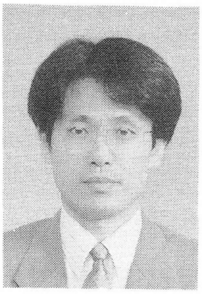
CONCRETE LIBRARY OF JSCE NO. 31, JUNE 1998

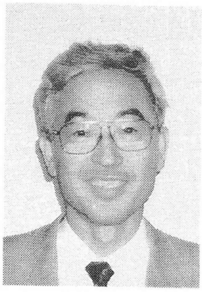
DISTINCTION BETWEEN POWDER AND SAND IN FRESH MORTAR

(Translation from Proceedings of JSCE, No.571/V-36, August 1997)



Yoshinobu EDAMATSU

Shozo YAMAGUCHI



Hajime OKAMURA

In this study, a method based on the particle size distribution properties and particle shape of sand is proposed for estimating the water-retaining and flow factors of sand. These are properties which affect mortar fluidity. Then, by investigating the action of powder and sand on mortar flow, a boundary particle size between the two, and the influence of fine sand particles and coarse powder particles on mortar flow, were investigated. From the results obtained, it became clear that the boundary particle size was about 0.09mm. By regarding fine sand particles of 0.09mm or less as powder and coarse powder particles of 0.09mm or more as sand, calculated values of relative flow area of mortar were equal to experimental values.

Key Words: *mortar, water-retaining factor, flow factor, boundary particle size*

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.

Shozo YAMAGUCHI is a consulting engineer of Takemoto Oil & Fat CO., LTD., Aichi, Japan. He consults on chemical admixtures for concrete, especially precast concrete products using self-compacting concrete. He is a member of the JSCE.

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

1. INTRODUCTION

It is well known that ingredient characteristics and mix proportions have an influence on concrete fluidity. To establish a method of mix design for self-compacting concrete, it is necessary to quantitatively evaluate the influence these factors have on the fluidity of fresh concrete. The deformability of fresh concrete is mainly affected by the deformability and mixture of the fresh mortar, so to quantify this influence it is necessary only to formulate the deformation of fresh mortar, namely, the mortar flow. Accordingly, we have formulated mortar flow using the characteristics of the materials used. This made it clear that the powder or sand properties which affect mortar fluidity could be quantitatively represented by the water-retaining factor or flow factor [1].

Furthermore, so as to establish a more efficient method of powder and mix design suitable for self-compacting concrete, we have proposed a method for estimating the water-retaining factor and flow factor, which hitherto had been obtained from paste flow tests in the absence of vibration [2]. This relies an knowing the particle size distribution, particle shape, and hydration properties of the cement [3].

Now, if the water-retaining factor and flow factor of the sand portion could also be estimated from particle size distribution and particle shape, the deformability of fresh mortar might conceivably be established without the need for mortar flow tests. The characteristics of the sand content, such as particle shape and particle size distribution, certainly have an influence on the deformability of fresh mortar [4]. Therefore, it is not unreasonable to conceive that the water-retaining factor and flow factor of sand can be estimated in a manner similar to that used for the powder portion.

We have previously formulated mortar flow in tests using sand particles larger than 0.15mm. The reason for this was that finer sand particles probably act as powder in fresh mortar [5]. In order to extend the evaluation method to cover any sand containing fine particles of 0.15mm or less, it is necessary to quantitatively evaluate the influence of fine particles on the deformability of fresh mortar. Occasionally, the powder may also contain particles of up to around 0.15mm, depending on the type powder, so it is also necessary to evaluate the influence of coarser powder particles.

In this study, methods of estimating the water-retaining factor and flow factor of powder are applied to sand, and their validity is investigated. Then, from the definitions of the effects of powder and sand on mortar flow, the particle size representing the boundary between the two and the influence each on mortar flow are clarified.

Note that this study deals with general sands and powders, so sand with particular characteristics, such as light- or heavy-weight sand, and powders with particularly tiny particles, such as silica-fume, are not covered.

2. CHARACTERISTICS OF SAND AND POWDERS

Fuji river sand fine aggregate (Fuji river2), mountain sand fine aggregate from Kisarazu (Kisarazu2), and Soma silica sand fine aggregate were used. The characteristics of each sand are given in Table 1 and Figs.1 and 2. Typical photographs showing the particle shape of each sand are shown in Photos.1, 2, and 3. Incidentally, in this study, the surface dryness condition of the sand was defined as that after applying a centrifugal force of 1000G for 20 minutes. The sand was dehydrated by the centrifugal method referred to in JIS (Japanese

Table 1 Properties of sand

Type	Specific gravity	Solid volume*) (%)	Absorption (%)	Percentage of residual weight sieve (%)								F.M.
				5mm	2.5	1.2	0.6	0.3	0.15	0.09	0.063	
Fuji river1	2.58	61.0	2.26	0	10	36	71	93	100	100	100	3.10
Fuji river2	2.58	61.0	2.71	0	9	34	67	87	94.0	96.4	97.4	2.91
Kisarazu1	2.58	69.1	2.41	0	15	34	55	84	100	100	100	2.88
Kisarazu2	2.58	69.1	2.63	0	14	31	51	77	92.0	95.4	96.5	2.65
Soma1	2.56	62.9	1.48	0	0	35	51	87	100	100	100	2.73
Soma2	2.55	62.9	1.84	0	0	26	37	62	74.5	85.8	93.8	1.99

*) Particles of 0.15mm or less were excluded

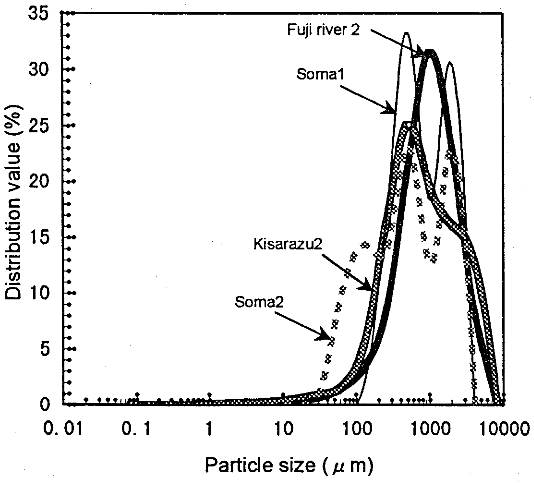


Fig.1 Particle size distribution of sand

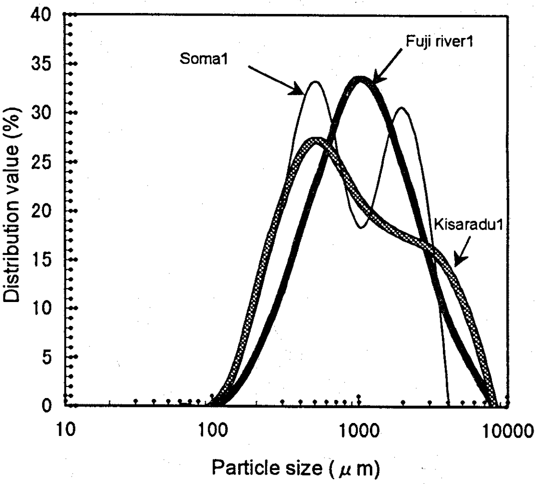


Fig.2 Particle size distribution of sand

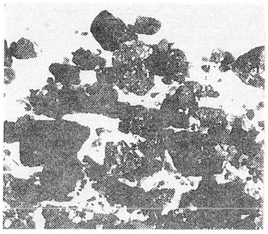
Industrial Standard) A 1802 " Methods of Test for Production Control of Concrete (Method of Test for Surface Moisture in Fine Aggregate by Centrifugal Force)".

Fuji river1 and Kisarazu1, which are shown in Table 1 and Fig.2, were sieved Fuji river2 and Kisarazu2 respectively so as to make 0.15mm of the minimum particle size. The Soma silica sand was of two types, Soma1 and Soma2. Soma1 comprised only coarse particles of 0.15mm or more. Soma2 comprised Soma1 plus fine particles of 0.15mm or less. The fine particles amounted to 26% as a volumetric ratio of the Soma1 content. The particle size distribution of Soma2 particles of 0.15mm or more was approximately equal to that of Soma1.

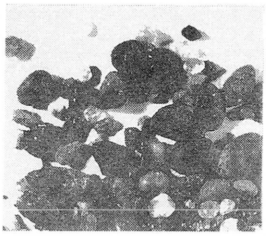
Kisarazu2 contains more coarse particles of 2500 μm or more and more fine particles of 600 μm or less than Fuji river2. Soma1 and Soma2 contain no coarse particle of 2500 μm or more. Thus the particle size distribution of Soma1 is narrower than that of the other sands. The peaks of Soma1 occur at about 500 and 2000 μm. This is because Soma1 is a blend of three kinds of silica sand, No.3, No.4, and No.5, which are of different particle sizes.

Kisarazu1 sand particles are rounded. Soma1 contains hardly any flat particles. Soma1 sand particles are regular. Fuji river1 sand particles are angular. Fuji river1 contains many flat particles.

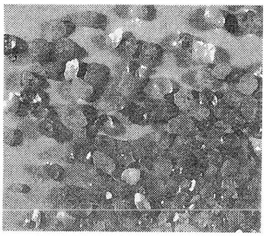
Moderate heat Portland cement (MC), limestone powder (LS), blast-furnace slag powder (BS), and fly ash (FA) were used in the mortars. These powders are used



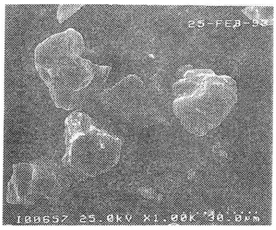
Phot.1 Fuji river1



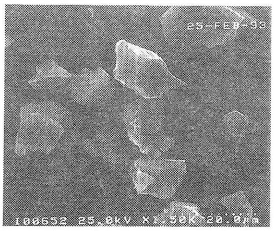
Phot.2 Kisarazu1



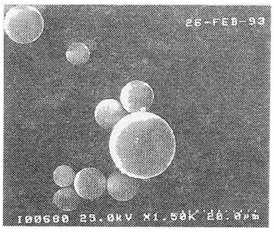
Phot.3 Soma1



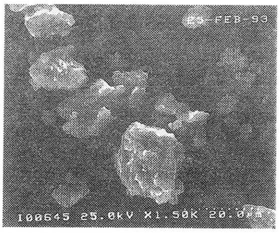
Phot.4 MC



Phot.5 BS



Phot.6 FA



Phot.7 LS

Table 2 Properties of powders

Type	Specific gravity	Fineness (cm²/g)
MC	3.20	3110
BS	2.89	4370
LS	2.69	4660
FA	2.33	3440

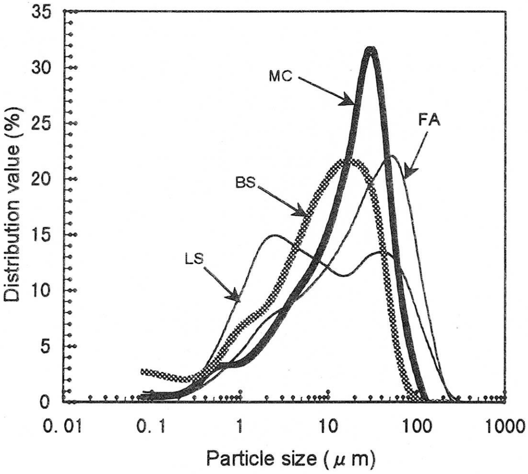


Fig.3 Particle size distribution of powder

to produce self-compacting concrete. Their properties are summarized in Table 2 and their particle size distributions are shown in Fig.3. Typical photographs showing particle shape, as taken with an SEM, are given in Photos.4, 5, 6, and 7.

The peak of MC occurs at about 30 μ m. The gradient in the direction of smaller particle size is gentle, but the distribution falls away rapidly above the peak. There are hardly any particles coarser than 100 μ m nor particles finer than 0.1 μ m. The distribution of BS is similar to that of MC, with only one peak. There are no coarse particles above 100 μ m, though there are more fine particles of 0.1 μ m or less. The form of the FA distribution is also similar. The peak, however, is higher than that of the cement, at about 55 μ m. FA contains a lot of coarse particles above 100 μ m. The distribution of LS is very different and has two peaks. LS contains a lot of coarse particles above 100 μ m, somewhat like FA.

MC and LS particles are extremely uneven polyhedrons, and their surfaces are not very angular. BS particles are more angular and sharper than those of other powders, and their surface is irregular but smooth. FA includes many globular particles.

3. BASIC EQUATION OF MORTAR FLOW

Relative mortar flow area (Eq.(1)) is given by the basic equation Eq.(2), and for a particular powder is determined by the volumetric water-powder ratio, the volumetric ratio of sand in the mortar, and the water-retaining factor and flow factor representing sand properties (Fig.4) [1]. The value of mortar flow (Eq.(1)) in the absence of vibration was measured according to "An experimental method of quality control of cement on fresh mortar properties in high-performance concrete (proposal) [2]".

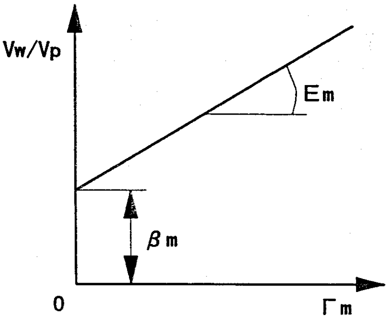


Fig.4 Basic equation of mortar flow (Vs: constant)

$$\Gamma m=\left(\frac{Fm}{100}\right)^2-1 \qquad (1)$$

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

$$Em=\left(Ep+Es\frac{Vs}{Vp}\right)\frac{1-Vs}{1-Vs\cdot(1+\beta s)} \qquad (3)$$

$$\beta m=\frac{\beta p(1-Vs)+\beta s\cdot Vs}{1-Vs(1+\beta s)} \qquad (4)$$

Where Γm is the relative flow area of the mortar, Fm is the value of the mortar flow (mm) in the absence of vibration, βm is the water-retaining factor of the mortar, Em is the flow factor of the mortar, Vw is the volumetric ratio of water in the mortar, Vp is the volumetric ratio of powder in the mortar, Vs is the volumetric ratio of sand in the mortar, βp is the water-retaining factor of the powder, Ep is the flow factor of the powder, βs is the water-retaining factor of the sand, and Es is the flow factor of the sand.

The water-retaining factor and flow factor of the sand, which are formulated as a function of the volumetric ratio of sand in the mortar (Vs), are given by Eq.(5) and Eq.(8).

$$\beta s=\beta s0+\beta sv \qquad (5)$$

$$\beta sv=A\cdot\left\{\frac{Vs(1+\beta p)}{1+Vs\cdot(\beta p-\beta sv)}-\frac{Vsi(1+\beta p)}{1+Vsi(\beta p-\beta s0)}\right\}^{1.5} \qquad (6)$$

$$Vsi=\frac{\gamma si}{1+\beta p-\gamma si(\beta p-\beta s0)} \qquad (7)$$

$$Es=Es0+Esv \qquad (8)$$

$$Esv=B\left(\frac{1}{Vsr-Vs}-\frac{1}{Vsr-Vsi}\right) \qquad (9)$$

Where β s0 is the absolute water-retaining factor of the sand, β sv is the

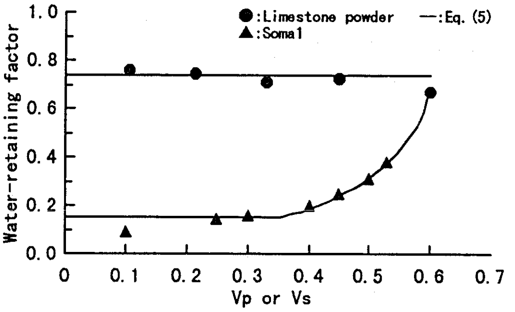


Fig.5 Relationship between volumetric ratio of powder or sand and water-retaining factor

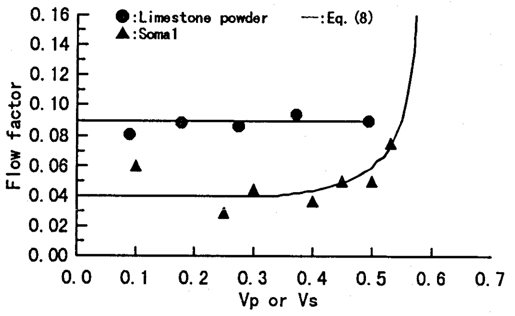


Fig.6 Relationship between volumetric ratio of powder or sand and flow factor

apparent water-retaining factor resulting from interactions of sand particles, Vsi is the volumetric ratio at the start of sand particle interaction, γ si is the volumetric ratio of sand to solid particles at the start of sand particle interaction, A is a constant, Es0 is the absolute flow factor of the sand, Esv is the apparent flow factor resulting from sand particle interaction, Vsr is the limit volumetric ratio of sand, and B is a constant.

Table 3 Material constants relating to water-retaining factor (Eq.(5)) and flow factor (Eq.(8))

Type	βs0	γsi	Vsi	A	Es0	Vsr	B
Somal	0.15	0.53	0.34	1.6	0.040	0.60	0.003
LS	0.74	–	–	–	0.090	–	–

4. DEFINITION OF POWDER AND SAND

The difference between the effect of powder and sand on mortar flow is defined here. As shown in Fig.5 and Fig.6, while the water-retaining factor and flow factor of LS are constant regardless of its volume, the values for Somal increase with volume beyond a certain limit. The absolute water-retaining factor and absolute flow factor of LS are bigger than those of Somal. Therefore, a powder was defined as a material for which the water-retaining factor and flow factor are constant regardless of volume. On the other hand, sand was defined as a material for which these factors are affected by volume.

Incidentally, the water-retaining factor of a powder is a volumetric ratio of the water retained by the powder to the oven dryness volume of the powder, while that of sand is the volumetric ratio of the water retained by the sand to the surface dryness volume of the sand. If the water-retaining factor of sand is regarded as a volumetric ratio to its oven dryness volume, the difference between the two becomes small.

The experimental values of the water-retaining factor and flow factor of LS shown in Fig.5 and Fig.6 are calculated by regarding LS as sand in the paste flow test with a blended powder of MC and LS. Incidentally, the experimental values for LS when the powder volumetric ratio is a maximum in these figures were obtained by a paste flow test with LS alone. In this case, the volumetric ratio of LS in the paste became limit.

5. ESTIMATE OF WATER-RETAINING FACTOR OF SAND

The water-retaining factor of a particular type of powder is proportional to

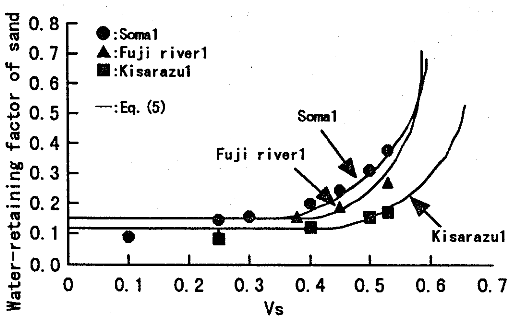


Fig.7 Relationship between Vs and water-retaining factor of sand with MC

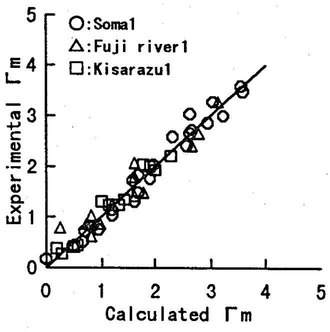


Fig.8 Relationship between calculated Γm and experimental Γm with MC

Table 4 Material constants relating to water-retaining factor of sand (Eq.(5)) with MC

Type	$\beta s0$	γsi	Vsi	A
Fuji river1	0.15	0.60	0.40	2.2
Kisarazu1	0.12	0.63	0.44	1.8
Soma1	0.15	0.53	0.34	1.6

characteristic values of the powder particle size distribution (Eq.(10)) [3]. Here, these characteristics are obtained by multiplying the particle size factor (Eq.(12)) by the distribution factor (Eq.(14)), which is the square root of the relative height of the distribution. The constant of proportionality in Eq.(10) represents the particle shape and the powder's degree of activation, and is defined as the shape factor. This may also apply to the water-retaining factor of sand. Because sand does not hydrate, the absolute water-retaining factor might conceivably be decided by the characteristics of particle size distribution and particle shape.

$$\beta p = SF \cdot PF \cdot HF \tag{10}$$

$$\beta s0 = SF \cdot PF \cdot HF \tag{11}$$

$$PF = \int p(x) \cdot pf_0(x)dx \tag{12}$$

$$pf_0(x) = 1.65 - 0.5\mathrm{Log}(x) \quad (pf_0(x) \geqq 0) \tag{13}$$

$$HF = \sqrt{H} = \sqrt{\frac{h}{0.3}} \tag{14}$$

Where PF is the particle size factor, SF is the shape factor, HF is the distribution factor, H is the relative value of the distribution's maximum height, pf0(x) is the standard particle size factor, p(x) is the particle size distribution curve, x is the particle size (μm), and h is the maximum value of the particle size distribution.

Figure 7 shows the relationship between Vs and the water-retaining factor of each sand with MC. The solid lines in Fig.7 represent Eq.(5). The material constants of Eq.(5) are given in Table 4. Incidentally, these material constants were chosen to give best agreement between experimental values of the relative flow area of the mortar (Γm) and values calculated using Eq.(2) (Fig.8). As shown in Table 4, the absolute water-retaining factor of Soma1 is equal to that

Table 5 Characteristics of sands

Type	PF	h	H	$\beta s0$
Fuji river1	0.17	0.34	1.12	0.15
Kisarazu1	0.21	0.27	0.91	0.12
Soma1	0.21	0.33	1.11	0.15

Table 6 Shape factor of sands and powders [3]

Type		Shape factor
Fuji river1		0.86
Kisarazu1		0.61
Soma1		0.69
MC	MC1	0.88
	MC2	0.86
	MC3	0.85
	MC4	0.92
	MC5	0.90
BS		0.91
LS		0.84
FA		0.61

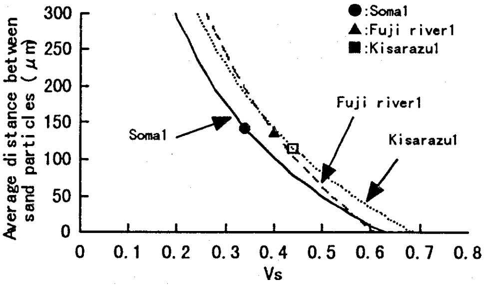


Fig.9 Relationship between Vs and average distance between sand particles

of Fuji river1. The absolute water-retaining factor of Kisarazu1 is smaller than both. Such differences depending on sand characteristics are investigated below.

The characteristics of particle size distribution were calculated from the characteristic values given in Table 5, and then the shape factor was obtained by substituting these values into Eq.(11). Incidentally, SF, PF, and HF into Eq.(10) and Eq.(11), which are not affected by the type of powder and sand, are decided by the particle size distribution, the particle shape and so on.

As shown in Table 6, the shape factor of Fuji river1 is equal to that of BS. The shape factor of Kisarazu 1 is equal to that of FA. The shape factor of Soma1 is a value midway between that of FA and LS. Fuji river1 (Phot.1) and BS (Phot.5) have similar angular particle shapes. Kisarazu1 (Phot.2) and FA (Phot.6) are rounded. But FA is more rounded. Thus, the shape factors of Fuji river1 and BS are conceivable similar, and also those of Kisarazu1 and FA are similar. Soma1 (Phot.3) is not as rounded as FA (Phot.6), and is not as uneven as LS (Phot.7). Thus, the shape factor of Soma1 is conceivably value between that of FA and LS. Therefore, if the shape factor of sand can be obtained appropriately, the absolute water-retaining factor of sand can be estimated using Eq.(11).

Next, differences in volumetric ratio at the start of interaction of sand particles (Vsi, Table 4) are investigated as follows. Vsi represents the volumetric ratio at the start of interaction of sand particles owe to contact or meshing. For a given paste quality in the mortar, the probability of contact among sand particles is considered determined by the separation between particles. Thus, because contact probability increases as the distance between sand particles falls, Vsi might conceivably decrease with separation.

Figure 9 shows the relationship between Vsi and the average distance between sand particles. Here, the average separation was calculated using Eq.(15). Incidentally, the average separation was defined as follow [6][7]. There is certain particle of any shape and of average diameter d in a unit volume. Then without a change in arrangement or particle shape of the particle, the particle diameter (d1 in an average diameter) is increased until the contact between particles. The average distance is the remainder between d1 and d. Incidentally, the average sand particle diameter is defined a particle size when the cumulative value of the particle size distribution grew 50%. The average particle diameter of Fuji river1 is 913 μm, of Kisarazu1 714 μm, and of Soma1 630 μm.

$$t=\left\{\left(\frac{\mathrm{Slim}}{100\,\mathrm{Vs}}\right)^{\frac{1}{3}}-1\right\}\cdot d \qquad (15)$$

Where t is the average distance between sand particles, d is the average sand particle diameter, Slim is the solid volume of sand, and Vs is the volumetric ratio of sand in the mortar.

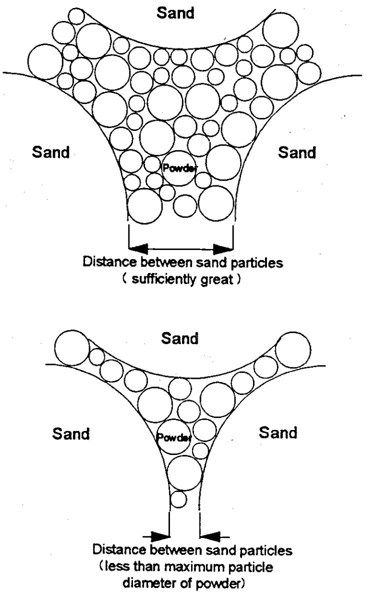


Fig.10 Arrangement of particles in fresh mortar

For a given powder, the reason for sand particles being in contact is explained as follows. As shown in Fig.10, when the distance between sand particles is sufficiently great, many powder particles are present between sand particles. Even if some of these particles move out of position in Fig.10, the contact probability among sand particles is very small because there are plenty of other powder particles between the sand particles. Thus the separation decreases gradually, and when it reaches the maximum powder particle diameter, the contact probability of there being only one powder particle between sand particles increases. Here, if that one powder particle moves from its position, the sand particles come into contact. When the separation decreases yet more, the contact probability also increases. Thus, the contact probability among sand particles can be considered related to the average separation between the particles.

As shown in Fig.9, over a large range of average separation (more than 150 μm), the Vs of Soma1 is the smallest and that of Fuji river1 is the biggest. Average separation of this range is sufficiently greater than the maximum particle diameter of MC (about 85 μm). Therefore the water-retaining factor of sand might conceivably become constant because the contact probability among sand particles is very low. When the average separation is less than 150 μm, the comparison with Vs at the same average separation is equal to that of Vsi. When MC is used, the apparent water-retaining factor by sand particle interaction might conceivably increase because the contact probability among sand particles rises at average separation of less than 150 μm. The symbols in Fig.9 mean the average separation at each Vsi. These average separation are about 130 μm. Thus the Vsi of various sands can be considered by the relationship between Vs and average separation.

The constant A, which represents the degree of interaction once interaction between sand particles begins, relates to an average ratio of powder to sand separation [8]. Thus, if an identical powder is used, the constant A increases with average separation between sand particles.

Figure 11 shows the relationship between Vs and the water-retaining factor of Soma1 with various powders. The absolute water-retaining factor is constant regardless of the type of powder, but the material constants of the water-retaining factor are different (Table 7). This difference is discussed below in terms of powder characteristics. Incidentally, these material constants were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(2) (Fig.12).

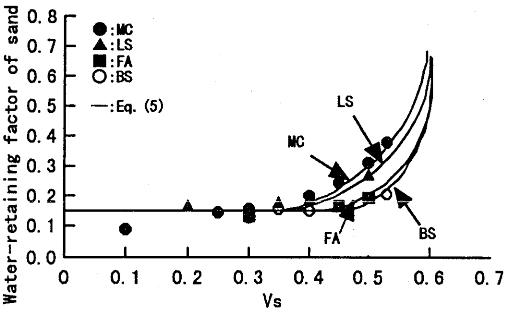


Fig.11 Relationship between Vs and water-retaining factor of sand with Somal

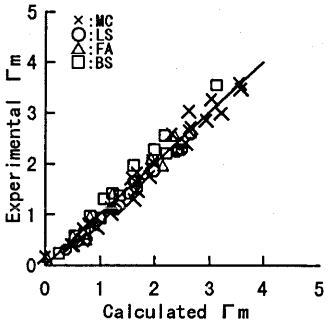


Fig.12 Relationship between calculated Γm and experimental Γm with Somal

Vsi is related to the average separation between sand particles and the powder particle diameter. Assume a particular sand. Then, Vsi is determined by the powder particle diameter. The average particle separation of the powders shown in Fig.11 are MC:18μm; BS:6μm; LS:7μm; and FA:21 μ m. The average particle diameter of BS is the smallest, so Vsi is greatest with BS. On the other hand, though the average particle diameter of LS is smaller than that of MC, it is equal to that of BS. However, with LS the Vsi value is smaller than with BS. The reason for this is that LS has a large proportion of coarse particles of 100μm or more, as shown in Fig.3. Though the average particle diameter of FA is the largest, its Vsi is larger than that of MC and LS. The reason for this is that the interaction of sand particles decreases owing to the globular shape of the particles in FA.

Table 7 Material constants relating to water-retaining factor of sand (Eq.(5)) with Somal

Type	$\beta s0$	γsi	Vsi	A
MC	0.15	0.53	0.34	1.6
BS		0.66	0.46	2.6
LS		0.51	0.36	1.5
FA		0.56	0.42	1.8

As mentioned above, Vsi is considered to be influenced not only by the average particle diameter of the powder but also by the powder particle shape and particle size distribution. In the case of powders with an equivalent average particle diameter, a powder including many coarse particles (i.e. with a wide particle size distribution) gives a lower Vsi.

6. ESTIMATE OF FLOW FACTOR OF SAND

The flow factor is proportional to the product of particle size factor and shape factor (Eq.(16)). Assuming the proportionality constant to be invariant, the constant term represents the surface state of the particles [3]. The following equation Eq.(16) applies to the flow factor of sand.

$$Ep = C \cdot PF \cdot SF + D \tag{16}$$

$$Es0 = C \cdot PF \cdot SF + D \tag{17}$$

Where C is a fixed number (in this study, 0.24), and D is an index representing the state of the particle surface. (D is smaller for a smoother surface.)

Figure 13 shows the relationship between Vs and the flow factor of each sand

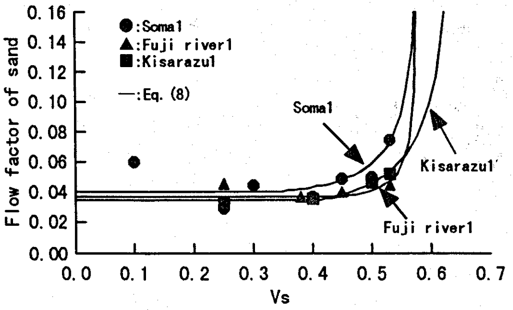


Fig.13 Relationship between Vs and flow factor of sand with MC

Table 8 Material constants relating to flow factor of sand (Eq.(8)) with MC

Type	Es0	Vsi	B
Fuji river1	0.035	0.40	0.001
Kisarazu1	0.037	0.44	0.005
Soma1	0.040	0.34	0.003

Table 9 Fixed number D representing particle surface state of sand and powder [3]

Type	D
Fuji river1	0.001
Kisarazu1	0.007
Soma1	0.006
MC	-0.13
LS	
FA	
BS	-0.18

with MC. The solid lines in Fig.13 represent Eq.(8). The flow factor increases rapidly when Vs is larger than 0.50. The reason for this is an increase in interactions between sand particles when Vs approaches the limit volumetric ratio of the sand (Vsr). In this study, Vsr is 95% of the unit solid volume of the sand. When Vs is equal to Vsr, the flow factor becomes infinite. The material constants in Eq.(8) are shown in Table 8. These material constants were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(2) (Fig.8). As shown in Table 8, the absolute flow factor depends on the sand used. This variation with sand characteristics is investigated below.

The index D representing the state of the particle surface was obtained by substituting the particle size factor, the shape factor (Table 6), and the absolute flow factor of each sand into Eq.(17). The proportional constant was 0.24,as with the powder. Note that indexes C and D, which are not affected by the type of powder and sand, in Eq.(16) and Eq.(17) are determined by the state of the particle surface and so on. As shown in Table 9, the D value of each sand is positive. For powders, however, it is negative value. The reason for this is that the particle size factor is calculated for particles of 2000 μm or less. Thus, interactions between coarser sand particles are not included in the particle size factor. The D index of sand is larger than that of powder owing to interactions between coarse sand particles. As mentioned above, the value of D for sand indicates not only the particle surface state but also the interaction of coarse sand particles. Therefore, if an appropriate value of D can be obtained, then the absolute flow factor can be calculated using Eq.(17).

Values of Vsi shown in Table 8 and Vsr are different depending on the sand used. Vsi, which represents the volumetric ratio of sand at the start of flow factor, is affected by the contact probability among sand particles. Thus, as a water-retaining factor, Vsi is determined by the average distance between sand particles, the average diameter of the powder, and the form of the particle size distribution. Vsr is rather smaller than a solid volume percentage of sand (in this study, 0.95 times as large as the solid volume percentage). Because the mortar when Vs is equal to Vsr can not be deformed, the apparent flow factor becomes infinite at Vsr.

Figure 14 shows the relationship between Vs and the flow factor of Soma1 with various powders. The absolute flow factor, which is a sand characteristic, is constant regardless of the type of powder. However, the absolute flow factor of FA is smaller than that of the other powders. Material constants of the flow factor are also different depending on the powder used (Table 10). These

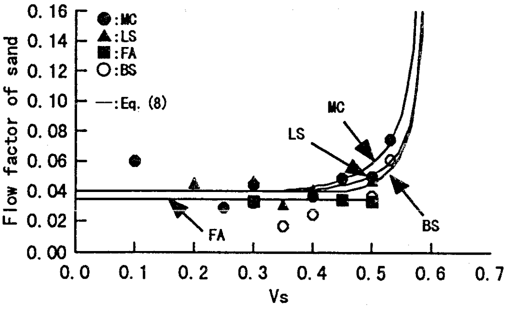


Fig.14 Relationship between Vs and flow factor of sand with Soma1

Table 10 Material constants relating to flow factor of sand (Eq.(8)) with Soma1

Type	Es0	Vsi	B
MC	0.040	0.34	0.003
BS		0.46	0.002
LS		0.36	0.002
FA	0.035	—	—

material constants were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(2) (Fig.12).

When FA is used, the contact friction between FA particles and sand particles is conceivably lower than that of other powders because of the globular shape of FA. In this study, the flow factor of each powder is held constant. Thus, if the deformability of fresh mortar is improved by a decrease in the contact friction between powder and sand, the absolute flow factor of sand becomes smaller. This is considered to be the cause of the decrease in the absolute flow factor with FA.

Vsi and Vsr for each powder are different depending on the powder used. Except for FA, the effect on flow factor is the same as that on the water-retaining factor. When FA is used, Vsi was not identified in the range of experimental Vs. However, it is assumed that Vsi for the flow factor is larger than that for the water-retaining factor. This is considered to be caused by the influence of FA particle shape.

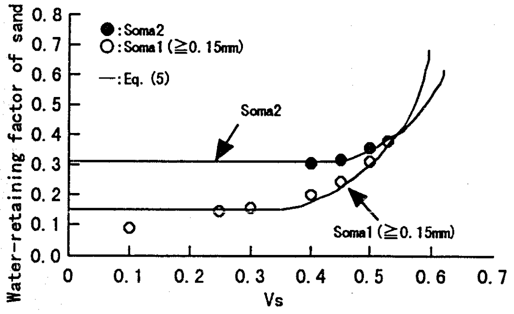


Fig.15 Relationship between Vs and water-retaining factor of sand with Soma silica sand, with MC

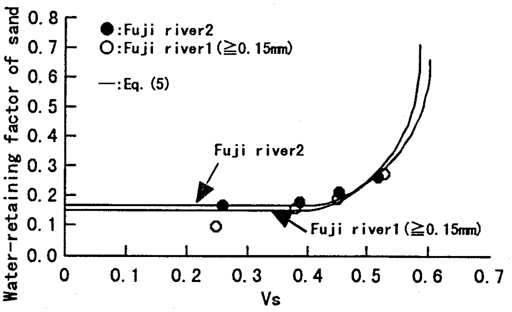


Fig.16 Relationship between Vs and water-retaining factor of sand with Fuji river sand, with MC

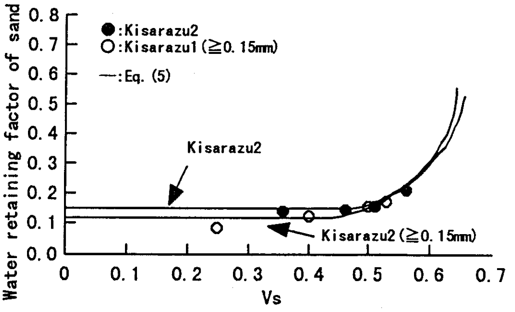


Fig.17 Relationship between Vs and water-retaining factor of sand with mountain sand in Kisarazu, with MC

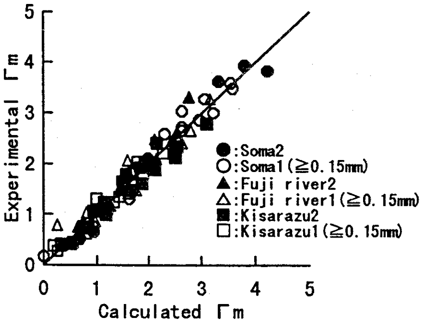


Fig.18 Relationship between calculated Γm by Eq.(2) and experimental Γm with MC

Table 11 Material constants relating to water-retaining factor of sand (Eq.(5))

Type	$\beta s0$	γsi	Vsi	A
Fuji river1(≧0.15mm)	0.15	0.60	0.40	2.2
Fuji river2	0.17	0.61	0.41	2.0
Kisarazu1(≧0.15mm)	0.12	0.63	0.44	1.8
Kisarazu2	0.15	0.67	0.47	2.1
Soma1(≧0.15mm)	0.15	0.53	0.34	1.6
Soma2	0.31	0.67	0.44	1.6

Table 12 Material constants relating to flow factor of sand (Eq.(8))

Type	Es0	Vsi	Vsr	B
Fuji river1(≧0.15mm)	0.035	0.40	0.59	0.001
Fuji river2	0.035	0.41	0.60	0.001
Kisarazu1(≧0.15mm)	0.037	0.44	0.66	0.005
Kisarazu2	0.037	0.47	0.64	0.003
Soma1(≧0.15mm)	0.040	0.34	0.60	0.003
Soma2	0.033	0.44	0.62	0.002

Table 13 Characteristics of sands

Type	Flow factor Eq.(17)	Flow factor Experimental Value	PF	SF	D
Fuji river1	0.042	0.035	0.20	0.86	0.001
Kisarazu1	0.044	0.037	0.25	0.61	0.007
Soma1	0.057	0.033	0.31	0.69	0.006

7. INFLUENCE OF FINE SAND ON WATER-RETAINING FACTOR AND FLOW FACTOR

7.1 Influence on water-retaining factor of sand

The relationship between Vs and the water-retaining factor of each sand, as calculated from Γm with MC and with Soma2, Fuji river2, and Kisarazu2, is shown in Figs.15, 16, and 17. The water-retaining factors of particles of 0.15mm or more are also shown. Material constants of the water-retaining factor are shown in Table 11. These material constants were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(2) as shown in Fig.18.

In all cases, the absolute water-retaining factor and Vsi increase when fine sand particles of 0.15mm or less are included in the sand. Because the fine sand particles are as small as powder particles, the absolute water-retaining factor of fine sand is larger than that of particles above 0.15mm. Therefore, when the fine sand, which has a large value of absolute water-retaining factor, is added to sand above 0.15mm, the absolute water-retaining factor of the sand as a whole becomes large. The reason for the increase in Vsi is that the fine sand acts as powder in the fresh mortar. The water-retaining factor of the powder is constant regardless of its volume. With Soma silica sand, the degree of the increase in absolute water-retaining factor and Vsi as a result of adding fine sand is larger than that with the other sands. The reason for this is that the fine sand ratio of Soma silica sand is larger than that of the others.

7.2 Influence on flow factor of sand

The relationship between Vs and the flow factor of each sand, as calculated from Γm with MC and with Soma2, Fuji river2, or Kisarazu2, is shown in Figs.19, 20, and 21. The flow factors of particles above 0.15mm in these sands are also shown. Material constants of the flow factors are shown in Table 12. These material constants were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(2) as shown in Fig.18.

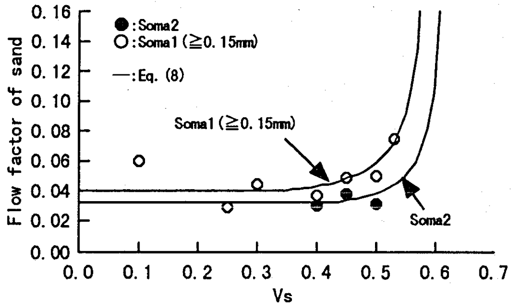


Fig.19 Relationship between Vs and flow factor of sand with Soma silica sand, with MC

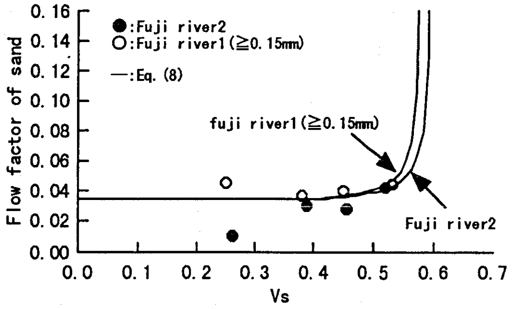


Fig.20 Relationship between Vs and flow factor of sand with Fuji river sand, with MC

In all cases, when fine sand particles of 0.15mm or less are included among the sand, Vsi increases. The reason for this is that the fine sand acts as powder in the fresh mortar. While the absolute flow factors of Fuji river2 and Kisarazu2 are equal to their respective absolute flow factors of particles above 0.15mm in spite of the fine sand ratio, that of Soma1 decreases with an increase in the fine sand ratio.

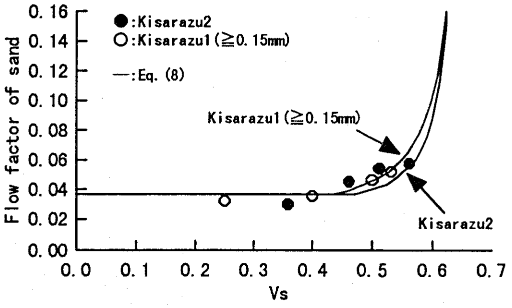


Fig.21 Relationship between Vs and flow factor of sand with mountain sand in Kisarazu, with MC

The absolute flow factor calculated by Eq.(17) is larger than the experimental value shown in Table 13 in all cases. This is clear in the case of Soma silica sand. This also indicates that the fine sand acts as powder in the fresh mortar. In this case, the experimental flow factor of the sand was calculated using the flow factor of MC alone. When a blend consisting of the fine sand particles and MC is regarded as the powder, the flow factor of the blended material is smaller than that of MC. The reason for this is that the particle diameter is smaller than that of MC, and the index D representing the state of the particle surface is small because it does not hydrate. The reason for the absolute flow factor of the sand including fine sand being smaller than the value calculated by Eq.(17) is that the flow factor of the MC, which is larger than that of the fine sand being treated as powder, is used in obtaining the experimental flow factor. The reason for the large decrease in absolute flow factor of Soma silica sand is that its fine sand ratio is larger than that of the other sands.

7.3 Handling of fine sand

In the previous sections, it was clarified that fine sand particles of 0.15mm or less increase the absolute water-retaining factor and Vsi of sand, causing the absolute flow factor to apparently decrease. The reason for this is that fine sand acts as powder in the fresh mortar. Therefore, it is appropriate to treat fine sand as a powder like cement in considering mortar flow. Thus, it is important that the boundary particle size at which the treatment switches between powder and sand needs to be clarified. This boundary particle size will be determined by comparing the relationship between the volumetric coarse sand ratio in the mortar (Vsc) and the water-retaining factor, the flow factor.

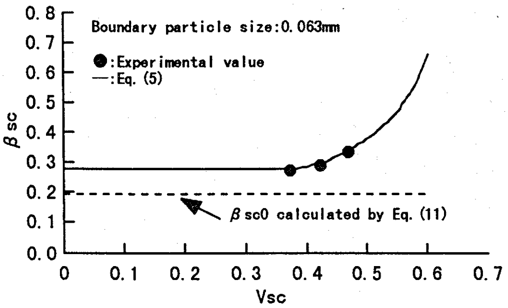


Fig.22 Relationship between Vsc and water-retaining factor of coarse sand for sand particles of 0.063mm or less treated as powder

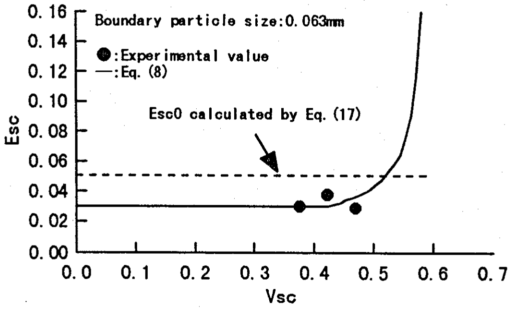


Fig.25 Relationship between Vsc and flow factor of coarse sand for sand particles of 0.063mm or less treated as powder

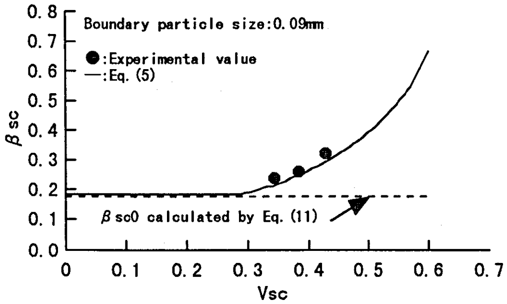


Fig.23 Relationship between Vsc and water-retaining factor of coarse sand for sand particles of 0.09mm or less treated as powder

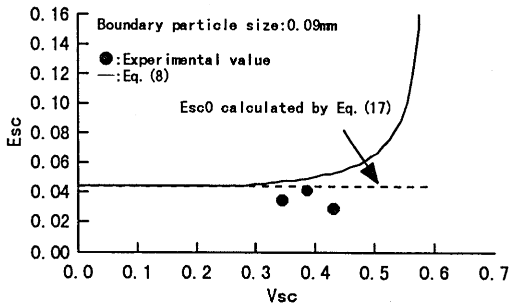


Fig.26 Relationship between Vsc and flow factor of coarse sand for sand particles of 0.09mm or less treated as powder

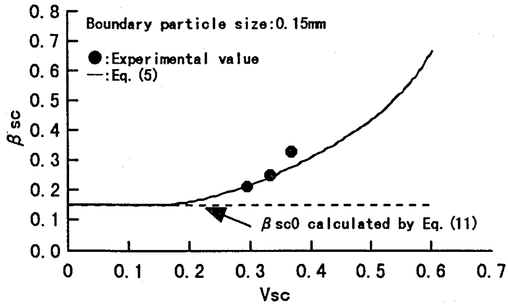


Fig.24 Relationship between Vsc sand and water-retaining factor of coarse sand for sand particles of 0.15mm or less treated as powder

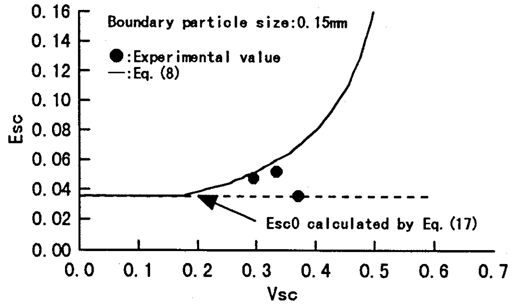


Fig.27 Relationship between Vsc and flow factor of coarse sand for sand particles of 0.15mm or less treated as powder

The boundary between fine sand and coarse sand is distinguished for Soma2. The boundary particle size was treated as a parameter, with values of 0.063mm, 0.09mm, and 0.15mm tried. Fine particles (the fine sand) smaller than these boundary sizes were regarded as powder. The relationship between Vsc and coarse sand water-retaining factor, where coarse sand is the sand larger than the

Table 14 Material constants relating to water-retaining factor (Eq.(5)) and flow factor (Eq.(8)) of coarse sand

Boundary particle size	βs0	γsi	Vsi	A	Es0	Vsr	B
0.15mm	0.15	0.29	0.17	0.9	0.036	0.60	0.017
0.09mm	0.18	0.44	0.27	1.2	0.038	0.60	0.003
0.063mm	0.28	0.60	0.38	1.5	0.030	0.60	0.003

Table 15 βs0 calculated by (Eq.(11)) and Es0 calculated by (Eq.(17)) for fine sand and coarse sand

Type	Boundary particle size	βs0	Eso	PF	SF	HF
Fine sand	0.15mm	0.66	-0.022	0.66	1.0	1.0
	0.09mm	0.76	0.002	0.76	1.0	1.0
	0.063mm	0.89	0.034	0.89	1.0	1.0
Coarse sand	0.15mm	0.15	0.036	0.22	0.69	1.02
	0.09mm	0.18	0.045	0.27	0.69	0.95
	0.063mm	0.19	0.051	0.31	0.69	0.91
	0mm(all)	0.21	0.057	0.35	0.69	0.88

boundary size, is shown in Figs.22, 23, and 24, respectively. Similarly, the relationship between Vsc and the flow factor of the coarse sand is shown in Figs.25, 26, and 27.

Table 16 Ratio of fine sand

Type	Fine sand ratio (%)		
	≦0.063mm	≦0.09mm	≦0.15mm
Fuji river2	2.6	3.7	6.0
Kisarazu2	3.6	4.6	8.0
Soma2	6.2	14.2	25.5

Incidentally, the reason for setting the minimum boundary particle size at 0.063mm was that the maximum particle diameter of a fine powder, such as BS, is approximately this diameter. The 0.15mm test was that this size was equal to the minimum size in a sieve analysis test of aggregate. The boundary size 0.09mm was set between the two.

The material constants shown in Table 14 were chosen to give best agreement between the experimental Γm and the calculated Γm using Eq.(18) as shown in Fig.18. The solid lines in these figures are now described. Equation (18) was changed to Eq.(2) by considering the influence of fine sand. The absolute water-retaining factor and absolute flow factor for the fine sand were calculated using Eq.(11) and Eq.(17) based on the sand particle size distribution below the boundary particle size (Table 15). These are described in these figures as dotted lines. In these calculations, the shape factor and the distribution factor were set to 1.

$$\frac{Vw}{Vp+Vsf} = Em\cdot\Gamma m+\beta m \tag{18}$$

$$Em = \left(Epsf+Esc\cdot\frac{Vsc}{Vp+Vsf}\right)\frac{1-Vsc}{1-Vsc\cdot(1+\beta sc)} \tag{19}$$

$$\beta m = \frac{\beta psf\cdot(1-Vsc)+\beta sc\cdot Vsc}{1-Vsc\cdot(1+\beta sc)} \tag{20}$$

$$\beta psf = \beta p+(\beta sf\,0-\beta p)\cdot\gamma sf \tag{21}$$

$$Epsf = Ep+(Esf\,0-Ep)\cdot\gamma sf \tag{22}$$

$$\gamma sf = \frac{Vsf}{Vsf + Vp} \qquad (23)$$

Where Vsf is the volumetric ratio of fine sand in the mortar ($Vsf = Vs \cdot \kappa sf/(1+Q)$), Vsc is the volumetric ratio of coarse sand in the mortar ($Vsc = Vs - Vsf \cdot (1+Q)$), Q is the absorption of sand (volumetric ratio), βsc is the water-retaining factor of coarse sand, Esc is the flow factor of coarse sand, βpsf is the water-retaining factor of the blend of fine sand and powder [3], Epsf is the flow factor of the blend of fine sand and powder [3], $\beta sf0$ is the absolute water-retaining factor of fine sand, Esf0 is the absolute flow factor of fine sand, and γsf is the volumetric ratio of fine sand to powder.

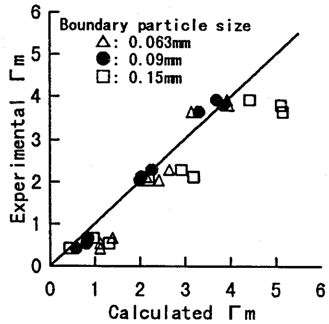


Fig.28 Relationship between calculated Γm by Eq.(18) and experimental Γm (with calculated $\beta s0$ and calculated Es0)

The fine sand ratios are shown in Table 16 for each boundary particle size. These ratio were obtained by measuring the particles of 0.15mm or less with a laser-diffraction measuring instrument which measures scatter (Cilas1064 by Cilas company). Methanol was used to disperse the powders, and dispersion was ensured by applying ultrasonic waves for 60 seconds before measurements.

At the boundary particle size of 0.063mm (Figs.22 and 25), the absolute water-retaining factor of the coarse sand (the straight solid line shown in Fig.22) is larger than the absolute water-retaining factor (the dotted line) calculated by Eq.(11). The absolute flow factor of the coarse sand (the straight solid line in Fig.25) is smaller than the absolute flow factor (the dotted line) calculated by Eq.(17). Vsi is larger than that of Somal (Vsi=0.34) which does not contain fine sand. This shows that powder is included among the coarse sand above 0.063mm.

At the boundary particle sizes of 0.09mm (Figs.23 and 26) and 0.15mm (Figs.24 and 27), the absolute water-retaining factor and absolute flow factor of the coarse sand in both cases (the straight solid lines shown in Figs.23 and 26) are approximately equal to the calculated values (the dotted lines). Vsi is smaller than that of Somal in both cases. At the boundary particle size of 0.15mm, Vsi is very small. Vsi decreases with an increase in coarse particles in the powder. When the sand includes fine particles, the coarse particle content of the powder increases, so Vsi is considered to become smaller than that of Somal, which includes no particles of 0.15mm or less, in any boundary particle size. The constant B related to flow factor is 0.003 with Somal, while it changes 0.017 at the boundary particle size of 0.15mm. This constant represents the rate of increase in flow factor after it being to increase. Therefore, the degree of contact and meshing among sand particles may conceivably increase with B. For the same sand, it is conceivable that the constant B is invariant. At the boundary particle size of 0.15mm, the reason for the constant B being large is conceivably that particles which should be regarded as sand are included among the fine sand of 0.15mm or less.

Using the water-retaining factor calculated by Eq.(11) and the flow factor calculated by Eq.(17), Γm was calculated using Eq.(17) with the material constants shown in Table 14 (at the boundary particle size of 0.15mm, B=0.003). Figure 28 shows the relationship between calculated Γm and experimental Γm. At the boundary particle size of 0.09mm, the calculated Γm is approximately equal

Table 17 β s0 calculated by (Eq.(11)) and Es0 calculated by (Eq.(17)) for fine sand and coarse sand

Type		β s0	Eso	PF	SF	HF
Fuji river2	Fine	0.93	0.093	0.93	1.0	1.0
	Coarse	0.16	0.037	0.18	0.86	1.05
Kisarazu2	Fine	0.95	0.098	0.95	1.0	1.0
	Coarse	0.13	0.033	0.22	0.61	0.94

Table 18 Material constants relating to water-retaining factor (Eq.(5)) and flow factor (Eq.(8)) for coarse sand

Type	β s0	γ si	Vsi	A	Es0	Vsr	B
Fuji river2	0.16	0.60	0.40	2.1	0.037	0.59	0.001
Kisarazu2	0.13	0.63	0.44	1.7	0.033	0.66	0.005

to the experimental Γm.

As mentioned above, with the Soma silica sand used in this study, it is considered that particles of 0.063mm or less clearly show powder properties, while particles above 0.15mm are clearly sand. The boundary between powder and sand is thus assumed to be in the range 0.063mm to 0.15mm.

With MC, Fuji river2, and Kisarazu2, and with fine sand of 0.09mm or less regarded as powder, Γm was calculated by Eq.(18). The relationship between calculated Γm and experimental Γm is shown in Fig.29. Here, the absolute water-retaining factors (Table 17) of the fine sand and the coarse sand were calculated by Eq.(11) and the absolute flow factors (Table 17) were calculated by Eq.(17). The absolute water-retaining factor and absolute flow factor of the blend of MC and fine sand were calculated using Eqs.(21) and (22). The constant B concerning Vsi and the flow factor of sand was set for the particles above 0.15mm in the sand (Table 18).

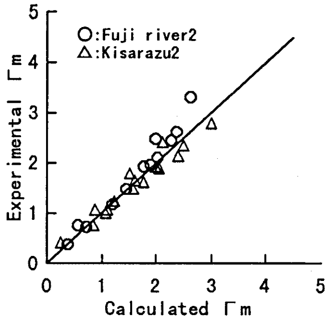


Fig.29 Relationship between calculated Γm by Eq.(18) and experimental Γm (with calculated β s0 and calculated Es0)

As shown in Fig.29, at the boundary particle size of 0.09mm, the calculated Γm is approximately equal to the experimental Γm in the case of sands other than Soma silica sand. This suggests that the boundary particle size may also be set to 0.09mm with a general sand.

As mentioned above, with MC, if the absolute water-retaining factor of the fine sand and the coarse sand and their absolute flow factors are calculated with a boundary particle size of 0.09mm, the calculated Γm may be obtained by Eq.(18) in the case of a general sand including fine particles.

Based on paste flow tests with powder of 0.09mm or less alone, such as BS or LS, it has been verified that a linear relationship exists between the relative flow area of paste and the volumetric ratio of powder to water; namely these water-retaining factors and flow factors are not affected by the powder volume [3].

Table 19 Ratio of coarse powder

Type	Coarse powder ratio (%)
MC	0
LS	5.5
BS	0
FA	7.8
MC40LS60	3.3
MC20BS80	0
MC40FA60	4.7

8. INFLUENCE OF COARSE POWDER ON MORTAR FLOW

As regards mortar deformation, it has become clear that fine sand particles of 0.09mm or less act as powder, while coarser sand particles act as sand. Powders including coarse particles of 0.09mm or more also exist. Therefore, it is conceivable that just as sand particles of 0.09mm or more act as sand, so powder particles of 0.09mm or more also act as sand. Accordingly, based on mortar flow tests with powder including coarse particles of 0.09mm or more alone, it is investigated whether coarse powder particles of 0.09mm or more act as sand.

8.1 Characteristics of powder

Blended powders, in which MC was blended with LS, BS, or FA, were used (Fig.30). Here, MC40LS60 means a volumetric ratio of 40% MC to 60% LS. Similarly, MC20BS80 means 20% MC to 80% BS, MC40FA60 means 40% MC to 60% FA. The percentage of coarse particles and coarse powder of 0.09mm or more is shown in Table 19. With MC alone, the calculated Γm was approximately equal to the experimental Γm when fine sand is regarded as powder. The reason for this is conceivably that MC includes coarse powder of 0.09mm or more.

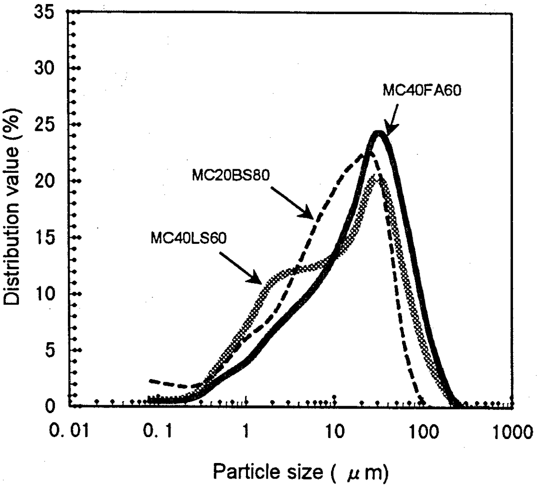


Fig.30 Particle size distribution of blended powders

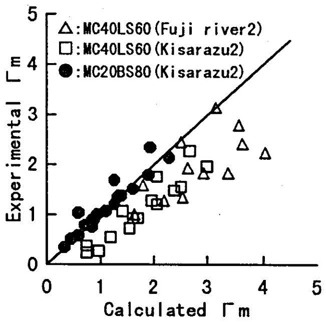


Fig.31 Relationship between calculated Γm by Eq.(18) and experimental Γm with fine sand treated as powder

8.2 Handling of coarse powder

With MC40LS60 and MC20BS80, with Fuji river2 and Kisarazu2 and regarding fine sand of 0.09mm or less as powder, Γm was calculated by Eq.(18). The relationship between calculated Γm and experimental Γm is shown in Fig.31. Here, the absolute water-retaining factors (Table 17) of the fine sand and the coarse sand were calculated by Eq.(11) and their absolute flow factors (Table 17) were the same as those of MC.

With MC40LS60, the calculated Γm is appreciably larger than the experimental Γm. However, with MC20BS80, the calculated Γm agree with the experimental Γm roughly. The reason for this is conceivably that, as shown in Table 19, like MC MC20BS80 does not include coarse powder of 0.09mm or more, and the distribution

Table 20 Material constants relating to water-retaining factor (Eq.(5)) and flow factor (Eq.(8)) for coarse sand

Type		βs0	γsi	Vsi	A	Es0	Vsr	B
MC40LS60	Fuji river2	0.16	0.47	0.31	1.4	0.037	0.59	0.001
MC40LS60	Kisarazu2	0.14	0.56	0.39	1.3	0.035	0.66	0.005
MC40FA60	Fuji river2	0.16	0.63	0.46	2.4	0.020	0.59	0.001
MC alone	Fuji river2	0.16	0.60	0.40	2.1	0.037	0.59	0.001

Table 21 Water-retaining factor calculated by (Eq.(11)) and flow factor calculated by (Eq.(17)) for fine powder and coarse powder

Type		Water-retaining factor	Flow factor	PF	SF	HF
LS	Fine	0.72	0.10	1.25	0.79	0.73
	Coarse	0.47	-0.02	0.60	0.79	1.0
FA	Fine	0.60	0.03	1.09	0.61	0.91
	Coarse	0.38	-0.04	0.62	0.61	1.0

Table 22 Water-retaining factor and flow factor of fine powder used in calculation of relative flow area

Type	Water-retaining factor	Flow factor
MC40LS60	0.81	0.10
MC40FA60	0.74	0.05

of BS is similar to that of MC, with only one peak. On the other hand, MC40LS60 includes coarse powder. The action of the coarse powder as sand is conceivably why the calculated Γm does not agree with the experimental Γm.

Therefore, powder can be distinguished as coarse particles (coarse powder) and fine particles (fine powder) at a boundary particle size of 0.09mm. Coarse powder of 0.09mm or more can be regarded as sand, and fine powder of 0.09mm or less can be regarded as powder. Then the basic equation of mortar flow (Eq.(18)) is changed to Eq.(24).

$$\frac{Vw}{Vpf+Vsf} = Em\cdot\Gamma m+\beta m \tag{24}$$

$$Em = \left(Ef+\frac{Esc\cdot Vsc+Epc\cdot Vpc}{Vpf+Vsf}\right)\times\frac{1-(Vsc+Vpc)}{1-\left\{Vsc\cdot(1+\beta sc)+Vpc\cdot(1+Q+\beta pc)\right\}} \tag{25}$$

$$\beta m = \frac{\beta f\left\{1-(Vsc+Vpc)\right\}+\beta sc\cdot Vsc+\beta pc\cdot Vpc}{1-\left\{Vsc\cdot(1+\beta sc)+Vpc\cdot(1+Q+\beta pc)\right\}} \tag{26}$$

$$\beta f = \beta pf+(\beta sf0-\beta pf)\cdot\gamma f \tag{27}$$

$$Ef = Epf+(Esf0-Epf)\cdot\gamma f \tag{28}$$

$$\gamma f = \frac{Vsf}{Vsf+Vpf} \tag{29}$$

Where Vpf is the volumetric ratio of fine powder in the mortar (Vpf = Vp-Vpc), Vpc is the volumetric ratio of coarse powder in the mortar (Vpc = Vp× κpc), Vp is the volumetric ratio of powder in the mortar, κpc is the coarse powder ratio, βpc is the water-retaining factor of coarse powder, Epc is the flow factor of coarse powder, βf is the water-retaining factor of the blend of fine sand and fine powder, Ef is the flow factor of the blend of fine sand and fine powder, β

Table 23 Material constants relating to water-retaining factor (Eq.(5)) and flow factor (Eq.(8)) for coarse sand
(Comparison between regarding coarse sand as sand and regarding coarse sand as powder)

Type	Distinction of coarse powder	Water-retaining factor				Flow factor			
		$\beta s0$	γsi	Vsi	A	Es0	Vsi	Vsr	B
LS	Sand	0.15	0.53	0.37	1.6	0.040	0.37	0.60	0.002
	Powder	0.15	0.51	0.36	1.5	0.040	0.36	0.60	0.002
FA	Sand	0.15	0.60	0.45	2.1	0.035	–	–	–
	Powder	0.15	0.56	0.42	1.8	0.035	–	–	–

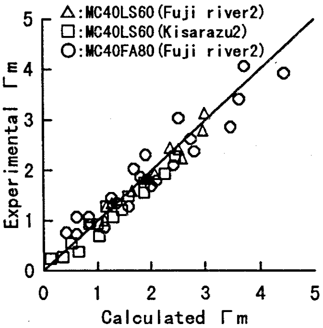


Fig.32 Relationship between calculated Γm by Eq.(24) and experimental Γm with fine sand treated as powder and coarse powder treated as sand

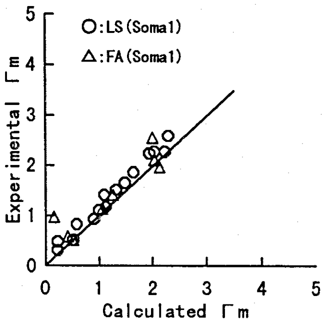


Fig.33 Relationship between calculated Γm by Eq.(24) and experimental Γm with coarse powder treated as sand with coarse sand.

pf is the water-retaining factor of fine powder, Epf is the flow factor of fine powder, and γf is the volumetric ratio of fine sand to powder.

With MC40LS60, at the boundary particle size of 0.09mm, the calculated Γm was obtained by Eq.(24). Then the relationship between the calculated Γm and experimental Γm is shown in Fig.32. Similarly, values for MC40FA60 including the coarse powder are compared. In all cases, calculated Γm is approximately equal to experimental Γm. The material constants relating to water-retaining factor and flow factor of the coarse powder and used in calculating Γm, are shown in Table 20. Here, the water-retaining factors (Table 21) of the coarse powder and the fine powder were calculated by Eq.(11) and their flow factors (Table 21) were calculated by Eq.(17). The water-retaining factor and flow factor of the blend of the fine powder (Table 22) and the fine sand were calculated by Eqs.(27) and (28). Incidentally, it is conceivable that because the flow factor of the coarse sand is affected by the particle shape of FA, its absolute flow factor is reduced. Thus, the calculated Γm was obtained by setting the absolute flow factor of the coarse sand smaller than the calculations shown in Table 17.

As shown in Table 20, Vsi with MC alone is 0.4, while Vsi with MC40LS60 is 0.31. The reason for the smaller Vsi is that particles having a diameter approximately equal to the boundary particle size increase with the coarse powder of LS and the fine sand. There is conceivably an interaction between the coarse powder and the fine sand.

As mentioned above, at the boundary particle size of 0.09mm, with absolute water-retaining factor and absolute flow factor calculated from the particle size distribution characteristics and the particle shape, the calculated Γm is obtained by Eq. (24). However, in this case, Vsi must be set to take into account the interaction between coarse powder and fine sand.

With Somal including no fine sand, and with LS alone or FA alone, if the coarse powder in these powders are treated as sand, Γm was calculated by Eq. (24). The relationship between calculated Γm and experimental Γm is shown in Fig.33. Here, the water-retaining factor and flow factor of the powders shown in Table 21 were used in Eq. (11). The calculated Γm is approximately equal to the experimental Γm. In both cases, regarding coarse powder as sand or as powder, the values of Vsi are compared. As shown in Table 23, both are approximately equal. This means that in the case of powder including coarse particles, interaction does not occur when sand including no fine particles is used.

9. CONCLUSION

In this study, based on the powder particle size distribution properties and particle shape, a method for estimating the water-retaining factor and flow factor of sand, which are properties affecting mortar fluidity, was proposed. Then, from the action of powder and sand on mortar flow, the boundary particle size between the two, and the influence of fine sand and coarse powder on mortar flow, were clarified.

The results can be summarized as follows.

(1) The absolute water-retaining factor of sand, like powder, was affected by the particle size factor, the maximum value of particle size distribution, and the sand particle shape, all of which are particle size distribution properties. It is a sand property regardless of the type powder.

(2) The absolute flow factor of sand, like powder, was affected by the particle size factor and the shape factor. It decreased when particles were globular, as in fly ash. With an uneven or angular particle, so as in cement or BS, it was a sand property regardless of the type of powder.

(3) In case of a particular powder, Vsi relates to the average distance between sand particles which was calculated by the average particle diameter and the solid volume percentage of the sand. However, with a particular sand but different powder average particle diameter, particle size distribution, and particle shape, Vsi also varied.

(4) Vsr was relates to the solid volume percentage. It is a sand property regardless of the type powder.

(5) The water-retaining factor and flow factor of powder were constant regardless of its volume. On the other hand, those of sand increased with volume when the sand volume exceeded a certain point. This is a difference between sand and powder in fresh mortar.

(6) Fine sand particles cause the absolute water-retaining factor of sand and Vsi to increase, and cause the absolute flow factor to decrease accordingly. From this result, it is clear that the boundary between powder and sand exists at about 0.90mm in this study.

(7) When coarse powder of 0.09mm or more is regarded as sand, the calculated Γm is approximately equal to the experimental Γm.

(8) In the case of the powders and sands in this study, Vsi decreased when the

both fine sand and coarse powder, were included in the fresh mortar. When only one of these was included, the variation in Vsi was small.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Kazumasa Ozawa, formerly Associate Professor in the Department of Civil Engineering at the University of Tokyo (and presently at the Research Center for Public Works Management at the Public Works Research Institute, Ministry of Construction), for his helpful suggestions and Mr. Hideki Endou of NIHON CEMENT Co., LTD., for his assistance in the experimental work and for taking the SEM photographs.

REFERENCES

[1]Edamatsu, Y., Yamaguchi, S., and Okamura, H.: "Quantification of Sand Property in View of Mortar Flow," Journal of Materials, Concrete Structures and Pavements, No.538/V-31, pp.37-46, 1996 (in Japanese)
[2]Okamura, H., Maekawa, K., and Ozawa, K.: "High Performance Concrete," pp.35-47, pp.172-176, Gihodo, 1993 (in Japanese)
[3]Edamatsu, Y., Shimokawa, K., and Okamura, H.: "Effect of Powder Character on Paste Flow," Concrete Library of JSCE, No.29, pp.249-264, 1997
[4]Uchikawa, H., Uchida, S., and Okamura, T.: "Influence of Fineness and Particle Size Distribution of Cement on Fluidity of Fresh Cement Paste, Mortar and Concrete," CAJ PROCEEDINGS OF CEMENT & CONCRETE, pp.42-47, 1989 (in Japanese)
[5]Yamaguchi, S., Edamatsu, Y., and Okamura, H.: "Characterization of sand in View of Mortar Flow," Proceedings of the Japan Concrete Institute, Vol.16, No.1, pp.83-88, 1994 (in Japanese)
[6]Takada, K.: "Prediction of Filling Capacity for Super-Flowable Concrete," Dissertation Submitted to the University of Tokyo for the Degree of Master of Engineering, pp.27-29, 1992 (in Japanese)
[7]Weymouth, C. A. G.: "Effects of Particle Interference in Mortars and Concretes (The Function of Grading of Aggregates)," Rock Products, pp.20-31, 1933
[8]Powers, T. C.: "The Properties of Fresh Concrete," John Wiley & Sons, pp.55-56, 1968