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EFFECT OF POWDER CHARACTER ON PASTE FLOW

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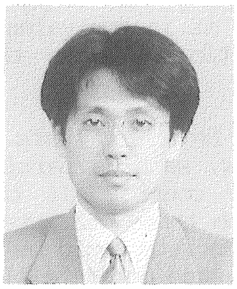
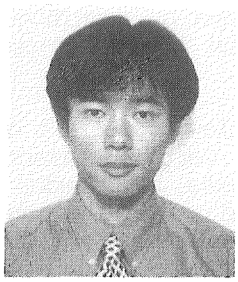
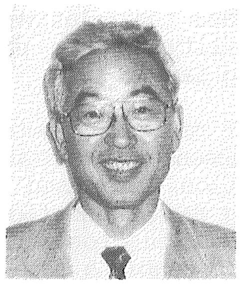


Yoshinobu EDAMATS



Kouji SHIMOKAWA



Hajime OKAMURA

The objective of this study is to propose a method for estimating water retaining factor and flow factor, which are powder properties that affect paste fluidity, from the particle size distribution, the particle shape, and the hydration properties of the cement. The results obtained are as follows. The water retaining factor is proportional to a product of an index representing particle size and an index representing the form of the particle size distribution, and the constant of proportionality represents the particle shape and hydration properties. The flow factor is proportional to the product of an index representing particle size and an index representing particle shape or the hydration properties, and a constant term represents the surface state of the powder assuming a proportionality constant to be invariant.

Key Words: *paste, powder, water retaining factor, flow factor particle size distribution, particle shape*

Yoshinobu EDAMATSU is a research engineer at the Cement/Concrete Research Laboratory of Sumitomo Osaka Cement CO., LTD., Osaka, Japan. His research interests include problems concerning mix design for self-compacting concrete. He is a member of the JSCE.

Kouji SHIMOKAWA is a research engineer at the Tsukuba Concrete Research Laboratory of Fujisawa Pharmaceutical CO., LTD., Ibaraki, Japan.

Hajime OKAMURA is a professor in the Department of Civil Engineering at the University of Tokyo, Tokyo, Japan. For the past twelve years he has studied self-compacting high-performance concrete. He is a Fellow of the JSCE.

1. Introduction

The powdered materials, such as cement and blast-furnace slag, contribute the smallest solid particles to concrete composite materials. It is well known that the size distribution and shape of these powder particles have an influence on concrete fluidity.

It has already been shown that the powder properties can be quantitatively represented by the water retaining factor or flow factor[1][2][3]. The water retaining factor is the maximum volumetric water-powder ratio at which the relative flow area of the paste remains 0, or the ratio at which the paste just begins to deform. The flow factor is the volumetric water-powder ratio required to increase the relative flow area by a unit quantity; it is equivalent to the deformability of the paste when the water-powder ratio is above the water retaining factor.

The water retaining factor and flow factor are obtained from flow tests on paste in the absence of vibration[1]. Certain characteristics, such as particle size distribution, are used as indexes for powder quality control. If the water retaining factor and flow factor could be estimated from these characteristics, powders suitable for self-compacting high-performance concrete could be produced. This would enable a more rational mix design system for such concrete[1].

The objective of this study is to propose a method for estimating water retaining factor and flow factor from powder characteristics. To this end, we clarify the relation between powder characteristics and water retaining factor and flow factor.

Incidentally, this study deals with general powders, so powders with particularly tiny particles, such as silica-fume, are not covered.

2. Characteristics of powders

Five moderate heat Portland cements of different brands and production lots, four limestone powders, two types of blast-furnace slag of different particle size distributions, and fly ash were used. These powders are used to produce self-compacting concrete. The particle-size distribution and particle shape of each powder is described below.

2.1 Particle size distribution

The particle size distribution of each powder is shown in Figs.1, 2, and 3. Measurements were made with a laser-diffraction measuring instrument which measures scatter; the Cilas1064 made by Cilas company. Methanol was used to disperse the powders, and dispersion was ensured by applying ultrasonic waves for 60 seconds before tasting measurements.

These figures were drawn from cumulative values of particle size distribution. The method used to plot them is described.

① Counted particle sizes are chosen at regular logarithmic intervals. Here, particle sizes is increased from 0.17 μm in logarithmic steps such that each size was double the previous one.

② The cumulative count at each particle size was obtained from the measurement value. Here, the cumulative count placing between two marching measurement

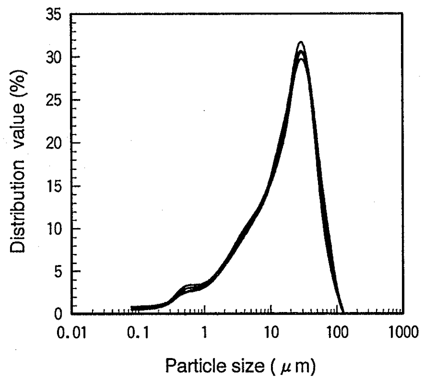


Fig.1 Particle size distribution (moderate heat Portland cement)

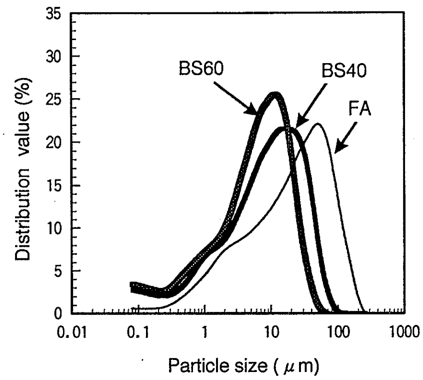


Fig.2 Particle size distribution (blast-furnace slag and fly ash)

values was obtained from a straight line approximation of two measurement values.

③ The value between marching particle sizes was calculated from the cumulative values.

④ The values were plotted in the figure, as the particle size is in logarithmic steps. Here, the particle size which corresponds to the value was central between marching particle sizes.

⑤ The two marching values are connected by the spline function[4].

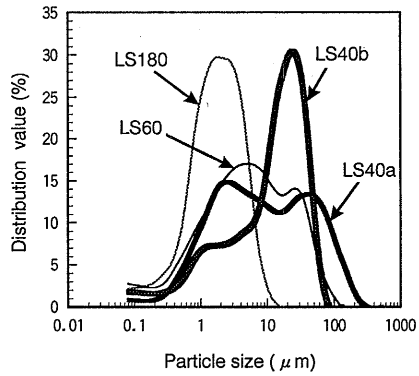


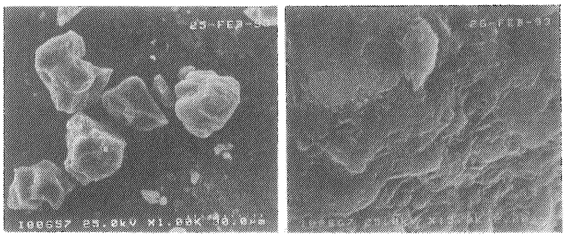
Fig.3 Particle size distribution (limestone powder)

Certain characteristics of these particle size distributions are discussed here. Despite different brands and production lots of these moderate heat Portland cement, the overall form of the particle size distributions do not differ. The peak occurs at about 30 μm. The gradient on the smaller particle size of the peak is gentle, but the other side is steep. These are hardly any particles coarser than 100 μm nor fine particles less than 0.1 μm.

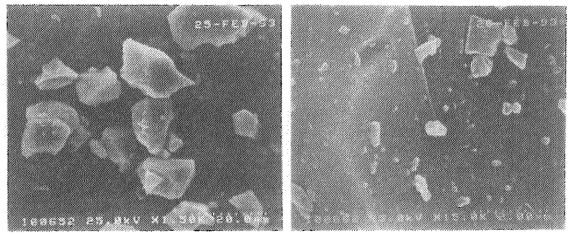
The distribution of blast-furnace slag is similar to that of moderate heat Portland cement, with only one peak. But because blast-furnace slag has its own fineness characteristics, the actual particle sizes are different. (The fineness of BS60 is 6,010 cm^2/g; and that of BS40 is 4,370 cm^2/g.) There are no coarse particles above 100 μm, but there are more fine particles less than 0.1 μm than in moderate heat Portland cement.

The form of the fly ash distribution is also similar to that of moderate heat Portland cement. The peak for fly ash is, however, larger than for the cement, at about 55 μm. Fly ash contains a lot of coarse particles larger than 100 μm.

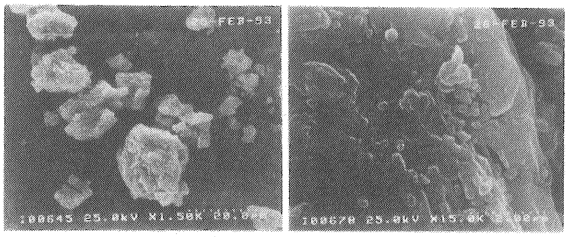
The limestone powders are of two characteristic types. One has only a single peak, as with the moderate heat Portland cement. The other has two peaks. This great difference in distribution results from differing production methods used for the different brands. Limestone powder can vary considerable in particle



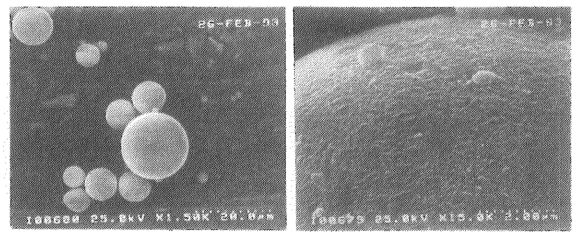
Phot.1 Particle shape
(moderate heat Portland cement)



Phot.3 Particle shape
(blast-furnace slag)



Phot.2 Particle shape
(limestone powder)



Phot.4 Particle shape
(fly ash)

size distribution even when the fineness is similar. On the other hand, the peak position may be different even when the form is similar. This result from a difference in fineness. (The fineness of LS40a is 4,660 cm^2/g; LS40b is 4,770 cm^2/g; LS60 is 6,440 cm^2/g; and LS180 is 18,000 cm^2/g.) Limestone powder contains fine particles down to less than 0.1 μm in larger quantities than in moderate heat Portland cement. LS40a contains a larger proportion of coarse particles more than 100 μm.

2.2 Particle shape

Typical photographs showing particle shape, as taken with an SEM, are shown in Phot.1, 2, 3, and 4.

Moderate heat Portland cement and limestone powder particles are extremely uneven polyhedrons, and the in surfaces are not very angular. Blast-furnace slag particles are more angular and sharper than those of other powders, and the in surface is irregular but smooth. Fly ash includes a lot of globular particles.

3. Basic equation of paste flow

A linear relation between the relative flow area (Eq.(1)) as calculated from the paste flow and the volumetric water-powder ratio has already been made clear[2][3]. The paste flow is given by the basic equation Eq.(2), and is determined by the flow factor and water retaining factor, both properties of the powder, and by the volumetric water-powder ratio. (Fig.4)

$$\Gamma p = \left(\frac{Fp}{100}\right)^2 - 1 \tag{1}$$

Table 1 Properties of powders

Type of powder		particle size factor (PF)	maximum value of particle size distribution (h)	distribution factor (HF)	shape factor (SF)	water retaining factor	
						Eq.(6)	test
moderate heat Portland cement	MC1	1.10	0.32	1.03	0.88	1.00	1.00
	MC2	1.11	0.31	1.01	0.86	0.96	0.96
	MC3	1.09	0.31	1.01	0.85	0.94	0.94
	MC4	1.09	0.30	0.99	0.92	0.99	0.99
	MC5	1.09	0.31	1.01	0.90	0.98	0.98
blast-furnace slag	BS40	1.24	0.22	0.85	0.91	0.95	0.97
	BS60	1.32	0.26	0.92		1.10	1.08
	BP1*1	1.30	0.25	0.91		1.07	1.07
	BP2*1	1.25	0.22	0.86		0.98	0.99
limestone powder	LS40a	1.20	0.15	0.70	0.84	0.71	0.67
	LS40b	1.31	0.31	1.01		0.99	0.87
	LS60	1.17	0.17	0.75		0.83	0.83
	LS180	1.54	0.30	0.99		1.29	1.49
	BP3*2	1.47	0.27	0.94		1.17	1.23
	BP4*2	1.27	0.18	0.77		0.82	0.78
fly ash		1.05	0.22	0.86	0.61	0.54	0.54

*1: BP1 and BP2 are blended powders in which BS40 was blended with BS60. The blending ratios are as follows: BP1, BS40:BS60=20:80; BP2, BS40:BS60=80:20.
*2: BP3 and BP4 are blended powders in which LS40a was blended with LS180. The blending ratios are as follows: BP3, LS40a:LS180=20:80; BP4, LS40a:LS180=80:20.

$$\frac{Vw}{Vp} = Ep \cdot \Gamma p + \beta p \qquad (2)$$

Where Γp is the relative flow area, Fp is the value of the paste flow (mm) in the absence of vibration, Vw is the volumetric ratio of water in the paste, Vp is the volumetric ratio of powder in the paste, Ep is the flow factor of the powder, and βp is the water retaining factor of the powder.

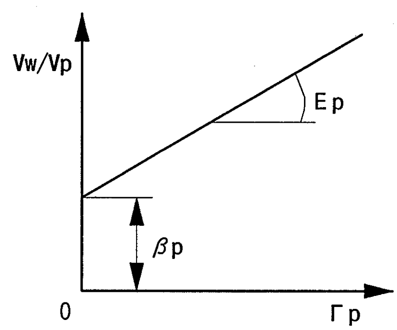


Fig.4 Basic equation of paste flow

The flow factor represents the degree of deformation of the paste after deforming it. The water retaining factor is the volumetric water-powder ratio when the paste begins to deform. Therefore, the amount of water needed to gain a certain relative flow area decreases with these factors. The smaller these factors are, the better properties of powders are evaluated.

4. Water retaining factor

The water retaining factor, which represents the volumetric water-powder ratio when the paste begins to deform, is a powder property that affects paste fluidity; it differs with the type of powder as shown in Table 1. Therefore, the differences of the water retaining factor with the characteristics of powders are considered.

It is generally accepted that the characteristics of the particle size distribution of a powder influence the fluidity of a paste made with that powder. With similar powders, of equal fineness, the fluidity of the pastes is influenced by the form of the particle size distribution. On the other hand, if the distribution is equal, the fluidity is influenced by powder fineness. That is, the fluidity of pastes made with similar powders is influenced by the average diameter of the particles and the form of the particle size distribution[5]. Thus, the characteristics of the particle size distribution can be represented numerically, allowing the relation between the water retaining factor and these characteristics to be clarified.

A number of functions to represent the characteristics of particle size distribution have been proposed. In this study, to simplify the calculations, the particle size factor shown in Eq.(3) was used.

$$PF = \int p(x) \cdot pf_0(x)\,dx \tag{3}$$

$$pf_0(x) = 1.65 - 0.5\mathrm{Log}(x) \quad (pf0(x) \geqq 0) \tag{4}$$

Where PF is the particle size factor, pf0(x) is the standard particle size factor, p(x) is the particle size distribution curve, and x is the particle size (μm).

The particle size factor can be calculated by integrating the standard particle size factor (Eq.(4), Fig.5), and the particle size distribution curve as described above in "2. Characteristics of powders." This factor is equivalent to powder fineness. The particle size factors of the powders are shown in Table 1. Particle size factor increases with falling particle size.

A standard particle size factor was developed as follows. Water retention has a close relation with the fineness, since the water is retained on the surface of powder particles or sand particles. Fineness is in inverse proportion to particle size, as the solid line in Fig.6 shows. When the particle size is small, however, it appears larger as a result of cohesion[6]. Therefore, the relation between particle size and fineness is shown by the dotted line in Fig.6.

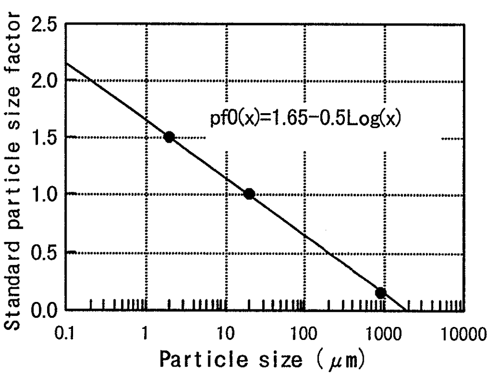


Fig.5 Relation between particle size and standard particle size factor

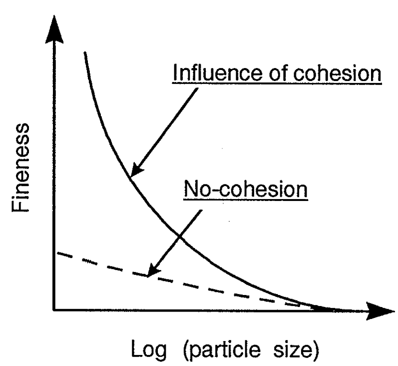


Fig.6 Relation between particle size and fineness

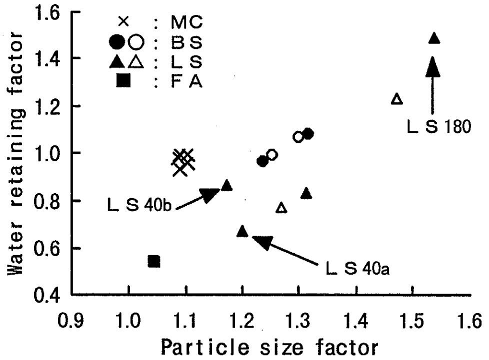


Fig.7 Relation between particle size factor and water retaining factor

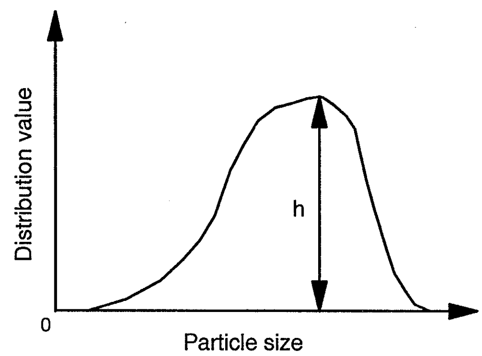


Fig.8 Maximum value of particle size distribution

Thus, as a first approximation, the relation between the logarithm of particle size and fineness was made proportional. The constant proportionality and the constant in Eq.(4) were set up such that the straight line goes through certain points as shown in Fig.5. These points were plotted from the average particle size of moderate heat Portland cement, limestone powder (LS180), and Fuji river sand, taking the water retaining factors as standard particle size factors. The particle size distributions of these powders were of analogous form. Because of representing equally the fineness of powder by the value blaine, these water retaining factors, which had a close relation with the fineness, was substituted for blaine. For the particle sizes greater than 2,000 μm, the standard particle size factor was set to 0. The reason for this was that the restraint among such particles was strong, the apparent water retaining factor due to this restraint was greater than the water retention of the particle surface.

Figure 7 shows the relation between particle size factor and water retaining factor. The water retaining factor increases with particle size factor, or with decreasing particle size. Even though the particle size factors of limestone powders LS40a and LS40b are approximately equal, their water retaining factors are very different. As shown in Fig.3, this results from a difference in the form of the particle size distribution. Incidentally, the open symbols in Fig.7 represent blended powders consisting of BS40 with BS60 as well as LS40a with LS180. Open symbols represent these blended powders throughout this text. The blending ratios are shown in the notation of Table 1.

To represent the form of the particle size distribution, the maximum value on the particle size distribution curve, as shown in Fig.8, was used. The maximum value for each powder is shown in Table 1. It decreases with increasing width of the particle size distribution.

Figure 9 shows the relation between maximum value of particle size distribution and water retaining factor. The water retaining factor increases with the maximum value of particle size distribution, or decreasing width of the distribution. Even though the maximum values for LS40a and LS40b are approximately equal, their water retaining factors are very different. This is caused by the very different the particle size factors of these powders, as shown in Fig.7. Thus, the water retaining factor is influenced by the average particle size and also the form of the particle size distribution.

Therefore, if the multiple of the particle size factor and the distribution

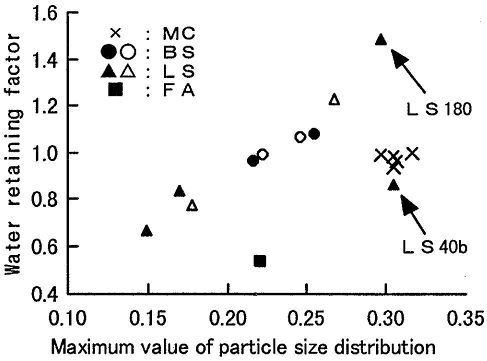


Fig.9 Relation between maximum value of particle size distribution and water retaining factor

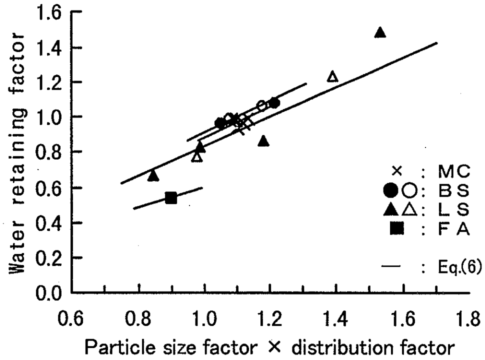


Fig.10 Relation between characteristic of particle size distribution and water retaining factor

factor is treated as a property of the particle size distribution, it is proportional to the water retaining factor in the case of the same material, as shown in Fig.10. Here, the distribution factor is the square root of a quotient which is divided the maximum value of the particle size distribution by 0.3, which is the same as for moderate heat Portland cement (Eq.(5), Table 1). The distribution factor is a relative index for comparing the particle size distribution of moderate heat Portland cement, as the standard powder, with that of another powder. The proportional relation between the property of particle size distribution and the water retaining factor is shown by Eq.(6), and the calculated constant of proportionality for each powder is given in Table 1.

$$HF=\sqrt{\frac{h}{0.3}} \tag{5}$$

$$\beta p = SF \cdot PF \cdot HF \tag{6}$$

Where HF is the distribution factor, h is the maximum value of particle size distribution, β p is the water retaining factor of the powder, PF is the particle size factor, and SF is the shape factor.

The constant of proportionality differs with the type of powder, and represents the particle shape and the powder's degree of activation. Accordingly, it is defined as the shape factor of a powder. The shape factor of fly ash, which has a spherical shape, is small, while that of blast-furnace slag, which has an angular shape, is large. Though the particle shape and the surface state of moderate heat Portland cement are similar to those of limestone powder, its shape factor is larger. This is a result of the greater surface area and the consumption of water by the hydration of ettringite. Because the degree of hydration differs, however, with the amount of C_3A or gypsum, and with the form of the gypsum, in the moderate heat Portland cement, the shape factor varies.

Figure 11 shows the relation between the particle size distribution and the water retaining factor of powders in which moderate heat Portland cement has been blended with admixtures: blast-furnace slag, limestone powder, and fly ash. The water retaining factors of these powders are shown in Table 2. The

Table 2 Properties of blended powders

Type of powder	volumetric ratio of admixture to blended powder	particle size factor (PF)	maximum value of particle size distribution (h)	distribution factor (HF)	shape factor (SF)	water retaining factor		
						Eq.(8)	test	test/Eq.(8)
blast-furnace slag	0.2	1.13	0.28	0.97	0.87	0.96	0.96	1.00
	0.6	1.18	0.24	0.90	0.92	0.97	0.99	1.02
	0.8	1.21	0.23	0.87	0.97	0.97	1.02	1.05
	1.0	1.24	0.22	0.85	0.92	0.97	0.97	1.00
limestone powder	0.2	1.12	0.27	0.95	0.86	0.91	0.92	1.02
	0.6	1.16	0.20	0.82	0.86	0.79	0.81	1.03
	0.8	1.18	0.17	0.74	0.88	0.73	0.78	1.06
	1.0	1.20	0.15	0.70	0.79	0.67	0.67	1.00
fly ash	0.2	1.09	0.28	0.97	0.82	0.88	0.88	1.00
	0.6	1.07	0.24	0.89	0.75	0.71	0.72	1.01
	0.8	1.06	0.22	0.86	0.70	0.63	0.64	1.02
	1.0	1.05	0.22	0.86	0.61	0.54	0.54	1.00
moderate heat Portland cement (MC2)		1.11	0.31	1.01	0.86	0.96	0.96	1.00

admixtures were blended in volumetric ratios of 0.2, 0.6, or 0.8 to the blended powder (Eq.(7)).

$$\gamma ad = \frac{Vad}{Vad + Vc} \qquad (7)$$

Where γad is the volumetric ratio of admixture to blended powder, Vc is the volumetric ratio of moderate heat Portland cement, and Vad is the volumetric ratio of the admixture.

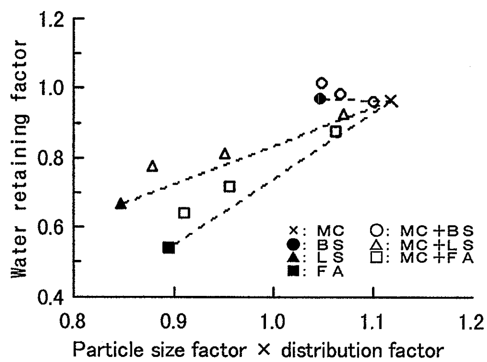


Fig.11 Relation between characteristic of particle size distribution and water retaining factor (blended powder with two types of powder)

The particle size factor of the blended powder is proportional to the volumetric ratio of admixture to blended powder. The distribution factor, however, falls below a straight line connecting moderate heat Portland cement and the admixture, as shown in Fig.12. This means that the characteristics of the particle size distribution are improved by blending.

In Fig.12, the point where the volumetric ratio of admixture to blended powder is 0 is the value for moderate heat Portland cement, while where it is 1 represents the value for the admixture. Therefore, the water retaining factor of blended powder in Fig.11 should fall bellow a dashed line connecting moderate heat portland cement and admixture. In fact, however, the water retaining factor is above the value plotted on the dashed line. This is caused by an increase in the hydration speed of moderate heat Portland cement as more admixture is added.

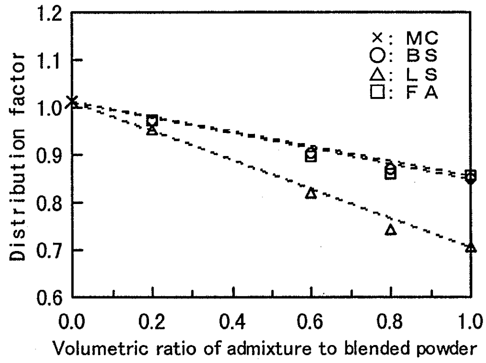


Fig.12 Relation between volumetric ratio of admixture to blended powder and distribution factor

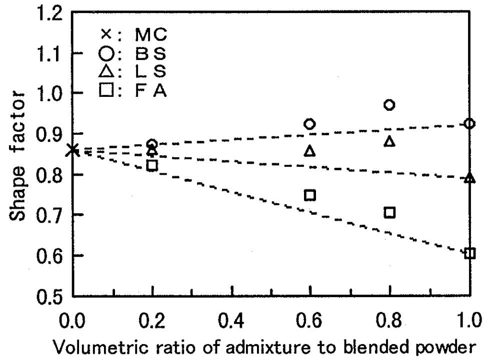


Fig.13 Relation between volumetric ratio of admixture to blended powder and shape factor

Generally, when ordinary Portland cement has been blended with blast-furnace slag, fly ash, or limestone powder, the hydration speed of the cement is assumed to decrease. However, the hydration of interstitial materials in the cement during mixing, or within a few minutes of adding the water, accelerates[7][8].

Therefore, the shape factor of a blended powder calculated by Eq.(6) is bigger than the value plotted on a straight line connecting the shape factors of the two powders, as shown in Fig.13. It is assumed that the difference between the two values increases with the volumetric ratio of admixture to blended powder, since the hydration speed of moderate heat Portland cement increases with the volumetric ratio of admixture.

In order to calculate the water retaining factor for a blended powder by Eq.(6), when blast-furnace slag, limestone powder, or fly ash is used as the admixture, the shape factor of moderate heat Portland cement needs to be set appropriately, according to the volumetric ratio of the admixture.

When moderate heat Portland cement is blended with another powder, the water retaining factor of the admixture remains constant whatever the volumetric ratio of the admixture, as shown in Fig.14. Therefore, the volumetric ratio of admixture to blended powder should be proportional to the volumetric ratio of water to blended powder, namely the water retaining factor of the blended powder.

As shown in Fig.15, however, the water retaining factor is higher than the values falling on a straight line connecting the two water retaining factors. As mentioned, this results from the influence of the admixture on the hydration rate of moderate heat Portland cement. When fly ash is

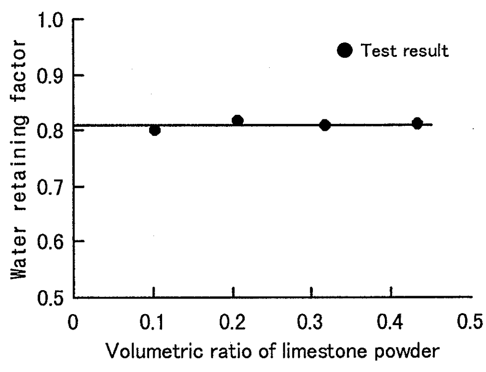


Fig.14 Relation between volumetric ratio of limestone powder and its water retaining factor (obtained from a paste test of powder in which moderate heat Portland cement was blended with limestone powder)

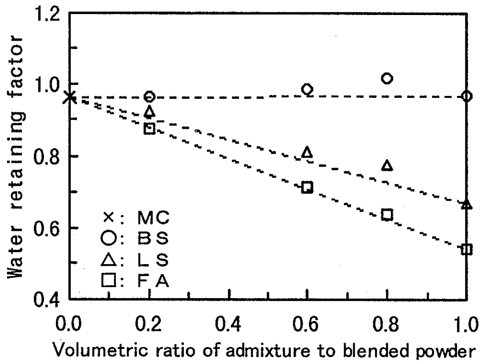


Fig.15 Relation between volumetric ratio of admixture to blended powder and water retaining factor

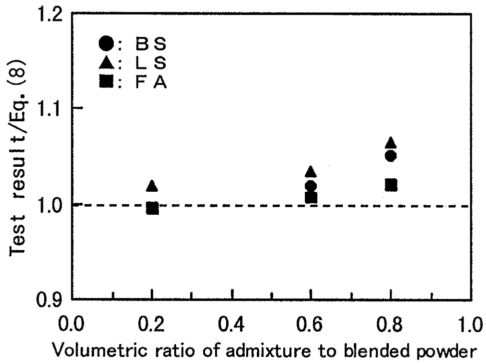


Fig.16 Comparison between test result of water retaining factor and calculation by Eq.(8)

blended, the influence is little, and the volumetric ratio of admixture to blended powder is approximately proportional to the water retaining factor.

On the other hand, when blast-furnace slag or limestone powder is added, the volumetric ratio of admixture to blended powder can be regarded as approximately proportional to the water retaining factor only if the volumetric ratio of admixture to blended powder is small (γad is below 0.6).

Therefore, as shown in Fig.16, when the volumetric ratio of admixture to blended powder is small, the water retaining factor of the admixture can be calculated by Eq.(8) from the water retaining factor of the blended powder and the blending ratio.

$$\beta p = \beta c + (\beta ad - \beta c) \cdot \gamma ad \qquad (8)$$

Where βp is the water retaining factor of the blended powder, βc is the water retaining factor of moderate heat Portland cement, βad is the water retaining factor of the admixture, and γ ad is the volumetric ratio of admixture to blended powder.

5. Flow factor

In flow tests on paste, the flow factor, which represents the ease of paste deformation, is a property of the powder that affects the fluidity of the paste. It differs with the type of powder, as shown in Table 3. Accordingly, such differences of the flow factor with the characteristics of powders are considered.

The flow factor is determined by the contact probability among the particles and by the degree of contact friction. The contact probability depends on the number of particles which exist per unit volume of paste. Therefore, it is higher when the particle size is small. The degree of contact friction when the particles come into contact depends on the shape of the particles and the in surface state.

The relation between particle size factor, which indicates the contact probability among the particles, and the flow factor is shown in Fig.17. The flow factor increases with particle size factor. In the case of the same

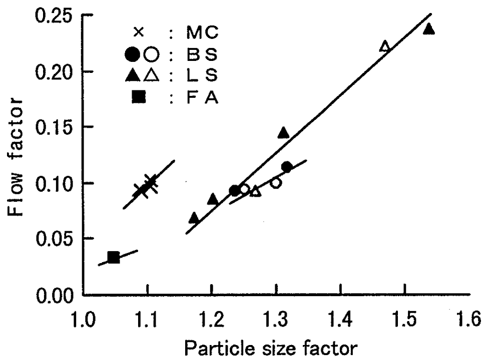


Fig.17 Relation between particle size factor and flow factor

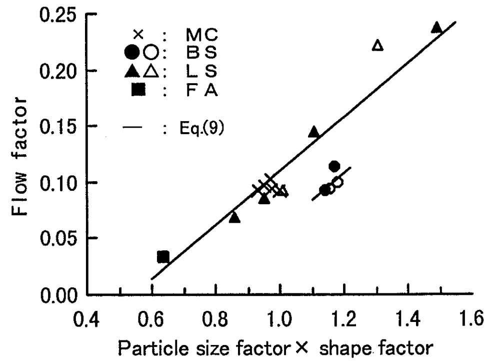


Fig.18 Relation between flow factor and product of particle size factor and shape factor

material, the flow factor increases with falling particle size. The degree of this increase differs with the type of powder. This difference is attributable to particle shape or its surface state.

Therefore, flow factor was indicated the relation with the product of shape factor calculated by Eq.(6) and the particle size factor, as shown in Fig.18. The flow factor, except in the case of blast-furnace slag, is approximately proportional to this product. Blast-furnace slag differs from the other powders because its surface is smooth and glassy. On the other hand, the contact friction of moderate heat Portland cement is strong, because needles of ettringite are formed on its surface by hydration. In this case, however, the influence of hydration is included in the shape factor.

Table 3 Properties of powders

Type of powder		particle size factor (PF)	shape factor (SF)	flow factor	
				Eq.(9)	test
moderate heat Portland cement	MC1	1.10	0.88	0.10	0.10
	MC2	1.11	0.86	0.10	0.10
	MC3	1.09	0.85	0.09	0.09
	MC4	1.09	0.92	0.11	0.09
	MC5	1.09	0.90	0.10	0.09
blast-furnace slag	BS40	1.24	0.91	0.09	0.09
	BS60	1.32		0.10	0.11
	BP1*1	1.30		0.10	0.10
	BP2*1	1.25		0.10	0.09
limestone powder	LS40a	1.20	0.84	0.10	0.09
	LS40b	1.31		0.08	0.07
	LS60	1.17		0.14	0.15
	LS180	1.54		0.23	0.24
	BP3*2	1.47		0.18	0.22
	BP4*2	1.27		0.11	0.09
fly ash		1.05	0.61	0.02	0.03

*1: BP1 and BP2 are blended powders in which BS40 was blended with BS60. The blending ratios are as follows: BP1, BS40:BS60=20:80; BP2, BS40:BS60=80:20.
*2: BP3 and BP4 are blended powders in which LS40a was blended with LS180. The blending ratios are as follows: BP3, LS40a:LS180=20:80; BP4, LS40a:LS180=80:20.

This relation between flow factor and the above product is indicated by Eq.(9). In this study, the proportional factor A in Eq.(9) is 0.24, and is constant. The fixed number B is an index representing the state of the particle surface. It is smaller for a smoother surface. The value for blast-furnace slag is -0.18, but the other powders are -0.13. The fixed numbers A and B were chosen to give best agreement between experimental values and calculated values using Eq.(9).

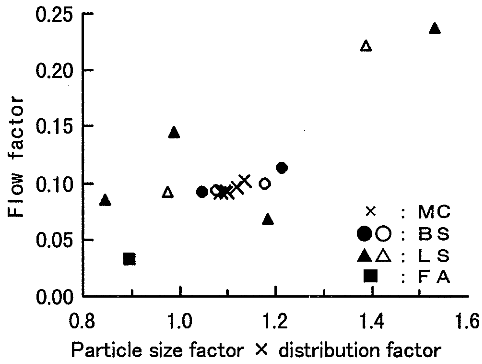


Fig.19 Relation between characteristic of particle size distribution and flow factor

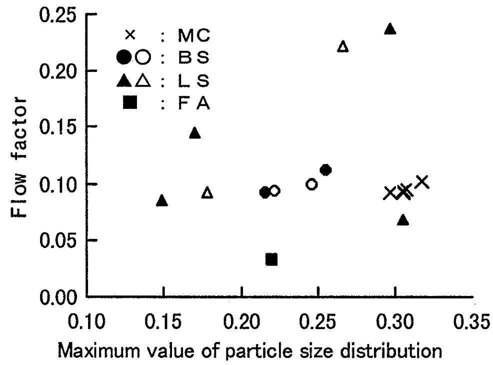


Fig.20 Relation between maximum value of particle size distribution and flow factor

$$Ep = A \cdot PF \cdot SF + B \qquad (9)$$

Where PF is the particle size factor, SF is the shape factor, A is a fixed number (in this study, 0.24), and B is an index representing the state of the particle surface.

Figure 19 shows, as in the case of water retaining factor, the relation between the flow factor and the characteristics of the particle size distribution. The relation between the flow factor of limestone powder and the characteristic of the particle size distribution is not correlative. This is because of a lack of correlation between the flow factor of limestone powder and the maximum value of particle size distribution, as shown in Fig.20.

The flow factor is determined by the average particle size, the particle shape, and the surface state of the particle. Therefore, as shown in Fig.21, the correlation between flow factor and water retaining factor is not very strong.

Figure 22 shows the relation between flow factor and the product of particle size factor and shape factor for blended powders, where moderate heat Portland cement is blended with an admixture: blast-furnace slag, limestone powder, and fly ash (Table 4). These admixtures were blended in

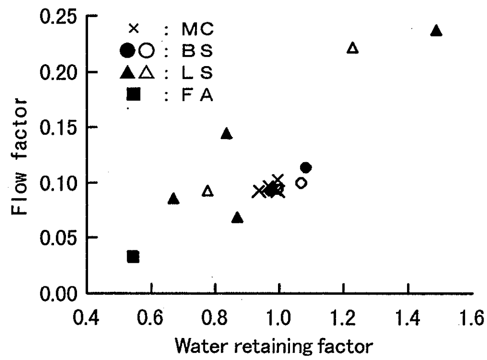


Fig.21 Relation between water retaining factor and flow factor

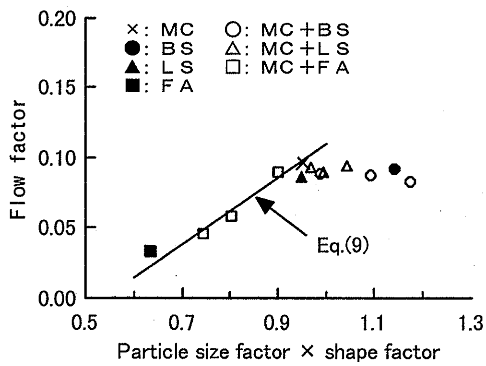


Fig.22 Relation between flow factor and product of particle size factor and shape factor (blended powder with two types of powder)

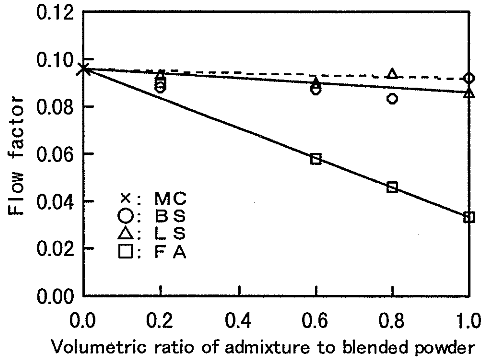


Fig.23 Relation between volumetric ratio of admixture to blended powder and flow factor

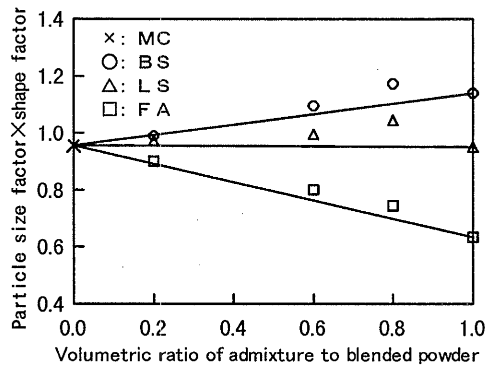


Fig.24 Relation between volumetric ratio of admixture to blended powder and product of particle size factor and shape factor

volumetric ratios of 0.2, 0.6, or 0.8 to the blended powder.

The flow factors of blended powders consisting of moderate heat Portland cement with limestone powder or fly ash can be represented by Eq.(9) with the fixed number B set at -0.13, as with the simple use of these powders. The flow factor of the blend containing blast-furnace slag can also be represented by Eq.(9). In this case, however, the fixed number B needs to be chosen according to the ratio of blast-furnace slag.

Table 4 Properties of blended powders

Type of powder	volumetric ratio of admixture to blended powder	flow factor		
		Eq.(10)	test	test/Eq.(10)
blast-furnace slag	0.2	0.10	0.09	0.90
	0.6	0.09	0.09	1.00
	0.8	0.09	0.08	0.89
	1.0	0.09	0.09	1.00
limestone powder	0.2	0.09	0.09	1.00
	0.6	0.09	0.09	1.00
	0.8	0.09	0.09	1.00
	1.0	0.09	0.09	1.00
fly ash	0.2	0.08	0.09	1.13
	0.6	0.06	0.06	1.00
	0.8	0.05	0.05	1.00
	1.0	0.03	0.03	1.00
moderate heat Portland cement (MC2)		0.10	0.10	1.00

As shown in Fig.23, in case of a blended powder of moderate heat Portland cement with limestone powder or fly ash, the flow factor is proportional to the volumetric ratio of admixture to blended powder. This is because the relation between the volumetric ratio of admixture to blended powder and the product of particle size factor and shape factor for the blended powder resembles the relation between the volumetric ratio of admixture to blended powder and the flow factor, as shown in Fig.24.

Therefore, the flow factor of such a blended powder is determined by the flow factor of each admixture and its blending ratio (Eq.(10), Table 4).

$$Ep = Ec + (Ead - Ec) \cdot \gamma ad \qquad (10)$$

Where Ep is the flow factor of blended powder, Ec is the flow factor of moderate heat Portland cement, Ead is the flow factor of the admixture, and γ ad is the volumetric ratio of the admixture to blended powder.

6. Conclusion

In this study, a method is proposed for estimating the water retaining factor and flow factor of powders using the particle size distribution, the particle shape, and the hydration property of the cement.

The results can be summarized as follows.

(1) Taking as a characteristic value of the powder particle size distribution a value obtained by multiplying the particle size factor by the distribution factor, it was clarified that the water retaining factor of a particular type of powder is proportional to this characteristic value.

(2) When the constant of proportionality in the relation between water retaining factor and the characteristic value is defined as the shape factor, it was found that the shape factor differs with the type of powder, and is determined by the particle shape and hydration properties of the cement.

(3) The flow factor increases in proportion with the product of the particle size factor and the shape factor. Assuming the proportionality constant to be invariant, it was clarified that it is an index representing the state of the surface of the particles.

(4) The water retaining factor of a blended powder in which moderate heat Portland cement was blended with blast-furnace slag, limestone powder, or fly ash can be calculated from the particle size distribution characteristic value by setting the shape factor of moderate heat Portland cement in accordance with the volumetric blending ratio of the admixture.

Incidentally, when the volumetric ratio of admixture to blended powder is below 0.6, the water retaining factor of the blended powder can be approximated by the water retaining factor of the admixture and the blending ratio.

(5) The flow factor of a blended powder in which moderate heat Portland cement was blended with limestone powder or fly ash can be calculated, as with the simple use of these powders, from the particle size factor and the shape factor. Also, it can be calculated from the flow factor of the admixture and the blending ratio.

The flow factor of a blended powder containing blast-furnace slag can also be calculated by setting the constant term in the equation according to the blending ratio of the blast-furnace slag.

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