研 究 速 報
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Effect of Water on the Energy Consumption During Mixing of Solid Particles
粉体混合時における練りまぜエネルギーに及ぼす水量の影響

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1. INTRODUCTION

Water is considered one of the most important constitutions of concrete. However, it should be understood that only adding water to concrete constitution does not produce a platic mix since there is no particulate motion equivalent to the molecular diffusion. The mechanical action so called mixing which all solid particles and water can be dispersed throughout the mixture is always necessary. It has already been reported by the authors[1)] that once water is added to the single material which average size is smaller than approximately 2.5 mm, the mixing energy can be enhanced due to the attractive force between particles. On the other hand, it can be reduced when water is added to the coarser particles. This paper presents the effect of water on the energy consumption during mixing of mixture of different materials at the different mix proportions. The relative workability, slump value, of mixture at different water content is also reported.

Table. 1 Properties of materials used in this study

Size (mm)	Coarse (G20)	Fine (sand)	Powder 1 (slag)	Powder 2 (cement)
15.0-20.0	20%	—	—	—
10.0-15.0	77%	—	—	—
5.0-10.0	3 %	—	—	—
2.5-5.0	—	20%	—	—
1.2-2.5	—	30%	—	—
0.6-1.2	—	20%	—	—
0.3-0.6	—	15%	—	—
0.15-0.3	—	7 %	—	—
<0.15	—	8 %	100%	100%
Blaine value (cm^2/g)	—	—	3940	3350
av. dia (mm)	10.15@	0.22@	0.00525*	0.00567*
Specific gravity	2.70	2.63	2.90	3.16
γ(%)	0.00	3.55	29.09	26.14
Absorption, α(%)	0.69	1.45	—	—
Water content. ω(%)	0.24	0.18	—	—

Notes: @ Calculated from the equation given by [2] as:

$$av.dia=\left(\frac{1}{\Sigma_{i=1}^{n} p_i d_i^{-3}}\right)^{1/3}$$

where p_i is solid volume fraction of the ith size group and d_i is (2/3) of the upper seive opening
* Calculated from "Blaine value"

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Table. 2 Mix proportion for mixture in this study

Mix no.	Coarse G20 (kg)	Fine sand (kg)	Powder 1 slag (kg)	Powder 2 cement (kg)
Mix 1	—	36.4	5.0	—
Mix 2	—	36.4	10.0	—
Mix 3	—	36.4	20.0	—
Mix 4	—	36.4	30.0	—
Mix 5	37.4	—	5.0	—
Mix 6	37.4	—	10.0	—
Mix 7	37.4	—	15.0	—
Mix 8	37.4	—	20.0	—
Mix 9	41.2	5.0	—	—
Mix 10	41.2	10.0	—	—
Mix 11	41.2	20.0	—	—
Mix 12	—	36.4	—	20.0
Mix 13	27.9	23.7	—	13.0

Note: Mixing volume is approximately 30 liters for all the cases

2. EXPERIMENTAL WORKS

All the experiments were carried out by a "Pan" type mixer which designed capacity is 50 liters and constant mixing speed as 74 rpm. All the experimental cases, mixing time was kept constant at 3 minutes. The properties of materials used are listed in Table 1. The coefficient of water retainability of each type of material (γ) is obtained from the test method proposed by Okamura et al[3]. All mix proportions of solid particles are given in Table 2.

The mixing energy is defined as the increment of the electrical power consumption during mixing from the electrical power required to drive the empty mixer. The mixer was loaded by the materials of a certain mix proportion and then mixed for 3 minutes to obtain the uniform distribution of solid particles before water was added. Different amount of water was added to simulate mixture with different water content. The slump test was performed for mix 3, mix 12 and mix 13 which represent slag mortar, cement mortar and concrete respectively.

3. RESULTS AND DISCUSSION

It has already been reported by the authors[4] that the electrical power consumed during mixing of solid particles in dry state depended not only on the type of mixture but also on mix proportion. For comparison, the electrical power consumed per unit solid volume of wet mix (E_w, Wh/1) was normallized by that required by dry mix (E_d, Wh/1) of the same solid mix proportion to obtain the non-dimensional factor so called "Energy factor, Q".

$$Q=\frac{E_w}{E_d} \qquad (1)$$

Water is always necessary in order to obtain the plastic or flowable mix. The plastic mix can not be obtained when amount of water in the mix is quite small. However, when amount of water exceeds a certain value so called water retained by solid particles, plastic mix can be developed. This water retained by solid particles can be divided into two types namely "water retained as solid phase" and "water retained as liquid phase"[5]. The water retained as solid phase is water absorbed by solid particles while the water retained as liquid phase consists of water retained by surface tension, trapped in agglomerated structure and retained by surface irregularity. The total water retained can be estimated from the summation of water retained by each phase as in the following:

$$W_{retained}=W_{retained,liquid}+W_{retained,solid} \qquad (2)$$

$$W_{retained}=\gamma_G W_G+\gamma_s W_s+\gamma_p W_p + (\alpha_G-\omega_G) W_G+(\alpha_s-\omega_s) W_s + (\alpha_p-\omega_p) W_p \qquad (3)$$

where

γ_G = coefficient of water retainability of coarse particles

γ_s = coefficient of water retainability of sand

γ_p = coefficient of water retainability of powder

W_G, W_s, W_p = weight of coarse particles, sand and powder in mixture respectively

$\alpha_G, \alpha_s, \alpha_p$ = absorption of coarse particles, sand and powder respectively

$\omega_G, \omega_s, \omega_p$ = water content of coarse particles, sand and powder respectively

Because of water which can be retained by coarse particles is very small and negligible, γ_G is taken as 0. For powder, due to their initially dry and their water absorption is much smaller than that retained on their surface, α_p and ω_p can also be neglected. For these reasons, equation (3) can be written as:

$$W_{retained}=\gamma_s W_s+\gamma_p W_p+(\alpha_G-\omega_G) W_G$$

$$+(\alpha_s-\omega_s)W_s \quad (4)$$

Consequently, free water which can be moved freely in mixture to produce the flowability and deformability of mixture can be estimated by subtracting the retained water from the total amount of water in mixture as:

$$W_{free}=W_{total}-W_{retained} \quad (5)$$

$$W_{free}=W_{total}-\gamma_s W_s-\gamma_p W_p-(\alpha_G-\omega_G)W_G -(\alpha_s-\omega_s)W_s \quad (6)$$

From the experimental results shown in Figs. 1 to 4, the "energy factor Q" were plotted against the amount of free water in mixture. It can be clearly seen that the mixing energy can be enhanced from the energy required in dry state when water is added to mixture. This enhancement can be observed greater in richer mix because cohesive strength provided by small particles is higher. For all the experimental cases, the maximum "energy factor, Q" can be obtained when almost no free water is available in mixture. In other words, amount of water in mixture is about the same as that retained by solid particles. However, this phenomenon can not be observed in mixture of G20+sand+water as shown in Fig. 3. The results show no tendency at all. This is mainly because solid particles can be easily segregated due to the inappropriate viscosity of mixture. From this observation, the crucial role of powder particles contribute to the segregation resistance of mixture[6] can also be confirmed since there is no powder available in this mixture.

Once amount of adding water is increased, the value of free water become larger than "O", the mixing energy can be significantly reduced and flowable mixture can be developed. This is mainly due to the reduction of cohesive strength because the interparticle distance can be increased, especially among powder particles. This decreases the resistance to movement of mixture.

As shown in Fig. 5, the slump value or relative workability of mixture can be increased linearly with the amount of free water. By least square method the following relation can be obtained:

$\text{Slump}=0.15\,W_{free}-4.4$ for Mix 13

$\text{Slump}=0.16\,W_{free}$ for Mix 12

$\text{Slump}=0.39\,W_{free}$ for Mix 3

where the unit of the slump is in centimeter and free

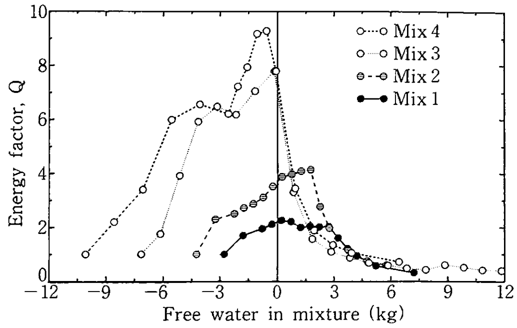

Fig. 1 Mixture of sand-slag-water

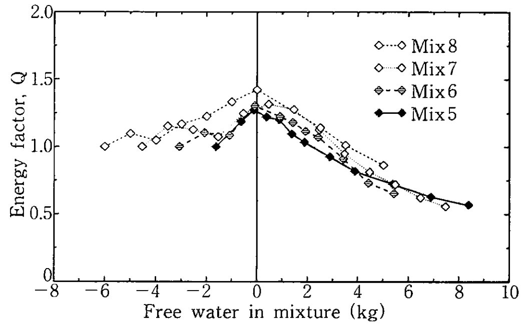

Fig. 2 Mixture of G20-slag-water

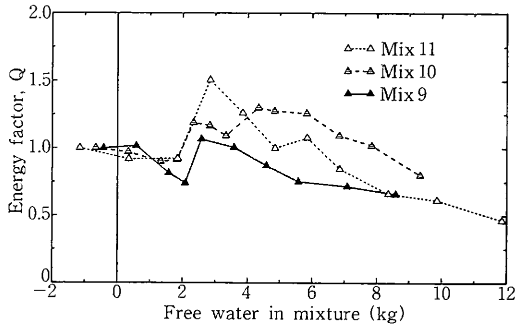

Fig. 3 Mixture of G20-sand-water

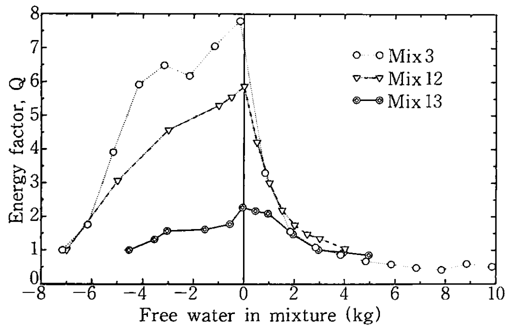

Fig. 4 Mixture of mortar and concrete

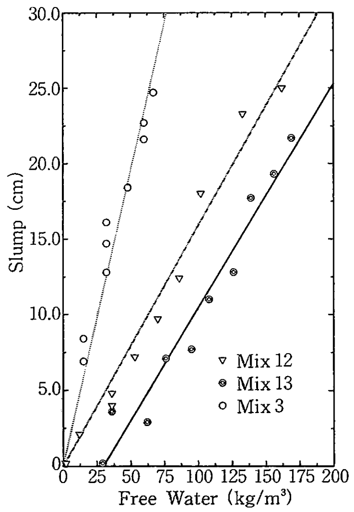

Fig. 5 Relation between free water and slump

water in *kg/m*^{3}

Although mix 3 and mix 12 contain the same solid proportion, relation between free water and slump are not the same. Nevertheless, the flowability for mix 12 and mix 13 are very similar. This is mainly attributed to the effect of powder particles since slag has been used for mix 3 while cement for mix 12 and mortar content in mix 13 is exactly the same as mortar in mix 12. From this observation, powder is believed to contribute greatly to the flowability of mixture.

4. CONCLUSIONS

1. The maximum mixing energy can be observed when no free water exist in mixture or amount of water in mixture is equal to the value which can be retained by solid particles.
2. The mixing energy can be significantly reduced and flowable mix can be developed by the existance of free water.
3. Relative workability of mixture, as indicated by slump value, can be increased linearly with amount of free water. Moreover, mortar and concrete are qualitatively the same.
4. Powder particles play important roles in order to prevent segregation and control the flowability of mixture.

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