Effects of Water-Reducing Admixtures on Initial Slump of Fresh Concrete

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Abstract

The aim of this paper is to present a model for predicting the slump of fresh concrete with the effect of water-reducing admixtures. Different brands and bases of water-reducing admixtures, which are available in market, exhibit different effectiveness on the slump of fresh concrete. To formulate a model with the effect of water-reducing admixtures, it is necessary to categorize their effectiveness. This paper introduces water-reducing efficiency (φ') as the indicator for the effectiveness and also the method for its determination. It was found that water-reducing admixtures increases the slope of slump-free water content curves, and reduces the water retainability coefficient and the effective surface area of the powder materials. Prediction models were formulated and the verifications of the proposed models with the actual test results showed satisfactory accuracy.

1. General Introduction

The traditional method of mix proportioning is based on the process of trial mixes and the number of trial mixes could be many. A consistency prediction model can minimize the process of mix proportioning by reducing the number of trial mixes.

Hanke [1] proposed a model to predict the flow of concrete and also presented a relationship between the concrete spread value and the free water content. Sam [2] found that the multivariate regression analysis (MRE) could be a suitable statistical tool for developing the prediction equation for workability. Kenneth [3] discussed the use of water-reducing admixtures as a solution to the problems associated with the use of low water/cement ratio.

Tangtermsirikul et al. [4,5] proposed a mathematical model for predicting the workability of fresh mortar and concrete just after mixing, based on the concept of water retainability and free water in fresh mixture. However, the effect of water-reducing admixtures was not considered. The use of water-reducing admixtures is general and the proposed workability prediction model will be incomplete if the effect of water-reducing admixtures is not included. This paper is therefore, an extension of their proposed model to include the effect of water-reducing admixtures.

2. Background of the Model

2.1 Initial model formulation

Ozawa et al. [6] verified that free water content has linear relationship with deformability of self-compacting concrete. Tangtermsirikul et al. [4,5] confirmed that the free water content also has a linear relationship with slump of normal concrete as shown in Fig. 1 and a linear equation was introduced to relate slump value with free water content as follows.

$$SL = \alpha_{SL} \cdot (W_{fr} - W_0) \quad (1)$$

where SL is slump value of fresh normal concrete (cm), α_{SL} is slope of slump-free water content curve (cm/kg/m^3 of concrete), W_{fr} is volume of free water in the fresh concrete mixture (kg/m^3 of concrete) and W_0 is minimum free water content required for initiating slump (kg/m^3 of concrete).

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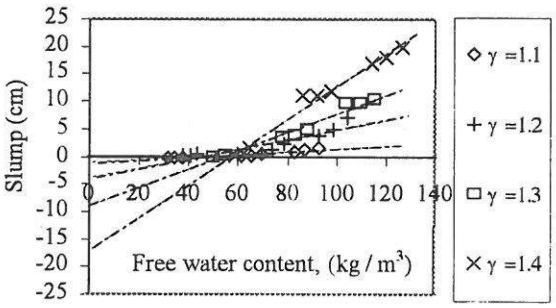

Fig. 1 Relationship between slump and free water content of fresh concrete

It was also found in their study [4,5] that the slope of slump-free water content curve increased with increase in the ratio of paste volume to volume of voids in the compacted aggregate phase (γ) as shown in Fig. 1 and Eq. (2).

$$\alpha_{SL} = \kappa \cdot \begin{pmatrix} 3.57 \cdot \gamma^4 - 21.34 \cdot \gamma^3 \\ + 46.74 \cdot \gamma^2 - 43.92 \cdot \gamma + 14.94 \end{pmatrix} \quad (2)$$

where κ is void content factor to take into account the effect of different void content in the compacted aggregate phase [10].

2.2 Free water content

Free water has been defined [4,5] as 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:

$$W_{fr} = W_u - W_{rp} - W_{ra'} \quad (3)$$

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

2.3 Water retainability of powder materials

According to Tangtermsirikul et al. [4,5], the water restricted by powder material includes water absorbed in powder particles and water retained on surface of powder particles. The total amount of water restricted by all powder materials can be obtained from Eq. (4).

$$W_{rp} = \sum_{i=1}^{n} \beta_{pi} . w_{pi} \quad (4)$$

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

The water retainability of cement and fly ash has been separately formulated as given by Eq. (5) for fly ash and Eq. (6) for cement.

$$\beta_p = 0.185 \, (\psi^{0.74} . S_p^{0.06} \xi_L) / \rho_p^{0.53} \quad (5)$$

$$\beta_p = 0.004 \, (\psi^{0.74} . S_p^{0.55} \xi_L) / \rho_p^{0.49} \quad (6)$$

where β_p is 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, and ξ_L is a coefficient indicating effect of loss on ignition on water retainability coefficient.

2.4 Surface water retainability of aggregates

The surface water retainability of aggregates can be computed from Eq. (7) [4,5].

$$W_{ra'} = \beta_{s'} w_{s'} + \beta_{g'} w_{g'} \quad (7)$$

where $\beta_{s'}$ and $\beta_{g'}$ are surface water retainability coefficients (excluding absorption) of fine and coarse aggregates, respectively, and $w_{s'}$ and $w_{g'}$ are saturated surface dry weights of fine and coarse aggregates, respectively (kg/m^3 of mix).

The surface water retainability coefficient of aggregates including sand and gravel has been derived as given by Eq. (8).

$$\beta_{agg'} = 2 \times 10^{-6} (S_{agg})^{0.9} \quad (8)$$

where $\beta_{agg'}$ is the surface water retainability coefficient (excluding absorption) of aggregates (g/g of SSD aggregate), and S_{agg} is specific surface area of the aggregate (cm^2/kg).

2.5 Additional free water due to filling effect of ultra-fine powders

It has been found that very fine powder particles could fill in the voids amongst cement particles and drive out water entrapped in these voids. This driven out water becomes available as additional free water and Eq. (3) for free water was modified to Eq. (9) [4].

$$W_{fr} = W_u - W_{rp} - W_{ra'} + W_{aa} \qquad (9)$$

where W_{aa} is additional free water due to filling effect of ultra-fine particles (kg/m^3 of concrete) [4].

2.6 Minimum free water content required for initiating slump (W_0)

The empirical equation for the amount of water required for balancing the inter-particle surface forces among the solid particles (W_0) has been derived as given by Eq. (10) [4,5].

$$W_0 = 8 \times 10^{-5} \cdot S_{eff}^{\ 0.76} / L \qquad (10)$$

where S_{eff} is effective surface area of solid particles (cm^2/m^3 of concrete) and L is lubrication coefficient to account for the lubrication effect of spherical shape powder particles [7,8].

The empirical equation for determining the lubrication coefficient has been derived as given by Eq. (11) [4].

$$L = 1 + (1.4 - \psi).(2.27\, r^{\,1.79})\, R^{(0.98 - 0.93\, r)} \qquad (11)$$

where R is ratio of specific surface area of the lubricating powder to cement, ψ is angularity factor of the lubricating powder and r is replacement ratio.

2.7 Effective surface area of solid particles

The effective surface area of solid particles has been defined as the surface area of solid particles that have the possibility to be in contacts and then produces resistance to the deformability of the fresh concrete mixture [4,5] and has been derived as:

$$S_{eff} = \eta_a.S_{ta} + 1000.\eta_p.\sum_{i=1}^{n} S_{pi}.w_{pi} \qquad (12)$$

where S_{ta} is surface area of total aggregates in the mixture (cm^2/m^3 of concrete), w_{pi} is absolutely dry weight of powder material type i (kg/m^3 of concrete), S_{pi} is specific surface area of powder material type i (cm^2/g), n is total number of kind of powder materials used in the mixture, and η_a and η_p are the effective contact area ratio of aggregate and powder, respectively.

3. Model Formulation on the Effect of Water-reducing Admixtures

3.1 General

Water-reducing admixtures are used in a concrete mix to reduce the water/cement ratio or water content while retaining the desired workability or alternatively to improve the workability at a given water/cement ratio [3,8].

Water-reducing admixtures are surface-active agents and are adsorbed on the powder particles giving them a negative charge, which leads to repulsion between the particles and results in stabilizing their dispersion. In addition, the charge causes the development, around each particle, of a sheath of oriented water molecules, which prevent a close approach of the particles to one another. Therefore, the particles have greater mobility and water freed from the restraining influence of the flocculated system becomes available to lubricate the mix so that the workability is increased [8].

Superplasticizers, also known as high-range water-reducing admixtures, are very high molecular weight polymers and more effective than normal water-reducing admixtures. The long molecules of the superplasticizers wrap themselves around the powder particles and give them a highly negative charge so that they repel each other [8].

There are different brands and bases of water-reducing admixtures and they have different effectiveness. To formulate a model with the effects of water-reducing admixtures, it is necessary to categorize their effectiveness. Water-reducing efficiency (φ′) is introduced as the indicator for the effectiveness.

The action of the water-reducing admixtures affects the slope of slump-free water content curves, water retainability coefficient and the effective surface area of the powder particles.

3.2 Water-reducing efficiency of the admixtures

A method for determining the water-reducing efficiency is introduced in this study. The water-reducing efficiency of the water-reducing admixtures is determined by using a metal mold in the form of a frustum of a cone with dimensions as follows: 40±3 mm inside diameter at the top, 90±3 mm inside diameter at the bottom and 75±3 mm in height.

A similar method for determining the water-reducing efficiency of an admixture has been described by Meyer and Perenchio [9] using the mini-slump technique that was developed by Kantro at the Portland Cement Association.

Cement paste, with a guessed value of water-cement ratio that would give a flow diameter of 180±5 mm, is placed in the mold. After filling, the mold is removed by raising it carefully in the vertical direction and the flow diameter is measured. The water-cement ratio is varied till the required flow diameter of 180±5 mm is obtained. This is firstly tested for obtaining the control mixture without water-reducing admixtures. Then for a 0.5% dosage of water-reducing admixture, the water-cement ratio is varied and the test repeated till the same flow diameter as that of the control mix is obtained.

The water-reducing efficiency (φ′) of the admixture is computed from Eq. (13) [10].

$$\varphi' = 1 - \frac{W_a}{W_0} \quad (13)$$

where W_o and W_a are quantity of water required to produce the required flow diameter without and with admixtures, respectively.

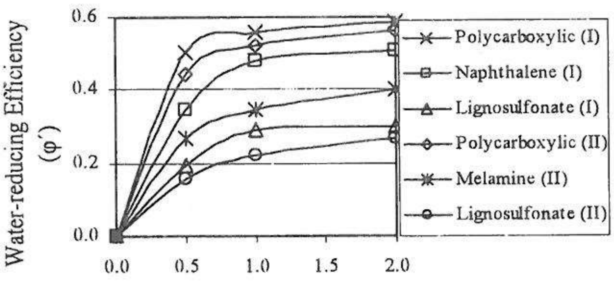

Fig. 2 Water reducing efficiency at various dosages of water-reducing admixture

The water-reducing efficiencies of the water-reducing admixtures from two different sources (denoted by I and II in Figs. 2, 3, 4, 5 and 6) are shown in Fig. 2.

3.3 Effect on slope of slump–free water content curve

The negative charge on the powder particles due to the water-reducing admixture causes repulsion between the particles and results in stabilizing their dispersion [8]. The deformation of the concrete during slump test, in this case, is considered to be due to an additional repulsive force in addition to the gravity force. Therefore, the particles gain greater mobility and the slope of the slump–free water content curve increases. A repulsion factor (ϕ_{rep}) is introduced to modify the slope of the slump–free water content curve (α_{SL}) given by Eq. (1) as shown in Eq. (14) [10].

$$SL = \phi_{rep}.\alpha_{SL}.(W_{fi} - W_o) \quad (14)$$

The repulsion factor is determined from the back analysis of the experimental data. It was found that lignosulfonate and naphthalene based water-reducing admixtures were less effective at lower water-binder ratio whereas polycarboxylic acid based water-reducing admixtures was more effective at lower water-binder ratio. This is considered to be due to the different nature of action of polycarboxylic based water-reducing admixtures from the lignosulfonate and naphthalene based water-reducing admixtures. Therefore, different equations are introduced from the analysis of the experimental data for the repulsion factor for lignosulfonate and naphthalene based water-reducing admixtures as given by Eq. (15) and for polycarboxylic acid based water-reducing admixture as given by Eq. (16).

$$\phi_{rep} = 1 + 83.9 \cdot \varphi^{0.5} \cdot \varphi'^{0.4} \cdot \gamma^{2.79} \cdot (w/b)^{4.9} \quad (15)$$

$$\phi_{rep} = 1 + 10.02 \cdot \exp\left(\frac{0.014}{(w/b)^{4.05}}\right) \cdot \left(1 - \frac{1}{\varphi^{9.43} \cdot \exp(53.6 \cdot \varphi)}\right) \cdot \varphi'^{2.23} \cdot \gamma^{2.96} \quad (16)$$

where φ is dosage of water-reducing admixture (% by weight of binder), φ' is water reducing-efficiency of admixture, γ is ratio of paste volume to volume of voids in the compacted aggregate phase and w/b is water to binder ratio.

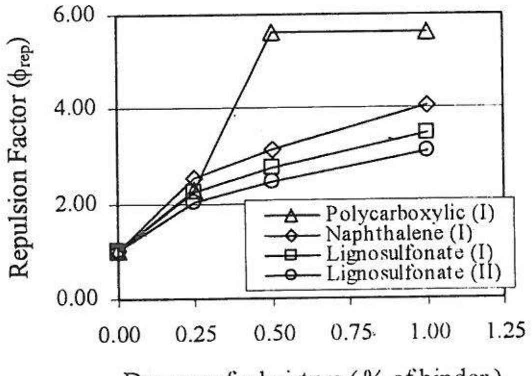

Fig. 3 Repulsion factors of water-reducing admixtures at various dosages

3.4 Effect on water retainability coefficient of cementitious materials

The negative charge on the powder particles, due to the water-reducing admixtures, causes repulsion between the particles and prevents the close approach of the particles to one another. The particles have a greater mobility and the water trapped in the flocculated system is freed, resulting in the reduction of water retainability of the powder materials.

A reduction factor (ϕ_{rb}) is introduced to incorporate the effect of water-reducing admixture on the water retainability of powder materials as given by Eq. (17) [10].

$$\beta_p' = \phi_{rb}\, \beta \quad (17)$$

where β_p' is water retainability coefficient of powder with application of water-reducing admixture and β_p is water retainability coefficient without application of water-reducing admixture.

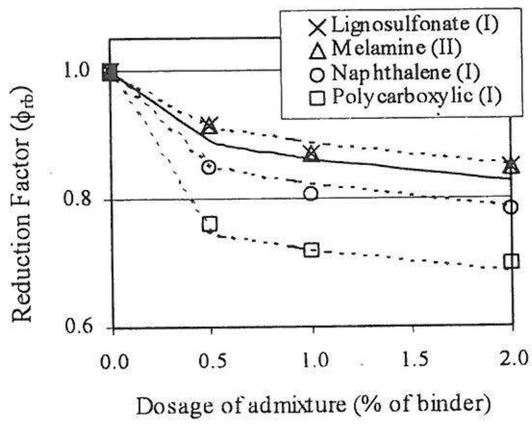

Fig. 4 Reduction factor for water retainability of cement

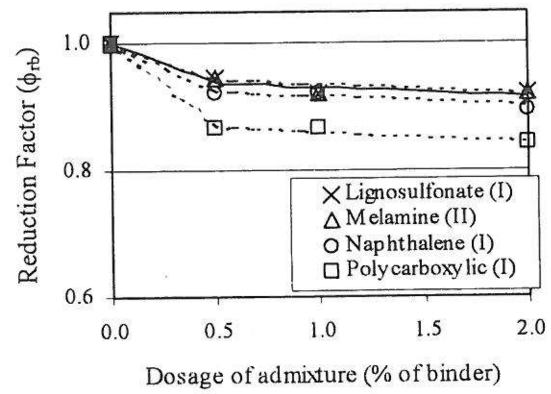

Fig. 5 Reduction factor for water retainability of fly ash

From the analysis of experimental results, it was found that the effect of water-reducing admixtures was more dominant on cement than on the fly ash. Therefore, the reduction factor (ϕ_{rb}) has been derived separately for cement type I as given by Eq. (18) and for fly ash I as given by Eq. (19) and as shown in Figs. 4 and 5, respectively.

$$\phi_{rb} = 1 - (0.08 + 0.73\ \varphi'^{\ 1.9})\ \varphi^{\ (0.51 - 0.69\ \varphi')} \quad (18)$$

$$\phi_{rb} = 1 - (0.06 + 0.75\ \varphi'^{3.3})\ \varphi^{\ (0.36 - 0.43\ \varphi')} \quad (19)$$

3.5 Effect on the effective surface area of powder particles

Since the powder particles are well dispersed and the close approach of the particles to one another is prevented when water-reducing admixtures are used, it results in the reduction of possible contacts among the particles. A reduction factor (ϕ_m) is therefore introduced in Eq. (12) to incorporate the reduction in the effective surface area as shown in Eq. (20) [10].

$$S_{eff}' = \eta_a.S_{ta} + 1000.\eta_p.\phi_m.\sum_{i=1}^{n} S_{pi}\, w_{pi} \quad (20)$$

where S_{eff}' is effective surface area with application of water-reducing admixture (cm^2/m^3 of concrete).

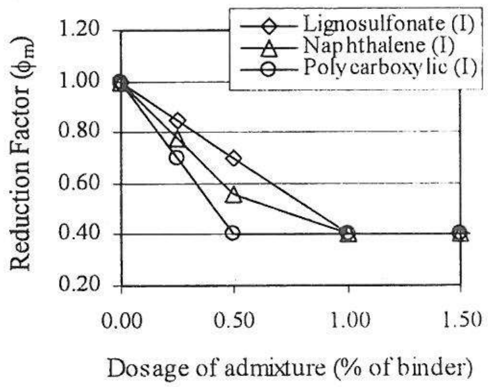

Fig. 6 Reduction factor for specific surface area

The reduction factor is considered applicable only to the effective surface area of powder particles as the repulsive force due to the negative charge is assumed to be inadequate to affect the aggregate particles. The reduction factor for effective surface area has been formulated from the analysis of experimental data as given in Eq. (21) and shown in Fig. 6.

$$\phi_m = 1 - (0.2 + 2\ \varphi')\ \varphi \quad \geq 0.4 \quad (21)$$

4. Verification Tests

Tests were conducted to obtain slump data by varying types of water-reducing admixtures and their dosages, water-binder ratio, ratio of volume of paste to volume of voids and replacement ratio of fly ash.

After verifying the accuracy of the prediction model by comparing the predicted slump values from the model with the test results, it was found that this model can be used to predict the initial slump of fresh concrete with water-reducing admixtures with satisfactory accuracy as shown in Fig. 7. However, the model still considers only the initial slump of conventional no-segregation concrete with water-reducing admixtures measured within 15 minutes after mixing at room temperature of 28±2 °C. The effect of temperature and slump loss will be published in the near future.

The details of properties of powder materials and mix proportions used for the verification are shown in Tables 1 and 2, respectively. Fly ash I and II were obtained from Mae Moh Power Plants at different times.

Table 1: Properties of cement and fly ashes

Chemical Composition by Weight (%)			
Compound	Cement	Fly ash I	Fly ash II
SiO_2	20.99	45.88	43.12
Al_2O_3	5.18	26.20	22.04
Fe_2O_3	3.20	10.94	9.78
CaO	64.63	8.28	12.55
MgO	1.30	2.83	3.09
SO_3	2.61	1.04	2.76
Na_2O	0.04	0.9	1.3
K_2O	0.40	2.78	5.22
TiO_2	0.25	0.51	-
P_2O_5	0.05	0.1	-
Physical Properties			
Specific Gravity	3.15	2.03	2.10
Loss on Ignition (%)	1.17	0.17	0.01
Blaine Fineness (cm^2/g)	3190	3460	2809

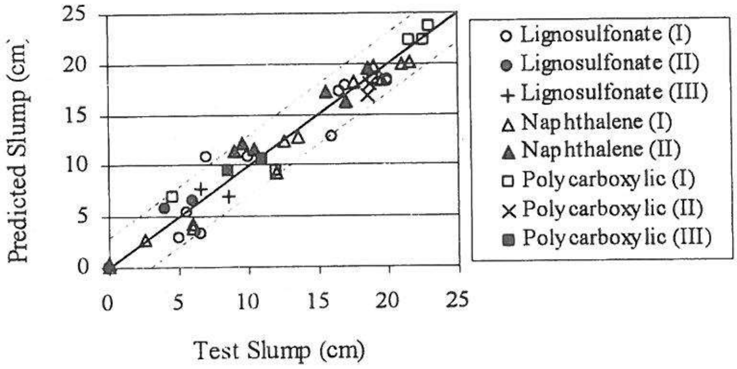

Fig. 7 Comparison of predicted and tested slump values of fresh concrete

5. Conclusions

The initial slump of fresh concrete increases with the application of water-reducing admixtures. The increase is considered to be due to increase in the slopes of slump-free water content curve (α_{SL}), reduction in the water retainability coefficient (β_p) and the reduction in the effective surface area of powder materials (S_{eff}).

The verification test proved that the proposed model could be used to predict the initial slump of fresh concrete with water-reducing admixtures with satisfactory accuracy.

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Mix	w/b	r (%)	γ	φ	φ'	Cement (kg/m³)	Fly Ash (kg/m³)	Water (kg/m³)	Gravel (kg/m³)	Sand (kg/m³)	TEST (cm)	Model (cm)
Lignosulfonate (I) (ASTM Type D) and Fly ash I												
1	0.30	0	1.2	0.50	0.20	450	0	135	1053	839	0.0	0.0
2	0.30	0	1.2	1.00	0.20	450	0	135	1053	839	0.0	0.0
3	0.40	0	1.2	0.50	0.20	387	0	155	1053	839	5.0	3.0
4	0.40	20	1.2	0.50	0.20	296	74	148	1053	839	6.5	3.3
5	0.50	0	1.2	0.25	0.20	340	0	170	1053	839	5.5	5.4
6	0.50	0	1.2	0.50	0.20	340	0	170	1053	839	7.0	10.9
7	0.50	0	1.2	1.00	0.20	340	0	170	1053	839	16.0	12.9
8	0.55	0	1.2	0.50	0.20	320	0	176	1053	839	17.0	17.9
9	0.55	20	1.2	0.50	0.20	246	62	169	1053	839	20.0	18.2
10	0.40	0	1.3	0.50	0.20	369	0	185	1018	811	16.5	17.2
11	0.40	20	1.4	0.25	0.20	347	87	173	982	783	10.0	10.9
12	0.40	20	1.4	0.50	0.20	347	87	173	982	783	20.0	18.3
Lignosulfonate (II) (ASTM Type D) and Fly ash II												
13	0.50	0	1.2	0.50	0.11	325	0	163	1071	854	4.0	5.9
14	0.50	30	1.2	0.50	0.11	215	92	154	1071	854	6.0	6.6
Lignosulfonate (III) (ASTM Type D) and Fly ash II												
15	0.50	0	1.2	0.50	0.13	325	0	163	1071	854	8.5	7.0
16	0.50	30	1.2	0.50	0.13	215	92	154	1071	854	6.5	7.7
Naphthalene (I) (ASTM Type F) and Fly ash I												
17	0.30	0	1.2	0.50	0.34	450	0	135	1053	839	0.0	0.0
18	0.30	0	1.2	1.00	0.34	450	0	135	1053	839	0.0	0.4
19	0.40	0	1.2	0.25	0.34	387	0	155	1053	839	2.5	2.8
20	0.40	0	1.2	0.50	0.34	387	0	155	1053	839	6.0	3.9
21	0.40	20	1.2	0.50	0.34	296	74	148	1053	839	6.0	4.2
22	0.50	0	1.2	0.25	0.34	340	0	170	1053	839	12.0	9.2
23	0.50	0	1.2	0.50	0.34	340	0	170	1053	839	12.5	12.4
24	0.50	0	1.2	0.75	0.34	340	0	170	1053	839	13.5	12.8
25	0.55	0	1.2	0.50	0.34	320	0	176	1053	839	19.0	19.8
26	0.55	20	1.2	0.50	0.34	246	62	169	1053	839	21.0	19.9
27	0.40	20	1.3	0.30	0.34	369	0	185	1018	811	17.5	18.2
28	0.40	20	1.4	0.30	0.34	347	87	173	982	783	19.5	18.4
29	0.40	20	1.4	0.50	0.34	347	87	173	982	783	21.5	20.1
Naphthalene (II) (ASTM Type F) and Fly ash II												
30	0.50	0	1.2	0.50	0.32	325	0	163	1071	854	9.0	11.5
31	0.50	30	1.2	0.50	0.32	215	92	154	1071	854	9.5	12.2
32	0.50	0	1.2	0.75	0.32	325	0	163	1071	854	10.4	11.6
33	0.50	0	1.2	1.00	0.32	325	0	163	1071	854	17.0	16.3
34	0.40	0	1.4	0.50	0.32	435	0	174	1003	799	15.5	17.3
35	0.40	30	1.4	0.50	0.32	285	122	163	1003	799	18.5	19.6
Polycarboxylic (I) (ASTM Type F) and Fly ash I												
36	0.30	0	1.2	0.50	0.50	450	0	135	1053	839	19.0	18.5
37	0.30	0	1.2	1.00	0.50	450	0	135	1053	839	23.0	23.6
38	0.40	0	1.2	0.50	0.50	387	0	155	1053	839	21.5	22.3
39	0.40	20	1.2	0.25	0.50	296	74	148	1053	839	4.5	7.0
40	0.40	20	1.2	0.50	0.50	296	74	148	1053	839	22.5	22.4
41	0.50	0	1.2	0.25	0.50	340	0	170	1053	839	12.0	9.5
42	0.50	20	1.2	0.25	0.50	261	65	163	1053	839	12.0	9.5
Polycarboxylic (II) (ASTM Type F) and Fly ash II												
43	0.40	0	1.2	0.50	0.47	371	0	148	1071	854	18.5	16.9
44	0.40	30	1.2	0.50	0.47	243	104	139	1071	854	18.7	18.0
Polycarboxylic (III) (ASTM Type F) and Fly ash type II												
45	0.40	0	1.2	0.50	0.38	371	0	148	1071	854	8.5	9.4
46	0.40	30	1.2	0.50	0.38	243	104	139	1071	854	11.0	10.6