OPC and fly ash class y at fly ash replacement ratio equal to 0.xx

The inclination and interception are notified as unit free water (E_{WP}) and retained water (β_{WP}), respectively. The effect of changing the fly ash replacement ratio on E_{WP} and β_{WP} are shown in Fig. 4.3

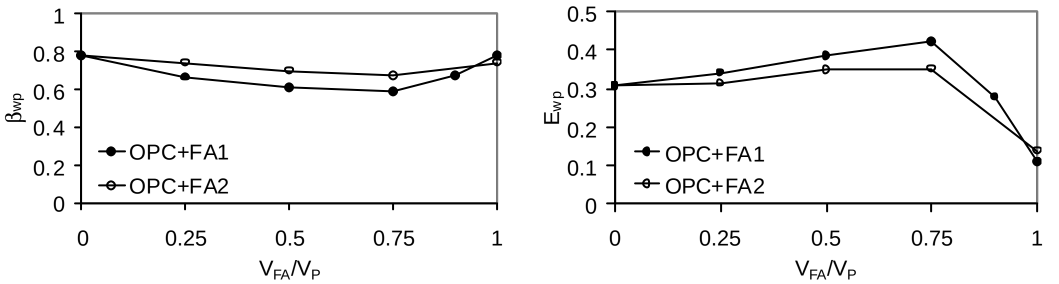


Fig. 4.3 Effect of changing fly ash replacement ratio of fly ash class1 and fly ash class2 on retained water (β_{WP}) and unit free water (E_{WP}) of mortar

It was found that there is optimum value for fly ash replacement ratio (V_{FA}/V_P) for both retained water (β_{WP}) and unit free water (E_{WP}). That optimum value seem to be occur at fly ash replacement ratio is about 0.75. From the range of fly ash replacement ratio from 0.0 up to 0.75, the relationship between retained water (β_{WP}) or unit free water (E_{WP}) and fly ash replacement ratio (V_{FA}/V_P) are seem to be linear relationship. As mention in chapter 3, fly ash in Japan has high silica content, which the maximum fly ash replacement ratio is less than 0.75 in practical work. So, this linear relationship between retained water (β_{WP}) or unit free water (E_{WP}) and fly ash replacement ratio (V_{FA}/V_P) from 0 until 0.75 is already enough for practical use.

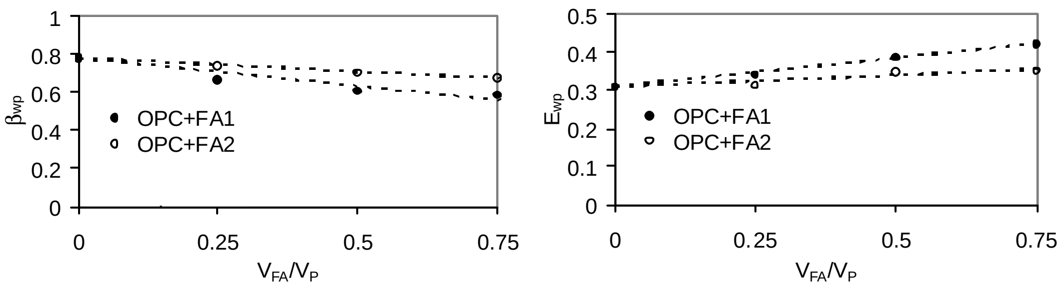


Fig. 4.4 Magnification of Fig. 4.3

It was shown that blended powder of OPC and FA1 (fineness ˜5,000) provides lower value of retained water (β_{WP}) than blended powder of OPC and FA2 (fineness ˜ 3,000). This may be explained by when fly ash is used to replace cement powder, fly ash act as lubricant material due to its spherical shape. Fly ash can not react with SP and produce repulsive force as same as cement. Even fly ash can act as lubricant material but it can not produce force as cement which results in existing of the optimum fly ash replacement ratio. When finer fly ash is applied at same volume (same V_{FA}/V_P) as the normal fineness fly ash, the amount of particle of finer fly ash (FA1) is much more than that of the normal fineness fly ash (FA2) which means applied more amount of lubricant materials to mortar.

For unit free water (E_{WP}), the blended of OPC and FA1 provides higher value than OPC and FA2. This may be explained by that increasing the water-powder ratio result as increasing the distance between particle, then the lubrication effect of fly ash is reduced. At high Vw/Vp, the coefficient A of each fly ash replacement ratio become close to each other. So, blended powder that provides low retained water has high unit free water.

4.2 Influence of Fly Ash on Relationship between SP/P and Flowability of Mortar

The relationship between SP/P and flowability of mortar can be considered independently to the water-powder ratio. The line represented the data that have same SP/P can be plotted. Each line can be expressed by Eq.4.2

$$\Gamma_m = B \cdot R_m \qquad (4.2)$$

where

Rm is the relative funnel speed of mortar, Γm is the relative flow area of mortar, and B is the inverse inclination of the line represents each SP dosage.

Each SP/P-line has its own corresponding coefficient B. Then the whole chart of relationship between SP/P and flowability can be represented by only one line. Each data point in the graph between SP/P and B do not mean only one mix proportion but mean all mixes which use that SP/P. One type of powder can be represented by one line. When the fly ash replacement ratio is changed, mortar can be treated as changing the powder type.

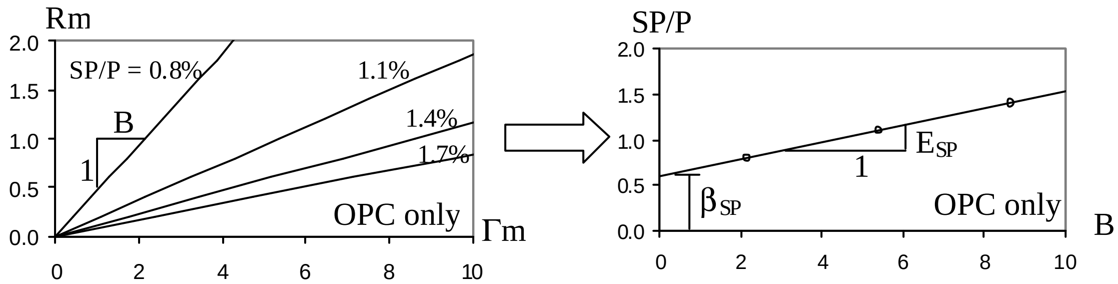
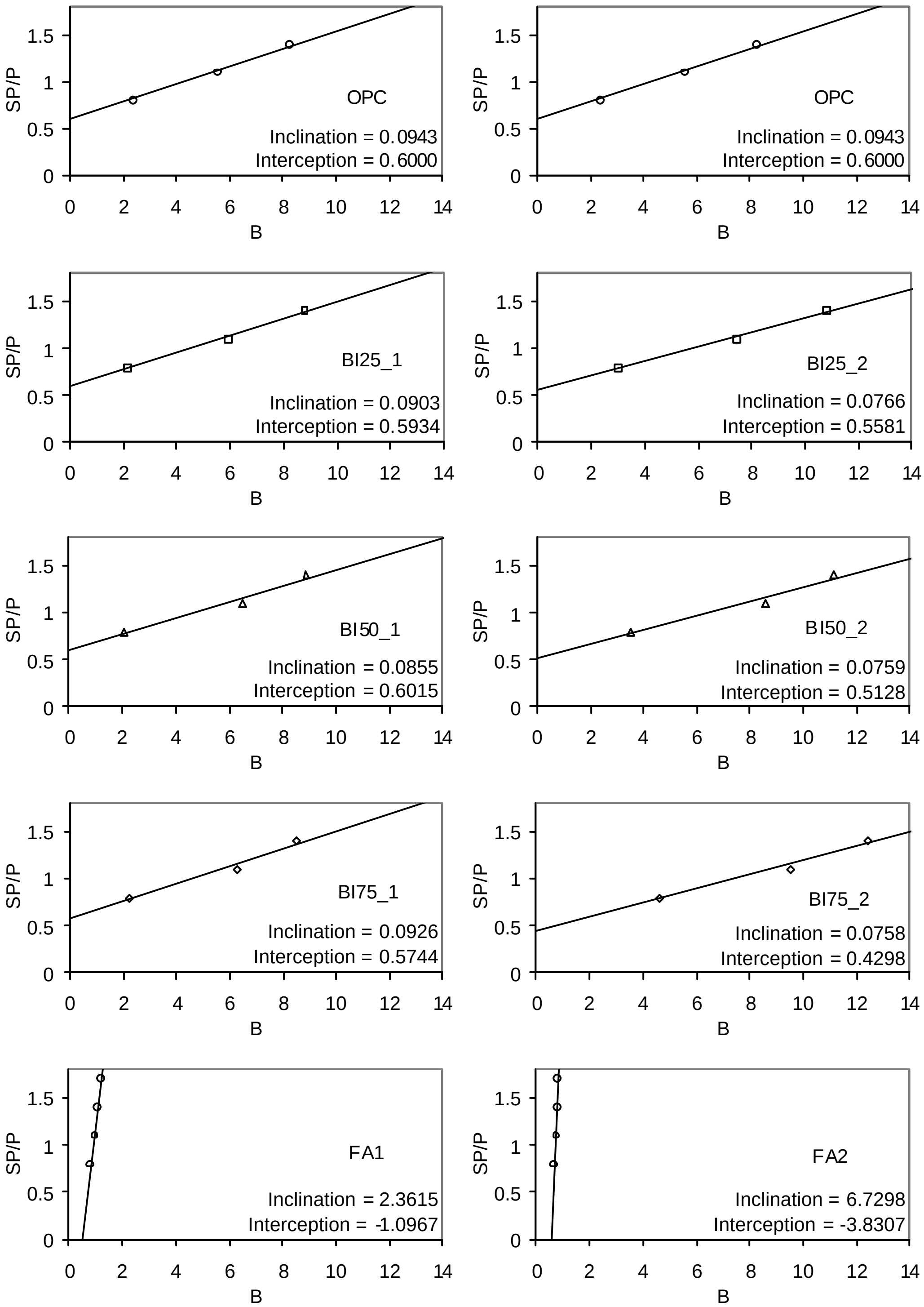


Fig. 4.2 Transform a flowability chart of OPC only mortar to be a line by using B

The SP dosage in mortar can be separated into 2 parts: retained SP dosage, which is the minimum superplasticizer dosage for mortar to disperse the powder particles, and dispersing SP dosage, which is the superplasticizer that excesses the minimum requirement to start the mortar flow then increase in this excess SP result as increase in flowability. From the graph between SP/P and B, each line composes of inclination and SP/P-axis interception. Considering flowability chart (Rm vs. Γm), when B equal to zero it place on Rm-axis which means the mortar has very high flow speed but the flow area is zero or means that mortar can not flow. Increasing SP/P result as increasing the value of B, then flow area (Γm) is increased. Then the SP/P-axis interception means the minimum SP dosage that mortar required to flow or means the retained SP dosage in mortar. The inclination means the amount of SP dosage that required for increase one unit of the coefficient B or means unit dispersing SP dosage.



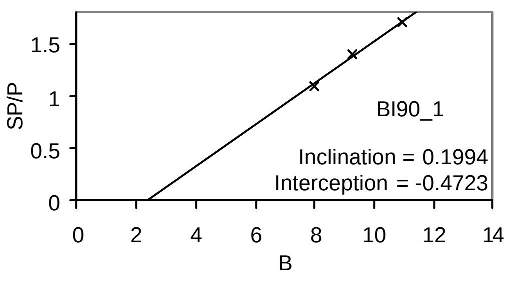


Fig. 4.6 Relationship between SP/P and B when vary fly ash replacement ratio and Blaine fineness of fly ash
BIxx_y means binary mixture between OPC and fly ash class y at fly ash replacement ratio equal to 0.xx

The inclination and interception are notified as dispersing SP dosage (E_{SP}) and retained SP dosage (β_{SP}), respectively. The effect of changing the fly ash replacement ratio on E_{SP} and β_{SP} are shown in Fig 4.7

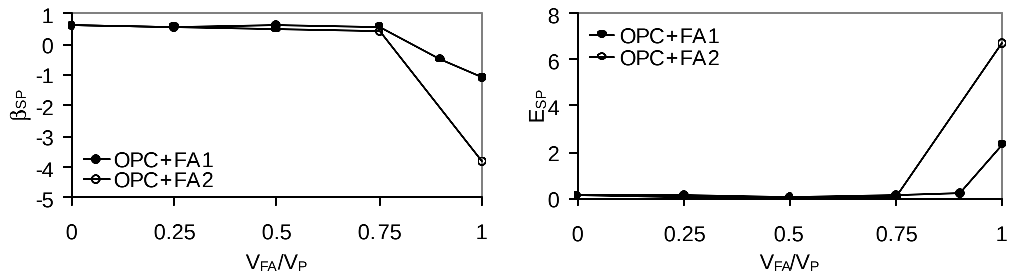


Fig. 4.7 Effect of changing fly ash replacement ratio of fly ash class1 and fly ash class2 on retained SP dosage(β_{SP}) and dispersing SP dosage (E_{SP}) of mortar

From fig 4.6 it was found that both of fly ash class 1 and class 2 are not reactive with this type of superplasticizer. Fly ash replacement ratios at 0.9 and 1.0 have retained SP dosage and dispersing SP dosage quit different from those of other fly ash replacement ratio. It seems to be that fly ash replacement ratio above 0.75 are less sensitive to SP as shown by large value of dispersing SP dosage. From the range of fly ash replacement ratio from 0.0 up to 0.75, the relationship between retained SP dosage (β_{SP}) and fly ash replacement ratio (V_{FA}/V_P) are seem to be linear relationship. As mention in chapter 2, the inclination of the graph between unit dispersing SP dosage and retained SP dosage represents the characteristic of type of superplasticizer.

The relationship between retained SP dosage and fly ash replacement ratio is linear, then the relationship between unit dispersing SP dosage and fly ash replacement ratio should be linear, too. So, these linear relationship between retained SP dosage (β_{SP}) or unit dispersing SP dosage (E_{SP}) and fly ash replacement ratio (V_{FA}/V_P) from 0 until 0.75 is acceptable.

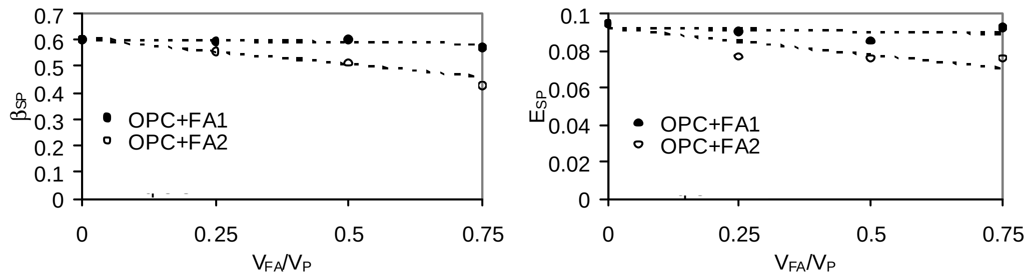


Fig. 4.8 Magnification of fig 4.7

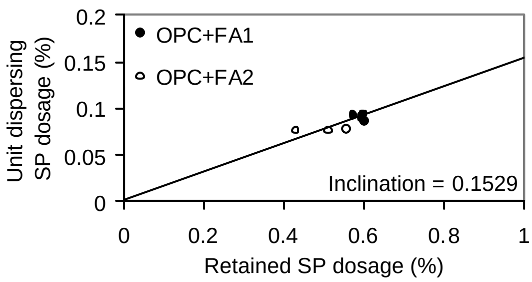


Fig. 4.9 Characteristic value of superplasticizer

It was shown that blended powder of OPC and FA1 (fineness ˜5,000) provides higher value of retained water (β_{SP}) than blended powder of OPC and FA2 (fineness ˜ 3,000). This may be explained by when normal fineness fly ash (almost same fineness as cement powder) is used to replace cement powder, mortar requires lower repulsive force to disperse the particle due to the lubricant effect of fly ash. When finer fly ash is applied at same volume (same V_{FA}/V_P) as the normal fineness fly ash, the amount of particle of finer fly ash (FA1) is much more than that of the normal fineness fly ash (FA2) which means increasing of surface area that SP can be adsorb.

For unit dispersing SP dosage (E_{SP}), the blended of OPC and FA1 provides higher value than OPC and FA2. This may be explained by that finer fineness fly ash required larger volume of SP in order to increase the thickness of SP on the solid particle to be same as the case of using normal fineness fly ash due to its larger surface area.

CHAPTER 5
PROPOSING MIX DESIGN METHOD

5.1 Equations for Predict Vw/Vp

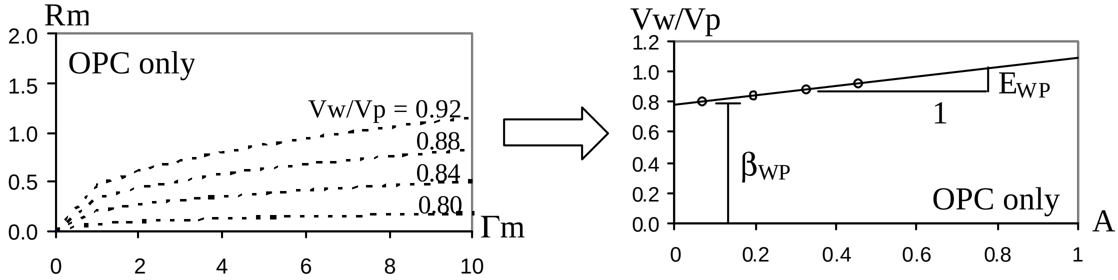


Fig. 5.1 Relationship between Vw/Vp and A

From the relationship between Vw/Vp and A that found in chapter 4, Vw/Vp and A have linear relation which can be expressed as

$$V_w / V_p = \beta_{wp} + A * E_{wp} \tag{5.1}$$

$$A = R_m / \Gamma_m^{0.4} \tag{5.2}$$

where

Vw/Vp is water-powder ratio, β_{WP} is retained water, E_{WP} is unit free water, A is the coefficient of the curvature indicates each Vw/Vp on flowability chart, Rm is the relative funnel speed of mortar, and Γm is the relative flow area of mortar.

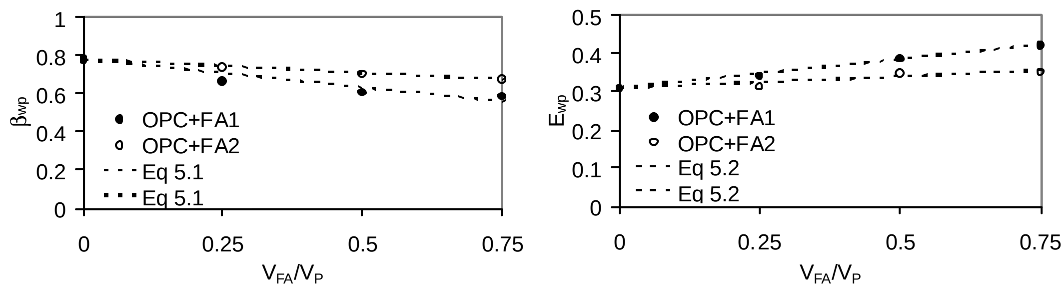


Fig. 5.2 Relationship between β_{WP} , E_{WP} and V_{FA}/V_P

The retained water (β_{WP}) and/or the unit free water (E_{WP}) have linear relationship with fly ash replacement ratio from 0 up to 0.75.

$$\beta_{WP,xx} = \frac{(\beta_{WP,75} - \beta_{WP,0})}{(0.75-0)} * (\frac{V_{FA}}{V_P}) + \beta_{WP,0} \tag{5.3}$$

$$E_{WP,xx} = \frac{(E_{WP,75} - E_{WP,0})}{(0.75-0)} * (\frac{V_{FA}}{V_P}) + E_{WP,0} \tag{5.4}$$

where

$\beta_{WP,xx}$ is the retained water of blended powder which use fly ash xx%, $\beta_{WP,75}$ is the retained water of blended powder which use fly ash 75%, $\beta_{WP,0}$ is the retained water of blended powder which use fly ash 0% or use cement only, V_{FA}/V_P is the fly ash replacement ratio, $E_{WP,xx}$ is the unit free water of blended powder which use fly ash xx%, $E_{WP,75}$ is the unit free water of blended powder which use fly ash 75%, $E_{WP,0}$ is the unit free water of blended powder which use fly ash 0% or use cement only.

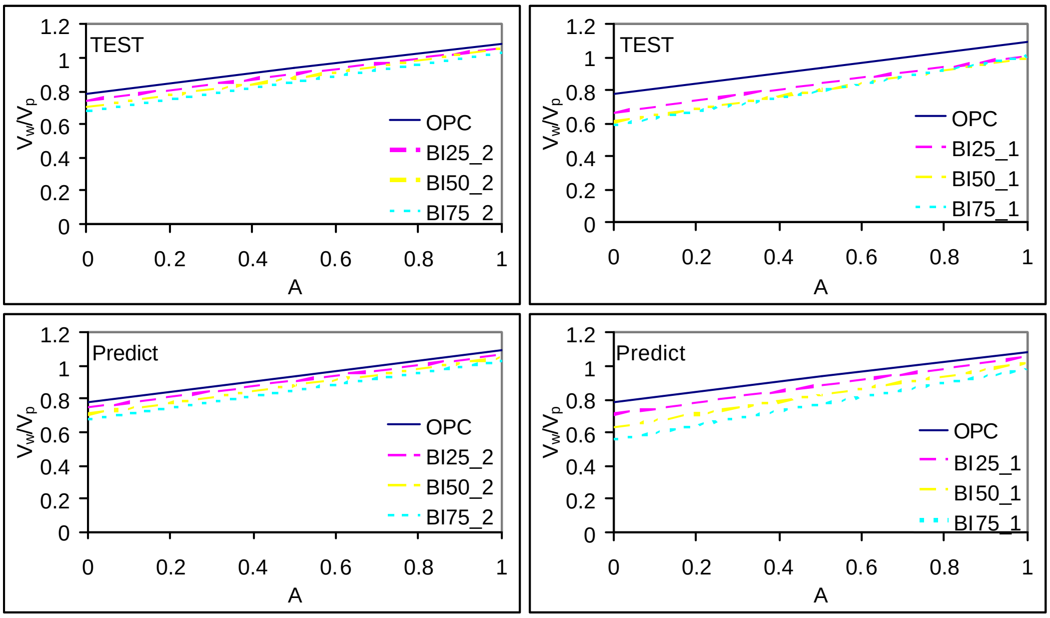


Fig. 5.3 Comparison between the predict value and the tested value

5.2 Equations for Predict SP/P

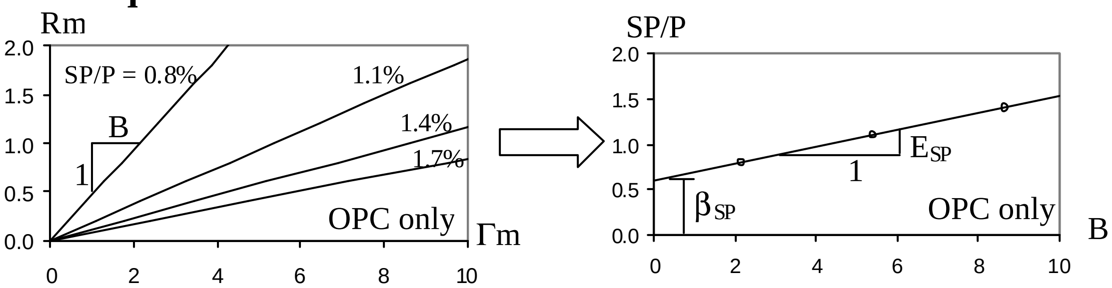


Fig. 5.4 Relationship between SP/P and B

From the relationship between SP/P and B that found in chapter 4, SP/P and B have linear relation which can be expressed as

$$SP/P(\%) = b_{SP} + B * E_{SP} \quad (5.5)$$

$$B = \Gamma_m / R_m \quad (5.6)$$

where

SP/P is superplasticizer dosage, β_{SP} is retained SP dosage, E_{SP} is unit dispersing SP dosage, B is the inverse inclination of each line of SP/P on flowability chart, Rm is the relative funnel speed of mortar, and Γm is the relative flow area of mortar.

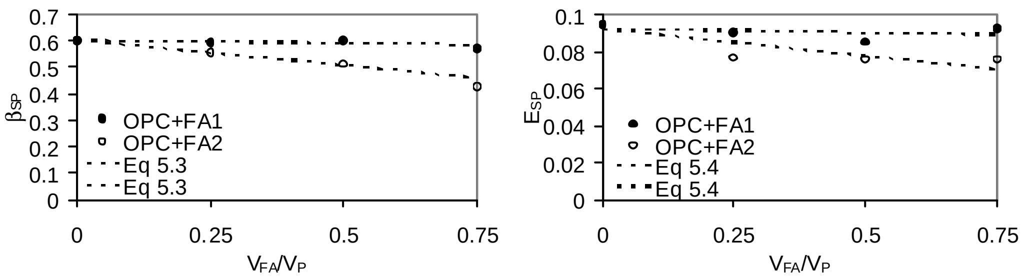


Fig. 5.5 Relationship between β_{SP}, E_{SP} and fly ash replacement ratio

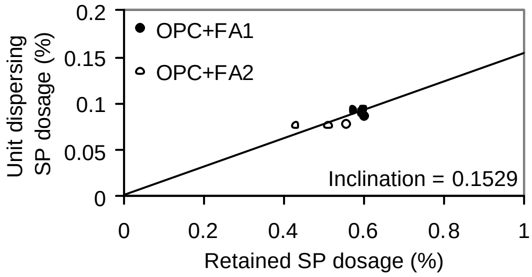


Fig. 5.6 Characteristic value of SP (SPindex = inclination of the graph = 0.1529)

β_{SP} and E_{SP} of blended powder at any fly ash replacement ratio (V_{FA}/V_P) from 0 to 0.75 can be estimated by Eq.(5.7) and Eq.(5.8)

$$b_{SP,xx} = \frac{(b_{SP,75} - b_{SP,0})}{(0.75-0)} * (\frac{V_{FA}}{V_P}) + b_{SP,0} \tag{5.7}$$

$$E_{SP,xx} = (SPindex) * b_{SP,xx} \tag{5.8}$$

where

$\beta_{SP,xx}$ is the retained SP dosage of blended powder which use fly ash xx%, $\beta_{SP,75}$ is the retained SP dosage of blended powder which use fly ash 75%, $\beta_{SP,0}$ is the retained SP dosage of blended powder which use fly ash 0% or use cement only, V_{FA}/V_P is the fly ash replacement ratio, $E_{SP,xx}$ is the unit dispersing SP dosage of blended powder which use fly ash xx%, SPindex is the characteristic value of SP which is the inclination of the graph of unit dispersing SP dosage and retained SP

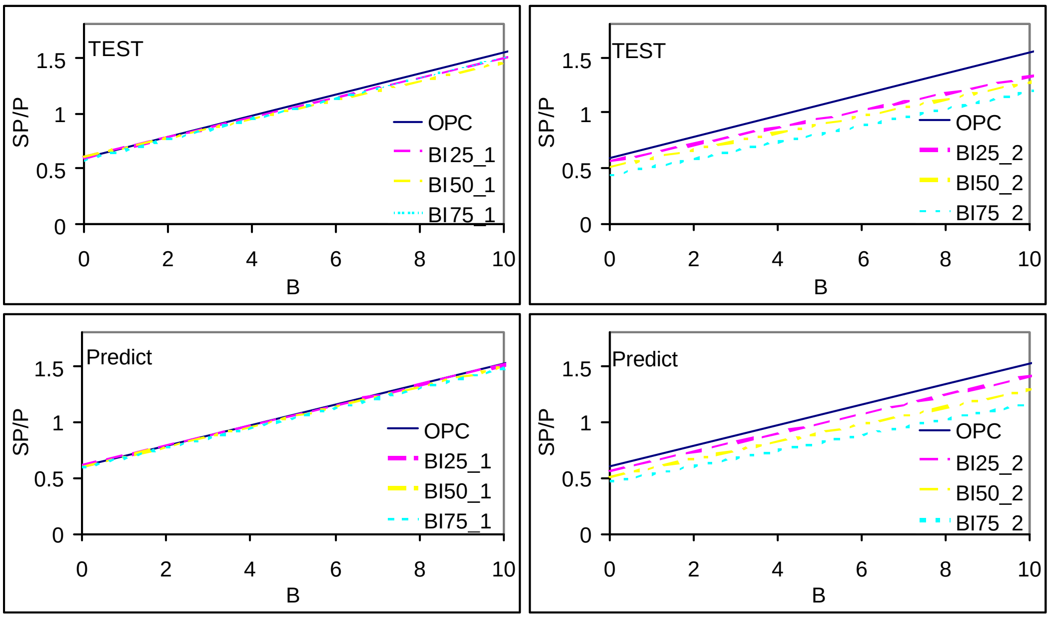


Fig. 5.7 Comparison between the predict value and the tested value

5.3 Effect of Fineness

In this research, two classes of fly ash were tested : fly ash class 1 which has Blaine fineness about 5,000 cm2/g and fly ash class 2 which has Blaine fineness about 3,000 cm2/g.

Table 5.1 Value of β_{WP},E_{WP},β_{SP},E_{SP} for blended powder of OPC and each of fly ash

	OPC+FA1	OPC+FA2
$\beta_{WP,75}$	0.5570	0.6719
$\beta_{WP,0}$	0.7796	0.7796
$E_{WP,75}$	0.4218	0.3547
$E_{WP,0}$	0.3079	0.3079
$\beta_{SP,75}$	0.5847	0.4592
$\beta_{SP,0}$	0.6030	0.6030
$E_{SP,75}$	0.0894	0.0702
$E_{SP,0}$	0.0922	0.0922

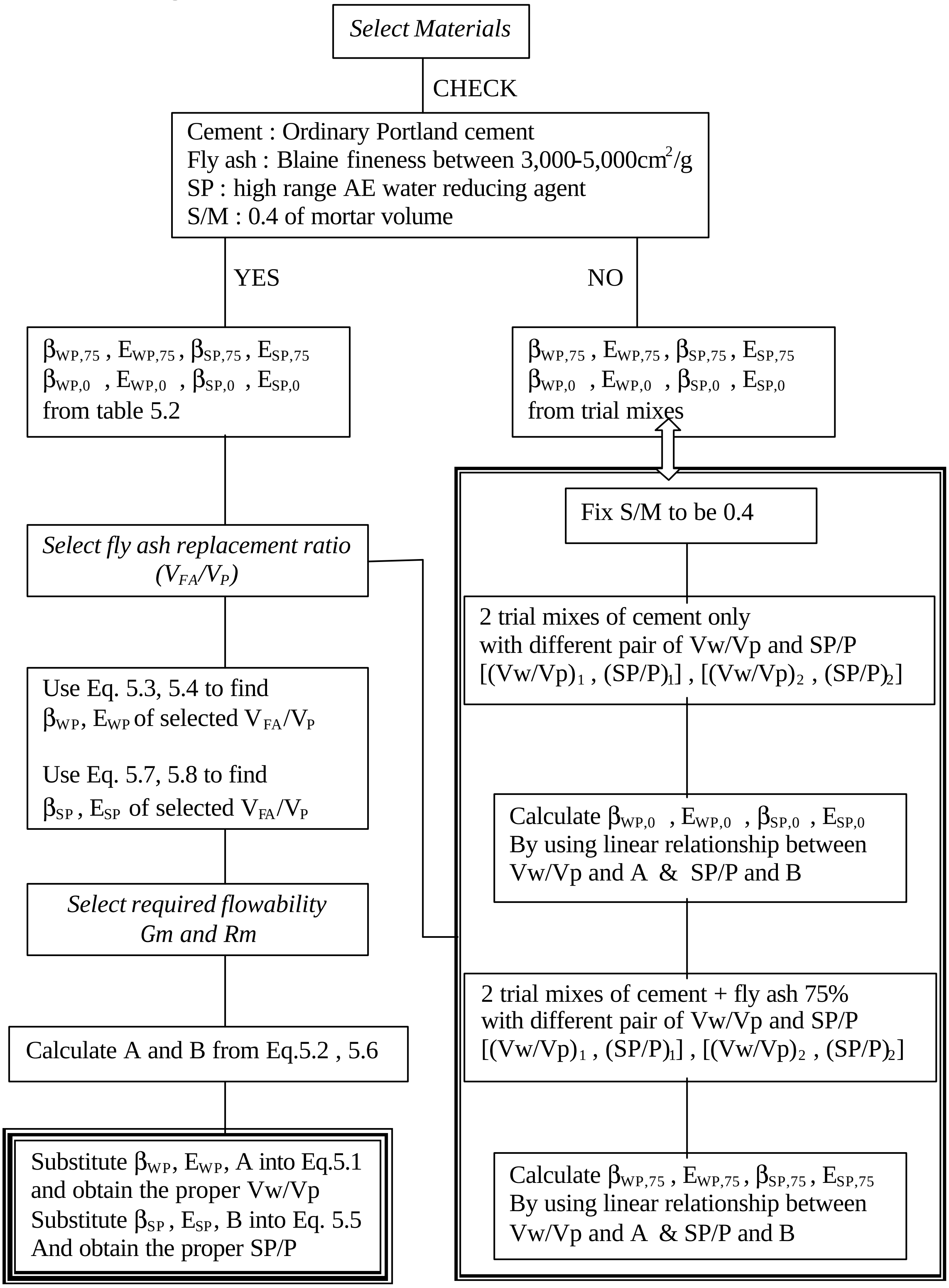
If assume that the blended powder of OPC and fly ash, which has fineness between 3,000-5,000 cm2/g, should have properties in between the properties of OPC:+FA1 and OPC+FA2. The β_{WP},E_{WP},β_{SP},E_{SP} values of fly ash may be obtained by linear interpolation of those of OPC+FA1 and OPC+FA2.

Table 5.2 Approximated value of β_{WP},E_{WP},β_{SP},E_{SP} for blended powder which has Blaine fineness in between 3,000 and 5,000 cm^2/g

	OPC+FA1	OPC+FA (3,000-5,000 cm^2/g)	OPC+FA2
$\beta_{WP,75}$	0.5570	"-4.56E5*(Blaine-3,000)+0.6719"	0.6719
$\beta_{WP,0}$	0.7796	0.7796	0.7796
$E_{WP,75}$	0.4218	"2.66E5*(Blaine-3,000)+0.3547"	0.3547
$E_{WP,0}$	0.3079	0.3079	0.3079
$\beta_{SP,75}$	0.5847	"4.98E5*(Blaine-3,000)+0.4592"	0.4592
$\beta_{SP,0}$	0.6030	0.6030	0.6030
$E_{SP,75}$	0.0894	"0.1529*$\beta_{SP,75}$"	0.0702
$E_{SP,0}$	0.0922	0.0922	0.0922

Anyway, these values are according to the case that use ordinary Portland cement as cement powder and use high range AE water reducing agent (polycarboxylate based agent) as superplasticizer. These values of β_{WP},E_{WP},β_{SP},E_{SP} may change due to changing of cement powder and superplasticizer. It is recommended to conduct the experiments in order to find out the value of β_{WP},E_{WP},β_{SP},E_{SP} that proper to the materials in use case by case.

5.4 Mix Design Method



CHAPTER 6
CONCLUSIONS

From the analysis of the experimental data, it can be concluded that:

1. Amount of retained water was reduced proportionally to the increasing of fly ash replacement ratio from 0 up to 0.75

2. Unit free water was increased proportionally to the increasing of fly ash replacement ratio from 0 up to 0.75

3. It was found that finer fly ash (fly ash class 1) provides stronger lubrication effect at any fly ash replacement ratio than the normal fly ash (fly ash class 2).

4. Effect of fly ash on deformability of mortar in low range water-powder ratio is greater than that in high range of water-powder ratio.

5. The unit dispersing SP dosage was reduced proportionally to the increasing of fly ash replacement ratio from 0 to 0.75

6. The retained SP dosage was reduced proportionally to the increasing of fly ash replacement ratio from 0 to 0.75

7.Totally 4 mixes, 2 from pure cement and 2 from binary mixes, are required to complete the chart represent all combination of those binary mixture.

REFERENCES

[1] Edamatsu, Y. , Yamaguchi, S. , and Okamura, H. , : "Effect of Powder Character on Paste Flow," Concrete Library of JSCE, No. 29, pp.249-264, 1997

[2] Edamatsu, Y. , Yamaguchi, S. , and Okamura, H. , : "Distinction Between Powder and Sand in Fresh Mortar," Concrete Library of JSCE, No.31,pp.347-369, 1998

[3] Neville, A.M. : "Properties of Concrete," Longman, pp. ,1981

[4] Okamura, H.,Maekawa, K., Ozawa, K., : "High Performance Concrete", Gihodo Shuppan, Tokyo, 1993 (in Japanese).

[5] Nawa, T., Izumi, T., Edamatsu, Y., : "State-of-the-art Report on Materials and Design of Self-Compacting Concrete", Proceedings of the International Workshop on Self-Compacting Concrete, pp.160-190, 1998

[6] Ouchi, M., : "History of Development and Applications of self-compacting Concrete in Japan", Proceedings of the International Workshop on Self-Compacting Concrete, pp.1-10, 1998

[7] Ouchi, M., : "State-of-art Report: Self-Compactability Evaluation for Mix-Proportion and Inspection.", Proceedings of the International Workshop on Self-Compacting Concrete, pp.111-120, 1998

[8] Okamura, H., and Ozawa, K. : "Mix-Design for Self-Compacting Concrete," Concrete Library International of JSCE, No.25, pp.107-120, 1995

[9] Ouchi, M. , Hibino, M. , Sugamata, T. , and Okamura, H. : "A Quantitative Evaluation Method for the Effect of Superplasticizer in Self-Compacting Concrete," Transactions of the Japan Concrete Institute, Vol.22, pp.15-20,2000

APPENDIX

Particle Size Distribution

Ordinary Portland Cement (OPC)

size(µm)	Cumulative (%)	size(µm)	Cumulative (%)	size(µm)	Cumulative (%)
0.04	0.08	5.30	27.60	46.00	98.46
0.10	0.90	5.60	28.79	50.00	99.47
0.25	3.48	6.00	30.29	53.00	99.83
0.40	5.28	6.50	32.07	56.00	100.00
0.50	6.08	7.00	33.73		
0.60	6.73	7.50	35.30		
0.70	7.29	8.00	36.81		
0.80	7.80	8.50	38.25		
0.90	8.27	9.00	39.64		
1.00	8.71	10.00	42.33		
1.10	9.14	11.00	44.91		
1.20	9.57	12.00	47.41		
1.30	9.98	13.00	49.81		
1.40	10.40	14.00	52.12		
1.50	10.82	15.00	54.36		
1.60	11.24	16.00	56.51		
1.70	11.67	17.00	58.58		
1.80	12.09	18.00	60.57		
2.00	12.95	19.00	62.49		
2.20	13.81	20.00	64.37		
2.40	14.69	21.50	67.17		
2.60	15.57	23.00	69.99		
2.80	16.47	24.50	72.85		
3.00	17.38	26.00	75.70		
3.20	18.30	28.00	79.36		
3.40	19.22	30.00	82.79		
3.60	20.14	32.00	85.93		
3.80	21.06	34.00	88.74		
4.00	21.98	36.00	91.19		
4.30	23.33	38.00	93.29		
4.60	24.66	40.00	95.05		
5.00	26.36	43.00	97.09		

Fly ash Class 2

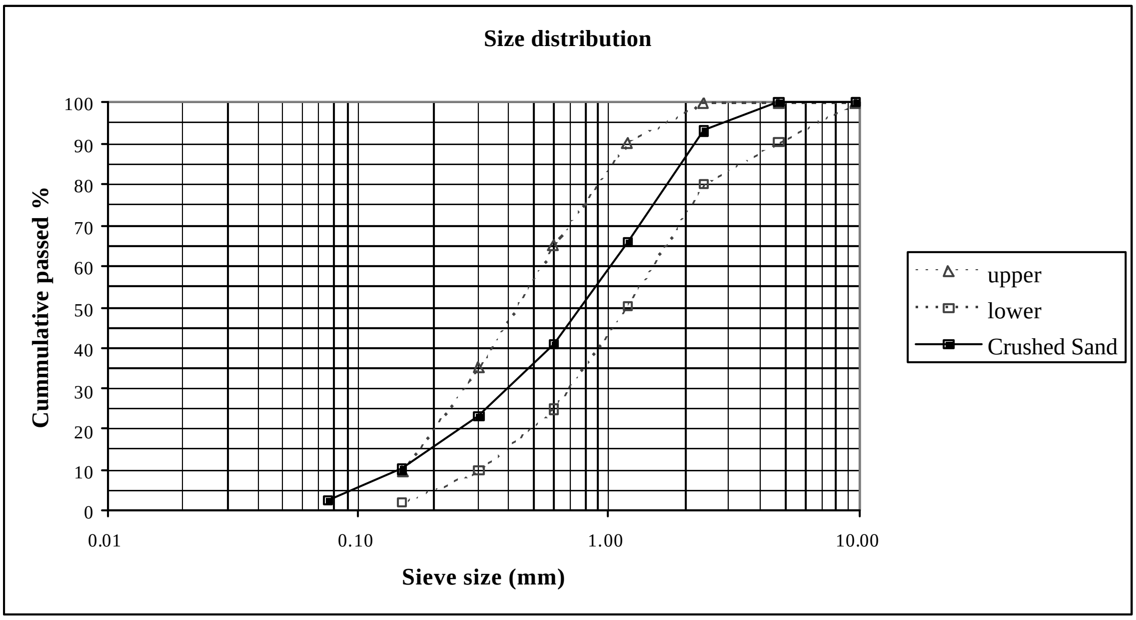
size(μm)	Cumulative (%)	size(μm)	Cumulative (%)	size(μm)	Cumulative (%)
0.04	0.04	5.30	21.79	46.00	82.73
0.10	0.53	5.60	22.71	50.00	85.34
0.25	2.02	6.00	23.92	53.00	87.08
0.40	3.09	6.50	25.40	56.00	88.65
0.50	3.66	7.00	26.84	60.00	90.49
0.60	4.17	7.50	28.25	63.00	91.70
0.70	4.66	8.00	29.61	66.00	92.78
0.80	5.13	8.50	30.94	70.00	94.04
0.90	5.60	9.00	32.23	75.00	95.37
1.00	6.07	10.00	34.69	80.00	96.45
1.10	6.53	11.00	37.01	85.00	97.33
1.20	6.99	12.00	39.20	90.00	98.03
1.30	7.44	13.00	41.27	95.00	98.57
1.40	7.89	14.00	43.24	100.00	98.99
1.50	8.34	15.00	45.14	110.00	99.54
1.60	8.78	16.00	46.97	120.00	99.82
1.70	9.21	17.00	48.75	130.00	99.95
1.80	9.65	18.00	50.48	140.00	100.00
2.00	10.49	19.00	52.16		
2.20	11.31	20.00	53.81		
2.40	12.11	21.50	56.22		
2.60	12.88	23.00	58.56		
2.80	13.62	24.50	60.81		
3.00	14.34	26.00	62.98		
3.20	15.03	28.00	65.71		
3.40	15.71	30.00	68.24		
3.60	16.37	32.00	70.56		
3.80	17.02	34.00	72.69		
4.00	17.67	36.00	74.67		
4.30	18.64	38.00	76.50		
4.60	19.59	40.00	78.21		
5.00	20.85	43.00	80.57		

Fly ash Class 1

size(μm)	Cumulative (%)	size(μm)	Cumulative (%)
0.04	0.00	5.30	53.73
0.10	0.15	5.60	56.15
0.25	0.76	6.00	58.47
0.40	2.27	6.50	61.36
0.50	3.77	7.00	64.66
0.60	4.58	7.50	67.66
0.70	5.65	8.00	70.39
0.80	7.11	8.50	72.89
0.90	8.91	9.00	75.19
1.00	10.82	10.00	77.34
1.10	12.70	11.00	81.34
1.20	14.49	12.00	85.07
1.30	16.18	13.00	88.40
1.40	17.77	14.00	91.24
1.50	19.28	15.00	93.59
1.60	20.71	16.00	95.47
1.70	22.06	17.00	96.92
1.80	23.35	18.00	98.00
2.00	24.56	19.00	98.77
2.20	26.80	20.00	99.29
2.40	28.84	21.50	99.63
2.60	30.74	23.00	99.89
2.80	32.56	24.50	100.00
3.00	34.35		
3.20	36.13		
3.40	37.90		
3.60	39.68		
3.80	41.47		
4.00	43.25		
4.30	45.04		
4.60	47.71		
5.00	50.34		

Properties of Sand

Sieve size	Retained weight	Percentage retained	Cumulative retained	Cumulative passed	JSCE	
(mm)	(g)	(%)	(%)	(%)	lower bound	upper bound
9.50	0.00	0.00	0.00	100.00	100.00	100.00
4.75	0.05	0.01	0.01	99.99	90.00	100.00
2.36	23.80	7.05	7.06	92.94	80.00	100.00
1.18	91.35	27.19	34.25	65.75	50.00	90.00
0.60	81.95	24.44	58.69	41.31	25.00	65.00
0.30	61.80	18.47	77.16	22.84	10.00	35.00
0.15	46.00	13.76	90.93	9.07	2.00	10.00
PAN	30.35	9.07	100.00	0.00		
Total	335.30	F.M. =	2.68			
		Gmax =	2.36			



Avg. Bulk Specific Gravity (Oven-Dry)	2.539
Avg. Bulk Specific Gravity (SSD)	2.582
Avg. Apparent Specific Gravity	2.653
Avg. Absorption (%)	1.695
Solid volume (%)	66.00

Mortar Experimental Results

Powder : Ordinary Portland Cement (OPC) , Fly ash Class 2 (FA2)
Note: BIxx means binary-mixture of OPC and FA2 which has volume of FA2 as xx% of total volume powder.

FA2 & [SP=0.0%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.66	0.0%	6.59	1.90
OPC	0.00	1.62	0.0%	6.00	1.69
OPC	0.00	1.60	0.0%	6.47	1.59
OPC	0.00	1.58	0.0%	5.41	1.51
OPC	0.00	1.54	0.0%	5.01	1.30
OPC	0.00	1.50	0.0%	4.21	1.01
OPC	0.00	1.40	0.0%	1.95	0.38
OPC	0.00	1.30	0.0%	0.00	0.00
OPC	0.00	1.20	0.0%	0.00	0.00
BI25	0.25	1.60	0.0%	7.42	2.45
BI25	0.25	1.50	0.0%	5.75	1.60
BI25	0.25	1.40	0.0%	3.72	0.99
BI25	0.25	1.36	0.0%	2.51	0.63
BI25	0.25	1.30	0.0%	1.63	0.27
BI50	0.50	1.60	0.0%	8.03	3.59
BI50	0.50	1.50	0.0%	7.45	2.67
BI50	0.50	1.40	0.0%	5.51	1.70
BI50	0.50	1.30	0.0%	3.28	0.86
BI75	0.75	1.50	0.0%	7.80	3.67
BI75	0.75	1.40	0.0%	6.67	2.48
BI75	0.75	1.30	0.0%	4.35	1.72
BI75	0.75	1.20	0.0%	2.59	0.72
FA	1.00	1.40	0.0%	7.43	4.63
FA	1.00	1.30	0.0%	6.83	3.37
FA	1.00	1.20	0.0%	5.23	2.36
FA	1.00	1.10	0.0%	3.10	1.27

FA2 & [SP=0.8%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.20	0.8%	3.69	7.64
OPC	0.00	1.10	0.8%	2.26	5.90
OPC	0.00	1.06	0.8%	1.66	4.92
OPC	0.00	1.00	0.8%	1.06	2.75
OPC	0.00	0.94	0.8%	0.00	0.07
OPC	0.00	0.90	0.8%	0.00	0.00
BI25	0.25	1.20	0.8%	4.37	9.03
BI25	0.25	1.10	0.8%	2.99	8.42
BI25	0.25	1.04	0.8%	1.66	6.16
BI25	0.25	1.00	0.8%	1.52	4.92
BI25	0.25	0.95	0.8%	1.01	3.16
BI25	0.25	0.90	0.8%	0.00	0.22
BI50	0.50	1.06	0.8%	2.64	8.82
BI50	0.50	1.00	0.8%	1.81	6.64
BI50	0.50	0.96	0.8%	1.41	5.42
BI50	0.50	0.90	0.8%	0.40	0.98
BI75	0.75	1.00	0.8%	2.58	9.71
BI75	0.75	0.94	0.8%	1.70	7.98
BI75	0.75	0.92	0.8%	1.53	6.91
BI75	0.75	0.90	0.8%	1.11	5.15
BI75	0.75	0.86	0.8%	0.64	3.15
FA	1.00	1.12	0.8%	4.47	3.08
FA	1.00	1.06	0.8%	3.17	2.19
FA	1.00	1.00	0.8%	2.02	1.17
FA	1.00	0.92	0.8%	0.00	0.00

FA2 & [SP=1.1%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.00	1.1%	1.59	7.70
OPC	0.00	0.98	1.1%	1.39	7.76
OPC	0.00	0.96	1.1%	1.22	6.99
OPC	0.00	0.92	1.1%	0.83	4.20
OPC	0.00	0.90	1.1%	0.27	1.44
BI25	0.25	0.90	1.1%	1.02	7.53
BI25	0.25	0.88	1.1%	0.92	7.12
BI25	0.25	0.86	1.1%	0.54	3.11
BI25	0.25	0.84	1.1%	0.16	1.68
BI50	0.50	0.90	1.1%	1.37	10.24
BI50	0.50	0.88	1.1%	1.24	9.89
BI50	0.50	0.86	1.1%	0.98	9.18
BI50	0.50	0.82	1.1%	0.49	6.31
BI75	0.75	0.88	1.1%	1.36	9.89
BI75	0.75	0.86	1.1%	1.34	10.22
BI75	0.75	0.84	1.1%	1.22	9.89
BI75	0.75	0.80	1.1%	0.75	8.92
BI75	0.75	0.78	1.1%	0.48	7.70
FA	1.00	1.28	1.1%	7.23	5.69
FA	1.00	1.24	1.1%	6.37	4.70
FA	1.00	1.18	1.1%	5.16	3.96
FA	1.00	1.04	1.1%	2.88	2.13
FA	1.00	1.00	1.1%	1.95	1.30
FA	1.00	0.96	1.1%	1.45	0.76
FA	1.00	0.92	1.1%	0.87	0.00

FA2 & [SP=1.4%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	0.92	1.4%	1.19	9.28
OPC	0.00	0.90	1.4%	0.99	8.53
OPC	0.00	0.88	1.4%	0.81	6.77
OPC	0.00	0.86	1.4%	0.36	3.22
OPC	0.00	0.84	1.4%	0.00	0.60
BI25	0.25	0.86	1.4%	1.04	10.18
BI25	0.25	0.84	1.4%	0.82	9.54
BI25	0.25	0.82	1.4%	0.62	7.24
BI25	0.25	0.80	1.4%	0.30	4.78
BI50	0.50	0.84	1.4%	1.19	10.70
BI50	0.50	0.82	1.4%	1.03	10.70
BI50	0.50	0.80	1.4%	0.82	10.36
BI50	0.50	0.78	1.4%	0.63	9.48
BI50	0.50	0.76	1.4%	0.25	7.68
BI75	0.75	0.84	1.4%	1.30	10.86
BI75	0.75	0.82	1.4%	1.15	10.67
BI75	0.75	0.80	1.4%	1.02	10.27
BI75	0.75	0.78	1.4%	0.74	10.11
BI75	0.75	0.76	1.4%	0.65	10.56
FA	1.00	1.20	1.4%	6.37	5.02
FA	1.00	1.10	1.4%	4.39	3.40
FA	1.00	1.00	1.4%	2.36	1.91
FA	1.00	0.90	1.4%	0.81	0.00

FA2 & [SP=1.7%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	0.90	1.7%	1.02	10.36
OPC	0.00	0.88	1.7%	1.09	10.58
OPC	0.00	0.84	1.7%	0.56	6.95
OPC	0.00	0.82	1.7%	0.20	4.03
BI25	0.25	0.88	1.7%	1.21	9.91
BI25	0.25	0.84	1.7%	1.10	10.74
BI25	0.25	0.80	1.7%	0.68	9.87
BI25	0.25	0.78	1.7%	0.42	8.45
BI50	0.50	0.84	1.7%	1.18	10.58
BI50	0.50	0.80	1.7%	0.96	10.38
BI50	0.50	0.76	1.7%	0.60	9.58
BI50	0.50	0.74	1.7%	0.30	9.30
BI75	0.75	0.82	1.7%	1.22	11.27
BI75	0.75	0.80	1.7%	1.07	10.74
BI75	0.75	0.76	1.7%	0.67	10.45
BI75	0.75	0.74	1.7%	0.55	9.82
FA	1.00	1.20	1.7%	6.22	4.95
FA	1.00	1.10	1.7%	4.04	3.30
FA	1.00	0.96	1.7%	1.44	0.80
FA	1.00	0.90	1.7%	0.63	0.00

Powder : Ordinary Portland Cement (OPC) , Fly ash Class 1 (FA1)
Note: BIxx means binary-mixture of OPC and FA1 which has volume of FA1 as xx% of total volume powder.

FA1 & [SP=0.0%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.66	0.0%	6.59	1.90
OPC	0.00	1.62	0.0%	6.00	1.69
OPC	0.00	1.60	0.0%	6.47	1.59
OPC	0.00	1.58	0.0%	5.41	1.51
OPC	0.00	1.54	0.0%	5.01	1.30
OPC	0.00	1.50	0.0%	4.21	1.01
OPC	0.00	1.40	0.0%	1.95	0.38
OPC	0.00	1.30	0.0%	0.00	0.00
OPC	0.00	1.20	0.0%	0.00	0.00
BI25	0.25	1.60	0.0%	7.03	2.10
BI25	0.25	1.50	0.0%	5.76	1.57
BI25	0.25	1.40	0.0%	3.55	0.99
BI25	0.25	1.30	0.0%	1.62	0.43
BI50	0.50	1.50	0.0%	6.68	1.78
BI50	0.50	1.40	0.0%	4.61	1.43
BI50	0.50	1.30	0.0%	2.22	0.77
BI50	0.50	1.20	0.0%	0.00	0.00
BI75	0.75	1.50	0.0%	6.79	2.11
BI75	0.75	1.40	0.0%	5.06	1.62
BI75	0.75	1.30	0.0%	2.28	0.90
BI75	0.75	1.24	0.0%	1.37	0.58
FA	1.00	1.40	0.0%	8.30	3.05
FA	1.00	1.30	0.0%	6.44	2.12
FA	1.00	1.20	0.0%	3.92	1.43
FA	1.00	1.10	0.0%	1.41	0.58

FA1 & [SP=0.8%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.20	0.8%	3.69	7.64
OPC	0.00	1.10	0.8%	2.26	5.90
OPC	0.00	1.06	0.8%	1.66	4.92
OPC	0.00	1.00	0.8%	1.06	2.75
OPC	0.00	0.94	0.8%	0.00	0.07
OPC	0.00	0.90	0.8%	0.00	0.00
BI25	0.25	1.06	0.8%	3.25	6.75
BI25	0.25	1.00	0.8%	2.15	4.94
BI25	0.25	0.94	0.8%	1.30	2.83
BI25	0.25	0.90	0.8%	0.73	1.74
BI50	0.50	1.10	0.8%	4.56	7.14
BI50	0.50	1.00	0.8%	2.53	5.47
BI50	0.50	0.94	0.8%	1.45	2.70
BI50	0.50	0.90	0.8%	0.73	1.31
BI75	0.75	1.10	0.8%	4.49	7.94
BI75	0.75	1.00	0.8%	2.23	4.86
BI75	0.75	0.94	0.8%	1.27	2.87
BI75	0.75	0.90	0.8%	1.03	2.46
FA	1.00	1.20	0.8%	6.99	5.35
FA	1.00	1.10	0.8%	4.77	3.75
FA	1.00	1.00	0.8%	2.78	2.50
FA	1.00	0.90	0.8%	0.64	0.29

FA1 & [SP=1.1%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	1.00	1.1%	1.59	7.70
OPC	0.00	0.98	1.1%	1.39	7.76
OPC	0.00	0.96	1.1%	1.22	6.99
OPC	0.00	0.92	1.1%	0.83	4.20
OPC	0.00	0.90	1.1%	0.27	1.44
BI25	0.25	1.00	1.1%	2.74	11.18
BI25	0.25	0.90	1.1%	1.60	8.86
BI25	0.25	0.86	1.1%	1.23	7.80
BI25	0.25	0.80	1.1%	0.58	3.69
BI50	0.50	0.90	1.1%	1.88	10.33
BI50	0.50	0.84	1.1%	1.33	10.02
BI50	0.50	0.80	1.1%	0.90	5.52
BI50	0.50	0.78	1.1%	0.61	2.43
BI50	0.50	0.74	1.1%	0.00	0.00
BI75	0.75	0.90	1.1%	1.78	11.25
BI75	0.75	0.84	1.1%	1.24	8.02
BI75	0.75	0.80	1.1%	0.79	4.40
BI75	0.75	0.78	1.1%	0.38	0.77
BI75	0.75	0.76	1.1%	0.00	0.00
FA	1.00	1.10	1.1%	5.82	5.20
FA	1.00	1.00	1.1%	3.32	3.62
FA	1.00	0.94	1.1%	1.78	2.11
FA	1.00	0.90	1.1%	0.96	1.04

FA1 & [SP=1.4%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	0.92	1.4%	1.19	9.28
OPC	0.00	0.90	1.4%	0.99	8.53
OPC	0.00	0.88	1.4%	0.81	6.77
OPC	0.00	0.86	1.4%	0.36	3.22
OPC	0.00	0.84	1.4%	0.00	0.60
BI25	0.25	0.90	1.4%	1.90	11.98
BI25	0.25	0.86	1.4%	1.44	11.48
BI25	0.25	0.80	1.4%	0.93	9.05
BI25	0.25	0.76	1.4%	0.60	6.06
BI50	0.50	0.80	1.4%	1.33	11.53
BI50	0.50	0.78	1.4%	1.11	10.09
BI50	0.50	0.74	1.4%	0.84	7.94
BI50	0.50	0.72	1.4%	0.62	5.10
BI75	0.75	0.80	1.4%	1.36	11.82
BI75	0.75	0.76	1.4%	1.13	9.82
BI75	0.75	0.74	1.4%	0.79	6.84
BI75	0.75	0.72	1.4%	0.74	5.27
FA	1.00	1.10	1.4%	6.41	6.00
FA	1.00	1.00	1.4%	4.00	4.52
FA	1.00	0.94	1.4%	2.20	3.04
FA	1.00	0.88	1.4%	1.02	1.34

FA1 & [SP=1.7%]

Powder	$V_{FA}/(V_C+V_{FA})$	$Vw/(V_C+V_{FA})$	SP Dosage	Relative funnel speed	Relative flow area
OPC	0.00	0.90	1.7%	1.02	10.36
OPC	0.00	0.88	1.7%	1.09	10.58
OPC	0.00	0.84	1.7%	0.56	6.95
OPC	0.00	0.82	1.7%	0.20	4.03
BI25	0.25	0.90	1.7%	1.90	11.67
BI25	0.25	0.80	1.7%	1.09	11.63
BI25	0.25	0.78	1.7%	0.98	11.48
BI25	0.25	0.74	1.7%	0.64	8.00
BI25	0.25	0.70	1.7%	0.00	2.23
BI50	0.50	0.84	1.7%	1.71	12.44
BI50	0.50	0.80	1.7%	1.42	12.40
BI50	0.50	0.74	1.7%	1.03	11.41
BI50	0.50	0.70	1.7%	0.85	9.71
BI75	0.75	0.80	1.7%	1.39	13.44
BI75	0.75	0.74	1.7%	1.27	11.96
BI75	0.75	0.70	1.7%	1.12	11.25
BI75	0.75	0.68	1.7%	0.29	8.53
FA	1.00	1.10	1.7%	5.90	5.95
FA	1.00	1.00	1.7%	3.30	4.70
FA	1.00	0.90	1.7%	1.38	2.41
FA	1.00	0.84	1.7%	0.48	0.29