A MODEL FOR PREDICTING WORKABILITY OF FRESH MORTAR AND CONCRETE

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Various parameters influencing consistency of fresh concrete and mortar and are utilized for predicting workability. Those parameters are ratio of paste volume to void content of densely compacted aggregate phase, free water content, surface area, shape and water retainability of aggregates and powder materials. It was found that slump of concrete varied linearly with free water, but non-linearly with other parameters. A mathematical model for predicting flow spread of mortar and slump of concrete was formulated and verified with the actual results. It was found that the model could be used for concretes and mortars made from various types of powder material, however, without chemical admixture with satisfy accuracy.

Key Words: workability, slump flow, particle shape, fineness, water retainability

1. INTRODUCTION

Generally, mix proportioning of concrete can be regarded as the process to select the proportion of different constituents to give the required properties of concrete. Nowadays, concrete may contain several types of cement, pozzolan, and powder material. One of the important properties of concrete is its workability in fresh state.

Workability means several properties of concrete, such as deformability, transportability, consolidation, ability to finish surface, or resistance to segregation. The slump test and flow table spread test are the popular methods for measurement of consistency and are usually used in mix design of the mixtures.

The traditional method for mix proportioning of fresh concrete is based on the process of trial mix, especially for concrete with various types of powder materials. It is beneficial if a consistency prediction model can be established to minimize the process of mix proportioning. According to the mentioned problems, this study will be useful for the development of mix proportioning method of concrete with various types of solid ingredients. It is noted here that the model proposed in this study is still applicable for mixtures without water reducer or superplasticizer whereas the effect of the mentioned admixtures will be studied in the future.

2. MODEL FORMULATION

Free water content had been verified to have relationship with deformability of various types of concrete[1), 2)]. It was also confirmed in this study that the relationship between free water content and slump of concrete was linear[3)]. The relationship between slump and free water content were plotted as shown in **Fig. 1**.

This paper considers only the initial slump or flow which are measured within 15 minutes after mixing, whereas environmental temperature is 28±2°C. In addition, this relationship is limited for no-segregation conventional concrete. It is not applicable for special concrete, such as self-compacting concrete, super workable concrete, and under water concrete with the use of viscosity agents.

A linear equation can then be introduced to relate slump with free water content as

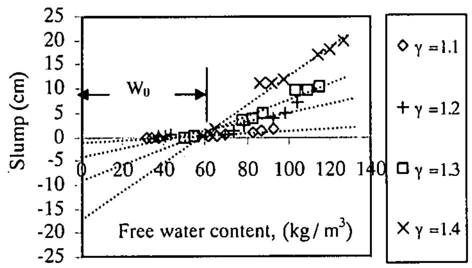

Fig. 1 Relationship between slump and free water content of fresh concrete

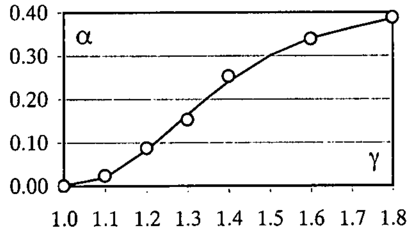

Fig. 2 Relationship between slope of slump-free water content curve (α) and ratio of paste volume to void content of compacted aggregate phase (γ)

$$SL = \alpha (W_{fr} - W_o) \quad (1)$$

where W_{fr} is volume of free water in the fresh concrete mixture (kg/m^3 of concrete), W_o is the minimum free water content required initiating slump (kg/m^3 of concrete), α is the slope of slump-free water content curve (cm/kg/m^3 of concrete), and SL is slump value of fresh concrete (cm.).

(1) Slope of slump-free water content curve

It was found from the author's studies that slopes of the slump-free water content curves increased with the increase of ratio between paste volume and void content of compacted aggregate phase (γ). It is noted here that some effect of aggregate properties are indirectly considered by γ, such as gradation and aspect ratio. The ràtio of paste volume to void content of compacted aggregate phase is defined as

$$\gamma = \frac{V_p}{V_{void}} \quad (2)$$

where V_p is the volume of paste in the unit volume (1 m^3) of fresh concrete and V_{void} is the volume of void in the densely compacted total aggregate (fine and coarse aggregate) in the unit bulk volume (1 m^3) of aggregate. The volume of paste can be derived as

$$V_p = V_c + V_w + V_{air} + V_{pow} \quad (3)$$

where V_c, V_w, V_{air} and V_{pow} are the volume of cement, water, air and other powder materials, respectively, in a unit volume (1 m^3) of concrete mixture

The relationship between slope of slump-free water content curve (α) and value of γ was found from the analysis of experimental data as shown in Eq. (4) and **Fig. 2**, and in the following equation.

$$\alpha = 3.57\gamma^4 - 21.34\gamma^3 - 46.74\gamma^2 - 43.92\gamma - 14.94 \quad (4)$$

3. FREE WATER CONTENT IN FRESH CONCRETE

Free water in this paper means the amount of water that is free, by any means, from being restricted by all solid particles in the fresh concrete and can be obtained from unit water content minus water retainability of powder materials and surface water retainability of aggregates as

$$W_{fr} = W_u - W_{rp} - W_{ra}' \quad (5)$$

where W_u is the unit water content in the mixture (kg/m^3 of concrete), W_{rp} is the restricted water by powder materials (kg/m^3 of concrete), and W_{ra}' is the restricted water at the surface of aggregates (kg/m^3 of concrete).

(1) Water retainability of powder materials

The total amount of restricted water by all powder materials can be derived from the summation of the product between the weight of each powder and its water retainability.

$$W_{rp} = \sum_{i=1}^{n} \beta_{pi} w_{pi} \quad (6)$$

where β_{pi} is the water retainability coefficient of powder material type i, w_{pi} is the absolutely dried weight of powder material type i (kg/m^3 of concrete), n is total number of powder materials used in the concrete.

a) Water retainability coefficient of powder

Water retainability is considered under the gravity effect. Since slump is the test condition under gravity. Water retainability of powder depends on many parameters, such as porosity, surface condition, shape, and size distribution of powder. Considering first the spherical powders, it is simply assumed that size and size distribution could be represented by specific surface area. Therefore, porosity is another parameter to be considered for water retainability of spherical powders. However, it is not easy to determine porosity of powder directly. Considering same type of powder, dense powder usually has higher specific gravity than porous powder. Therefore, specific gravity is adopted to represent porosity when considering similar type of powder.

Based on physical properties, It was found that restricted water on granular powder is greater than spherical powder. Therefore, angularity factor of powder is introduced to account for the effect of particle shape on water retainability.

Angularity factor is used to represents the ratio of the specific surface area of a certain size group of irregular particles to the specific surface area of the same size group of spheres is then applied to account for the irregularity of the particles including aggregates and powder. Loudon[4] found that angularity factor of a certain size group is related to the void content of particles as expressed by the following equation.

$$\psi = 1 + 4.44\,(\varepsilon - 0.42) \qquad (7)$$

where ε is the void content in a single size-group in the loose state of the solid particle. In this study, angularity factor is recommended as follows.

1. ψ = 1.0 for spherical materials, such as fly ash and silica fume.
2. ψ = 1.1 for rather spherical materials, such as river gravel and river sand.
3. ψ = 1.2 – 1.3 for semi-round or semi-granular powder and aggregate.
4. ψ = 1.4 for granular powder and aggregate, such as crushed limestone aggregate and powder, and ground blast furnace slag.

In addition, it was found that when powder is size-classified (powder having rather uniform size), it would be able to restrict more water than original powder. This is because amount of void of uniform-size powder is normally greater than well-distributed powder as well as non-classified powder. Classifying factor is then required for classified powder. The water retainability of powder is expressed as in the following equations. (Exaple of relationship are shown in **Fig. 3** and **Fig. 4**)

$$\beta_p = \xi_c\,\xi_s\,[(0.116\,Sp0.166) / (\rho p1.034)] \qquad (8)$$

$$\xi s = 1 + [0.056(S_p)^{0.35}]\,[\psi - 1] \qquad (9)$$

where β_p is the surface water retainability coefficient of powder, g/g of dried weight, ρ_p is specific gravity of powder, g/cm^3, S_p is specific surface area of powder, cm^2/kg, ψ is angularity factor, ξ_s is shape function of powder, ξ_c is a classifying factor, which is introduced to account for the effect of size classifying on water retainability coefficient of powder. In this paper, ξ_c is equal to 1.5 for powder that was made rather uniform size distribution (such as classified fly ash) and 1.0 for powder with normal size distribution.

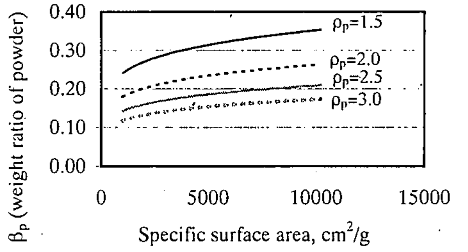

Fig. 3 Relationship between water retainability of ordinary spherical powder ($\xi_s = \xi_c = 1.0$) and specific surface area of powder with varied specific gravity

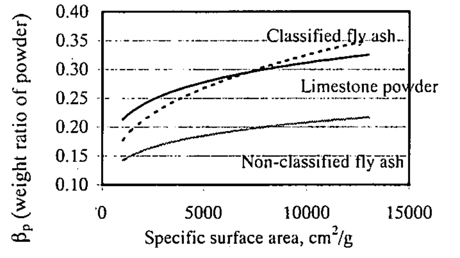

Fig. 4 Relationship between water retainability of several types of powder and their specific surface area at same specific gravity of 2.5

(2) Surface water retainability of aggregates

In mix design of concrete, unit water content does not include the absorption of aggregates. So the restricted water in addition to the absorbed water in the aggregate particles is considered here. The surface water retainability of aggregates can be expressed as

$$W_{ra}' = \beta_s'\,w_s' + \beta_g'\,w_g' \qquad (10)$$

where β_s', β_g' are the surface water retainability coefficients (excluding absorption) of fine and coarse aggregates, respectively, and w_s', w_g' are saturated surface dried weights of sand and gravel, respectively (kg/m^3 of concrete).

a) Water retainability coefficient of aggregates

An equation for calculating surface water retainability coefficient of aggregates was derived by back analysis of various slump test results using the slump prediction model proposed in this paper[3]. It was assumed that the water retainability of aggregates depends on irregularity and size of the particles so that specific surface area can be considered an appropriate parameter. The derived surface water retainability coefficient of aggregates including sand and gravel is as follow.

$$\beta_{agg}' = 2 \times 10^{-6}\,(S_{agg})^{0.9} \qquad (11)$$

where β_{agg}' is the surface water retainability coefficient (excluding absorption) of aggregate (g/g of SSD aggregate) and S_{agg} is specific surface area of aggregate (cm^2/kg). In practice, the water retainability of coarse aggregate can be neglected due to its small value when compared to that of the fine aggregate.

b) Determination of specific surface area of fine and coarse aggregates

In this study, a calculation method was used to compute surface area of aggregate by first assuming that the shape of aggregate particle is spherical. The specific surface area of aggregate on spherical shape basis can be calculated from the gradation as expressed in the following equation[3].

$$S_0 = \frac{6000}{D_{av} \times \rho} \quad (12)$$

where

$$D_{av} = \frac{\sum D_i M_i}{\sum M_i} \quad (13)$$

where S_0 is the specific surface area of aggregate on spherical shape basis (cm^2/g), D_{av} is the average diameter of the aggregate particles (cm), D_i is the average dimension between the upper sieve and the sieve i on which aggregate particles are retained (cm), M_i is the percentage of retaining on the corresponding sieve of the aggregate group i, (%), and ρ is the specific gravity of the aggregate.

Then angularity factor is applied to account for the irregularity of the particles. As the result, the specific surface area of irregular aggregate can be estimated by multiplying the angularity factor to the specific surface area of the assumed spherical aggregate, that is calculated from sieve analysis as

$$S_g = \psi_g \times S_{go} \quad (14)$$

$$S_s = \psi_s \times S_{so} \quad (15)$$

where S_s and S_g are the specific surface area of irregular fine and coarse aggregates, respectively (cm^2/g). ψ_s and ψ_g are the angularity factors of fine and coarse aggregates, respectively (obtained from Eq. (7)). S_{so} and S_{go} are the specific surface area of the assumed spherical fine and coarse aggregates, respectively (cm^2/g).

(3) Additional free water due to filling effect of fine powders

It was found in this study that if very fine powder is used in the concrete, some of these particles could fill in the voids among cement particles. This filling powder can drive away the water that is entrapped in those voids. This driven-out water is considered to increase the amount of free water. As the result, Eq. (5) for free water is modified by introducing the additional free water due to filling effect of fine powders (W_{aa}) as

$$W_{fr} = W_u - W_{rp} - W_{ra}' + W_{aa} \quad (16)$$

The volume of additional free water is equal to the volume of the fillable particles in the voids among cement as in Eq. (17) and the additional free water content in weight can be determined as in Eq. (18).

$$V_{aa} = V_{fill} \quad (17)$$

$$W_{aa} = V_{fill} \times \rho_w \quad (18)$$

where V_{aa} is volume of additional free water due to filling effect of fine powders (m^3 of concrete), V_{fill} is volume of the fillable particles in the voids among cement (m^3 of concrete), and ρ_w is specific gravity of water.

V_{fill} is assumed to be the function of solid volume of cement (V_c, m^3 of concrete) and a filling coefficient (F) by the assumption that higher cement content results in larger amount of voids for being filled by the finer powder. So,

$$V_{fill} = F \times V_c \quad (19)$$

a) Filling coefficient, F

It is reasonable to assume that finer filler particles are easier to fill the voids among cement particles and higher content of filler results in more filler particles to fill the voids. Consequently, the major parameters that affect this coefficient were assumed to be size of filler particles and size of cement particles, which are indirectly considered in this study as the ratio of specific surface area of the filling powder to that of cement and the amount of the filling powder, which is represented by replacement ratio (r).

However, the ability to fill of fine filler is considered different for spherical and non-spherical powders, i.e. for the same specific surface area of filling powders, spherical powder is easier to fill in voids among cement particles than non-spherical powder due to smaller size and interparticular friction. As the result, spherical powder should be more effective than the non-spherical powder when considering the same specific surface area. Therefore specific surface area ratio of filling powder to cement (R) was modified to be the normalized ratio of specific surface area of filling powder to surface area of cement (R') by a shape factor of powder (ψ) to take into account the effect of different particle shape.

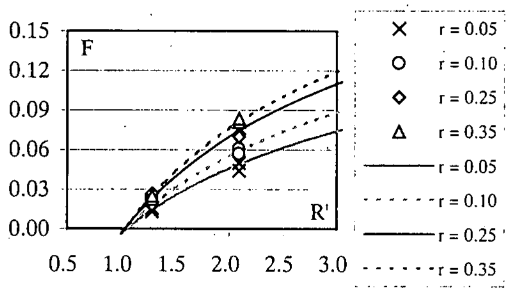

Fig. 5 Relationship between filling coefficient and ratio of specific surface area of filling powder to cement

$$R' = R\,(1.05 / \psi^{0.15}) \tag{20}$$

and
$$R = S_p / S_c \tag{21}$$

where S_p and S_c is the specific surface area of powder and cement, respectively (cm^2/g). ψ is angularity factor derived from Eq. (7).

The relationship between R′ and filling coefficient (F) with different replacement ratio (r) of the filling powder was derived from back analysis of test results of flow spread of mortar as shown in **Fig. 5**, and in the following equations.

$$F = 0.25 - 0.69 / \exp(R')^{a} \tag{22}$$

where
$$a = 0.6\,(r)^{0.25} \tag{23}$$

4. MINIMUM FREE WATER CONTENT REQUIRED TO INITIATE SLUMP (W_O)

It can be observed from **Fig. 1** that the amount of free water of the mixture below the point that the curve intercepts the free water content axis (W_0) does not produce slumps. This is considered that the amount of free water is not enough to overcome the interparticle surface forces, which include friction and cohesion among solid particles.

The interparticle surface forces vary with the numbers of feasible interparticle contact among the solid particles, and particles with larger surface area result in more contacts. As the result, the interparticle surface forces can be considered to vary with the surface area of the solid particles that have possibility to be in contact, which is defined in this study as effective surface area (S_{eff}, cm^2/m^3 of concrete). Then, the amount of water for balancing these interparticle surface forces (W_0) can be expressed as a function of S_{eff}.

It is well known that spherical fillers can reduce interparticular friction among larger particles, i.e. cement-to-cement, cement-to-aggregate, and aggregate-to-aggregate frictions. This effect is identified as lubrication effect in this paper. Lubrication is thought to reduce friction and therefore W_0. In this study, a lubrication coefficient (L) was introduced to account for lubrication effect of spherical-shape powder. The empirical equation for W_0 was derived as

$$W_0 = [8\times10^{-5}\,(S_{eff})^{0.76}] / L \tag{24}$$

(1) Effective surface area of solid particles

The effective surface area of solid particles indicates the possible contacts among the fine aggregates, coarse aggregate and powder. It was derived as in the following equation.

$$S_{eff} = S_{tagg} + \eta\,(S_{pow}) \tag{25}$$

$$S_{pow} = 1000 \sum_{i=1}^{n} S_{pi}\, w_{pi} \tag{26a}$$

$$S_{tagg} = 1000\,(S_s\, w_s + S_g\, w_g) \tag{26b}$$

where S_{tagg} and S_{pow} are surface area of total aggregates and total powder materials in concrete, respectively (cm^2/m^3 of concrete). w_s, w_g , and w_{pi} are the saturated surface dried weight of fine aggregate, coarse aggregate, and the absolutely dried weight of powder material type i, respectively (kg/m^3 of concrete). S_s, S_g, and S_{pi} are the specific surface area of fine aggregate, coarse aggregate, and powder material type i, respectively (cm^2/g). n is total number of powder materials used in the concrete. η is the effective contact area ratio indicating the ratio of surface area of powder materials, which is effectively contacting around aggregates, which was derived as

$$\eta = 0.026 e^{-3\times10^{-8}(S_{tagg})} \tag{27}$$

(2) Lubrication coefficient, L

The lubrication coefficient was formulated by back analysis of test results. The major parameters that affect this coefficient were considered to be the ratio of specific surface area of powder to specific surface area of cement and replacement ratio as in **Fig. 6.** This is because finer powders are more efficient than coarser powders in lubrication, and more amount of powder is also more effective. The shape factor, ψ, was introduced to incorporate the effect of particle shape on the lubrication effect by considering that granular particles will have no lubrication effect whereas spherical particles will have perfect lubrication. So, the equation for lubrication effect was derived as,

$$L = 1 + b\,R^{c}\,(1.4 - \psi) \tag{28}$$

where
$$b = 8.35\,r^2 - 0.24\,r + 0.19 \tag{29a}$$

$$c = -15.6\, r^2 + 6.0\, r + 0.5 \quad (29b)$$

where R is the ratio of specific surface area of powder to specific surface area of cement, ψ is angularity factor obtained from Eq. (7), and r is replacement ratio.

5. VERIFICATION

This model was verified by using test results of slump of fresh concrete and flow spread of mortar. For predicting flow spread of mortar, slump values were converted by a linear equation to flow spread values by the reasonable assumption that test results of slump of mortar and those of flow of the same mortar tested by a specific flow test method will have a unique relationship. The conversion equation is formulated by regression analysis of the relationship between test of flow table spread following ASTM 230-92 and computed slump from the model of several control mix proportions as in **Fig. 7**. For the flow between 150 to 250 millimeters, the conversion equation can be expressed as follow.

$$FTS = 14.6\, SL + 160 \quad (30)$$

where FTS is the value of flow table spread (millimeters) and SL is the value of computed slump (centimeters).

Test results were obtained from several studies[3), 5)] including those conducted by the authors for obtaining slump data of fresh concrete and flow spread data of mortar with varied replacement percentage of powder material, water to cementitious ratio and the ratio of paste volume to void content of compacted aggregate phase. It is noted here that all mixtures were without water reducers or superplasticizer. After verifying the accuracy of the model by comparing the predicted results from the model with the test results, it was found that the developed model can be used to predict the slump of fresh concrete and flow spread of mortar with a satisfactory accuracy as shown in **Fig. 8** and **Fig. 9**, respectively. The details of mix proportions and properties of powders used for verification of slumps and flow spreads are shown in **Table 1** and **Table 2**, respectively.

6. CONCLUSIONS

Based on the proposed model and verification tests, the following conclusions can be made.

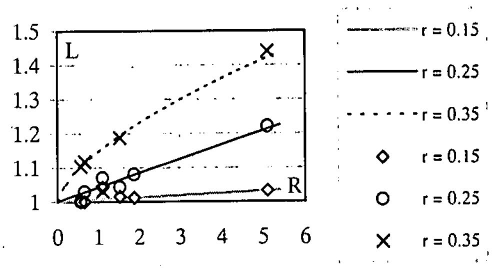

Fig. 6 Relationship between lubrication coefficient and ratio of specific surface area of powder to cement

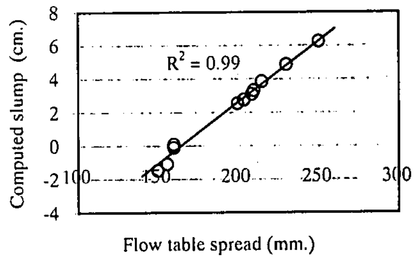

Fig. 7 Relationship between the tested flow table spread and computed slump of mortars

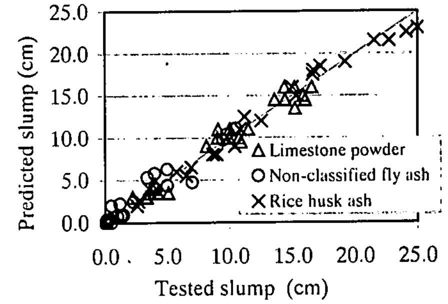

Fig. 8 Comparison between the predicted and tested slump of fresh concrete

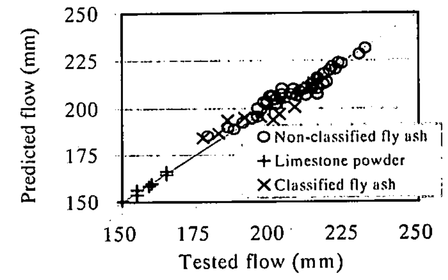

Fig. 9 Comparison between the predicted and tested flow spread of mortar

1. It was confirmed in this study that the slump of fresh concrete varied linearly with free water content in the mixture and found that slump varies nonlinearly with the ratio of paste volume to void content of aggregate phase.
2. Free water content could be obtained when knowing unit water content, water retainability

of powder materials and surface water retainability of aggregates, and the additional free water from fillable powder.
3. The amount of minimum free water required to initiate slump is considered to be the result of inter-particular surface forces among solid particles in the mixtures and then considered to be the function of the effective surface area of the solid particles in the mixture.
4. Filling effect of fine particles depends on the particle size, particle shape and its amount in the mixtures. More filling effect will be obtained when filling particles are smaller, spherical and larger in content.
5. Lubricating effect by fine spherical particles is considered to reduce the amount of minimum free water required to initiate slump.
6. The verification tests showed that this model could be used to predict slump of fresh concrete and flow of mortars, without chemical admixtures, with a satisfactory accuracy.

Table 1 Mix proportions, physical properties of powder, and verification of slump of concrete

Powder type	Fineness (cm^2/g)	Specific gravity	Cement (kg/m^3)	Powder (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	γ	Test (cm)	Computed (cm)	Error (cm)
Concrete replaced by limestone powders (LS1 and LS2)											
C	3200	3.14	275	0	165	1124	823	1.2	3.0	2.8	0.2
C	3200	3.14	323	0	194	1057	774	1.4	14.0	12.5	1.5
LS1	4100	2.67	343	18	181	1057	774	1.4	8.1	9.0	-0.9
LS1	4100	2.67	324	36	180	1057	774	1.4	9.1	11.0	-1.9
LS1	4100	2.67	305	54	180	1057	774	1.4	10.0	11.0	-1.0
LS1	4100	2.67	286	72	179	1057	774	1.4	10.9	9.5	1.4
LS1	4100	2.67	289	32	193	1057	774	1.4	14.4	14.5	-0.1
LS1	4100	2.67	272	48	192	1057	774	1.4	15.2	13.5	1.7
LS1	4100	2.67	306	16	193	1057	774	1.4	13.6	14.5	-0.9
LS1	4100	2.67	256	64	192	1057	774	1.4	16.0	14.5	1.5
LS2	6670	2.68	261	14	165	1124	823	1.2	3.4	3.0	0.4
LS2	6670	2.68	247	27	164	1124	823	1.2	3.6	3.5	0.1
LS2	6670	2.68	232	41	164	1124	823	1.2	3.8	4.0	-0.2
LS2	6670	2.68	218	54	163	1124	823	1.2	4.0	4.5	-0.5
LS2	6670	2.68	390	21	164	1057	774	1.4	2.2	3.0	-0.8
LS2	6670	2.68	369	41	164	1057	774	1.4	3.3	3.0	0.3
LS2	6670	2.68	347	61	163	1057	774	1.4	4.2	3.5	0.7
LS2	6670	2.68	326	81	163	1057	774	1.4	5.1	3.5	1.6
LS2	6670	2.68	343	18	181	1057	774	1.4	9.0	10.0	-1.0
LS2	6670	2.68	324	36	180	1057	774	1.4	10.0	10.0	0.0
LS2	6670	2.68	305	54	180	1057	774	1.4	10.8	10.0	0.8
LS2	6670	2.68	286	72	179	1057	774	1.4	11.5	11.0	0.5
LS2	6670	2.68	306	16	193	1057	774	1.4	14.4	16.0	-1.6
LS2	6670	2.68	289	32	193	1057	774	1.4	15.2	16.0	-0.8
LS2	6670	2.68	272	48	192	1057	774	1.4	15.9	15.0	0.9
LS2	6670	2.68	256	64	192	1057	774	1.4	16.5	16.0	0.5
Concrete replaced by non-classified fly ash (NF) of Kitticharoenkiat[3]											
C	3122	3.15	344	0	137	854	1128	1.10	0.0	0.0	0.0
NF	1824	1.90	221	95	126	854	1128	1.10	0.0	0.0	0.0
NF	1824	1.90	117	176	117	854	1128	1.10	0.0	0.0	0.0
C	3122	3.15	284	0	156	854	1128	1.10	0.4	0.4	0.0
NF	1824	1.90	186	80	146	854	1128	1.10	0.2	0.3	0.1
NF	1824	1.90	99	149	137	854	1128	1.10	0.1	0.3	0.2
C	3122	3.15	242	0	170	854	1128	1.10	1.5	0.9	-0.6
NF	1824	1.90	160	68	160	854	1128	1.10	1.3	0.8	-0.5
NF	1824	1.90	86	129	151	854	1128	1.10	1.0	0.7	-0.3
C	3122	3.15	376	0	150	827	1093	1.20	0.5	0.0	-0.5
NF	1824	1.90	242	104	138	827	1093	1.20	0.2	0.0	-0.2
NF	1824	1.90	128	192	128	827	1093	1.20	0.1	0.0	-0.1
C	3122	3.15	311	0	171	827	1093	1.20	2.3	2.5	0.2
NF	1824	1.90	203	87	160	827	1093	1.20	1.2	2.2	-1.0
NF	1824	1.90	109	163	149	827	1093	1.20	0.5	2.0	1.5
C	3122	3.15	265	0	186	827	1093	1.20	7.0	4.7	-2.3
NF	1824	1.90	175	75	175	827	1093	1.20	5.0	4.4	-0.6
NF	1824	1.90	94	142	165	827	1093	1.20	4.0	4.1	0.1
C	3122	3.15	409	0	163	800	1058	1.30	0.2	0.0	-0.2
NF	1824	1.90	263	113	150	800	1058	1.30	0.0	0.0	0.0

NF	1824	1.90	139	209	139	800	1058	1.30	0.0	0.0	0.0
C	3122	3.15	338	0	186	800	1058	1.30	5.0	6.3	1.3
NF	1824	1.90	221	95	173	800	1058	1.30	4.0	5.8	1.8
NF	1824	1.90	118	177	162	800	1058	1.30	3.4	5.3	1.9
C	3122	3.15	288	0	202	800	1058	1.30	10.5	11.1	0.6
NF	1824	1.90	190	81	190	800	1058	1.30	9.8	10.4	0.6
NF	1824	1.90	103	154	180	800	1058	1.30	9.5	9.7	0.2
Concrete replaced by rice husk ash (RHA) of Kitticharoenkiat[3]											
C	3122	3.15	350	0	210	727	1012	1.30	10.4	9.0	1.4
C	3122	3.15	350	0	228	708	986	1.35	16.7	18.0	-1.3
C	3122	3.15	350	0	245	690	960	1.40	24.1	22.5	1.6
RHA	8240	2.15	315	35	210	727	1012	1.30	8.7	8.0	0.7
RHA	8240	2.15	315	35	228	708	986	1.35	15.0	16.0	1.0
RHA	8240	2.15	315	35	245	690	960	1.40	21.5	21.5	0.0
RHA	8240	2.15	280	70	210	727	1012	1.30	5.7	6.0	-0.3
RHA	8240	2.15	280	70	228	708	986	1.35	10.9	11.0	-0.1
RHA	8240	2.15	280	70	245	690	960	1.40	17.2	18.5	-1.3
RHA	8240	2.15	280	70	263	671	934	1.45	25.0	23.0	2.0
RHA	8240	2.15	245	105	210	727	1012	1.30	2.7	2.5	0.2
RHA	8240	2.15	245	105	228	708	986	1.33	6.5	5.5	1.0
RHA	8240	2.15	245	105	245	690	960	1.36	11.2	12.5	-1.3
RHA	8240	2.15	245	105	263	671	934	1.39	16.6	17.5	-0.9
RHA	8240	2.15	245	105	280	652	908	1.42	22.7	21.5	1.2
RHA	8240	2.15	210	140	228	708	986	1.30	2.6	2.0	0.6
RHA	8240	2.15	210	140	245	690	960	1.35	6.9	6.5	0.4
RHA	8240	2.15	210	140	263	671	934	1.40	12.6	12.0	0.6
RHA	8240	2.15	210	140	280	652	908	1.45	19.2	19.0	0.2
RHA	8240	2.15	175	175	245	690	960	1.40	3.6	4.0	-0.4
RHA	8240	2.15	175	175	263	671	934	1.45	9.0	8.0	1.0
RHA	8240	2.15	175	175	280	652	908	1.50	15.3	15.0	0.3

Table 2 Mix proportions, physical properties of powder, and verification of flow spread of mortar

Powder type	Fineness (cm^2/g)	Specific gravity	Cement (kg/m^3)	Powder (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	γ	Test (mm)	Computed (mm)	Error (mm)
Mortar replaced by limestone powders (LS1 and LS2)										
C	3150	3.15	587	0	235	1477	1.2	159	158	-1
LS1	4100	2.67	372	200	229	1477	1.2	150	150	0
LS2	6670	2.68	372	200	229	1477	1.2	150	150	0
LS1	4100	2.67	432	144	230	1477	1.2	155	154	-1
LS2	6670	2.68	432	144	231	1477	1.2	155	156	1
LS1	4100	2.67	525	58	233	1477	1.2	160	160	0
LS2	6670	2.68	525	58	233	1477	1.2	165	165	0
LS1	4100	2.67	556	29	234	1477	1.2	160	160	0
LS2	6670	2.68	556	29	234	1477	1.2	165	166	1
C	3150	3.15	516	0	258	1477	1.2	209	208	-1
LS1	4100	2.67	327	176	252	1477	1.2	200	200	0
LS2	6670	2.68	327	176	252	1477	1.2	200	200	0
LS1	4100	2.67	380	127	253	1477	1.2	204	203	-1
LS2	6670	2.68	380	127	254	1477	1.2	205	206	1
LS1	4100	2.67	461	51	256	1477	1.2	209	208	-1
LS2	6670	2.68	461	51	256	1477	1.2	213	213	0
LS1	4100	2.67	488	26	257	1477	1.2	210	209	-1
LS2	6670	2.68	488	26	257	1477	1.2	215	215	0
Mortar replaced by classified fly ash (CF) and non-classified fly ash (NF)										
C	3150	3.15	450	0	225	1350	1.168	183	186	3
NF	4860	2.2	338	113	225	1350	1.192	186	194	8
CF	10180	2.43	337	112	225	1350	1.187	201	194	-7
CF	4790	2.29	337	112	225	1350	1.192	191	195	4
CF	2570	2.06	338	113	225	1350	1.202	0	0	0
NF	5510	2.47	338	113	225	1350	1.186	197	195	-2
CF	9670	2.62	337	112	225	1350	1.187	203	197	-6
CF	4600	2.52	337	112	225	1350	1.199	208	201	-7
CF	1820	2.42	337	112	225	1350	1.187	177	184	7
Mortar replaced by several types of non-classified fly ash (NF) of Yamamoto et al.[5]										
C	3190	3.10	450	0	225	1350	1.21	202	202	0

NF	3330	2.43	337	112	225	1350	1.21	219	214	-5
NF	2900	2.19	337	112	225	1350	1.20	209	206	-3
NF	4070	2.19	337	112	225	1350	1.24	230	228	-2
NF	4530	2.28	338	113	225	1350	1.24	232	232	0
NF	3160	2.17	338	113	225	1350	1.24	221	222	1
NF	4490	2.15	338	113	225	1350	1.19	201	206	5
NF	3910	2.12	337	112	225	1350	1.18	196	200	4
NF	3380	2.05	337	112	225	1350	1.15	179	185	6
NF	5000	2.32	337	112	225	1350	1.20	216	215	-1
NF	3030	2.23	337	112	225	1350	1.24	224	223	-1
NF	3670	2.08	338	113	225	1350	1.20	212	207	-5
NF	3230	2.21	337	112	225	1350	1.20	188	189	1
NF	3410	2.26	337	112	225	1350	1.19	199	204	5
NF	3850	2.30	338	113	225	1350	1.20	208	210	2
NF	2410	2.19	337	112	225	1350	1.19	199	203	4
NF	2350	2.18	337	112	225	1350	1.17	194	195	1
NF	4150	2.18	337	112	225	1350	1.16	191	192	1
NF	3500	2.18	337	112	225	1350	1.20	204	207	3
NF	4780	2.22	338	113	225	1350	1.15	186	190	4
NF	4020	2.27	338	113	225	1350	1.20	204	210	6
NF	3340	2.30	338	113	225	1350	1.21	218	213	-5
NF	2430	1.98	338	113	225	1350	1.20	202	205	3
NF	3670	2.10	338	113	225	1350	1.23	222	220	-2
NF	3290	2.26	337	112	225	1350	1.20	204	207	3
NF	3550	2.15	338	113	225	1350	1.19	198	203	5
NF	4000	2.29	337	112	225	1350	1.20	212	210	-2
NF	3220	2.23	337	112	225	1350	1.23	220	220	0
NF	3870	2.28	338	113	225	1350	1.23	223	224	1
NF	3380	2.24	337	112	225	1350	1.20	216	208	-8
NF	3950	2.14	337	112	225	1350	1.17	196	196	0
NF	4140	2.24	337	112	225	1350	1.20	216	210	-6
NF	3290	2.24	337	112	225	1350	1.20	216	207	-9
NF	3130	2.30	338	113	225	1350	1.20	207	207	0
NF	3690	2.12	337	112	225	1350	1.20	207	207	0
NF	3830	2.23	337	112	225	1350	1.20	210	209	-1
NF	4140	2.26	337	112	225	1350	1.20	214	210	-4

Notes: 1. C denotes the mixtures using cement only

2. Specific surface area of gravel and sand is 2.5 and 28 cm^2/g, respectively, and specific gravity of gravel and sand is 2.7 and 2.6, respectively in every mix proportions

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フレッシュコンクリート及びモルタルのワーカビリティー予測モデル

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フレッシュコンクリートのワーカビリティー予測には,ペースト・空隙体積比,自由水量,骨材及び粉体材料の比表面積,形状等の様々なパラメーターが用いられており,なかでもワーカビリティーの良い指標となるスランプは自由水量に比例し,その他のパラメーターとは非線形関係にあることが明らかにされている.本研究では,フレッシュコンクリートのスランプ及びモルタルのフロー予測の数学的モデルを構築し,実験値との比較検討を行った.その結果,減水剤等を用いない場合の,様々な粉体材料を用いたコンクリート及びモルタルに対し十分な精度を得られることを確認した.