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ELECTRICAL POWER CONSUMPTION DURING MIXING OF SOLID PARTICLES

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Mixing of solid particles, which can be obtained from concrete constituent, were studied as the original point to deal with the problem of mixing concrete. Since mixing of solid particles has been considered as a fully mechanical operation, mixing will never occur unless input energy is applied. Therefore, the electrical power consumed by the mixer was selected as the parameter. This power consumption was experimentally obtained. By applying some assumptions for the state of mixture, the interaction between two different particles can be estimated from binary mixture. The method to predict the electrical power consumption for mixing of the mixture between coarse-fine-powder is also proposed.

Keywords : *mixing, solid volume, single material, mixture, electrical power consumption, energy factor*

1. INTRODUCTION

For concrete engineering; mixing must be one of the oldest processes and it has always been regarded as a simple operation. It remained one of the most neglected operations in the concrete engineering practice. Not so many serious attempts were made to investigate it in the past. This is partly because comparatively crude methods of mixing concrete can be made effective if they operate for a sufficient period of time ; but mainly it is because the fundamentals of the process are not fully understood. Therefore, the mechanism of mixing concrete is not yet well known.

It has already been reported by Uomoto et al. [1)~3)] that the inspection of the distribution of coarse particles and mortar in concrete may not be enough to evaluate good mixing. The properties of concrete both in fresh and hardened state can be significantly changed according to the electrical power consumption during mixing although concrete becomes a uniform mix as electrical power consumption increases. In order to obtain the same property concrete, concrete has to be mixed with the same total electrical power consumption per *unit volume* of concrete (EPC) regardless of the type of mixer. Although mix proportion has some effect on the relation between concrete properties and EPC,it was found that the relation is almost the same and the value of EPC at 0.5 Wh/l was proposed as the most sufficient value to mix normal concrete.

In order to study the electrical power consumption during mixing concrete, that of mixing of solid particles was studied as the original point. In most of the practical cases, it is possible to mix each concrete constituent in a dry state for a certain period of time before water is added. This paper presents experimental results of solid mixing, not only for each single material but also for the mixture, and the empirical method to predict the electrical power consumption during mixing of mixture between coarse-fine-powder is also proposed.

2. EXPERIMENTAL OUTLINE

The experiments were carried out with a "Pan" type mixer whose capacity was designed as 50 liters and constant rotation speed for all mixing volume as 74 rpm. The properties of materials used are shown in **Table 1**. In all the cases, mixing time was kept constant at 180 sec. The mixing energy is defined as the increment of the electrical power consumption during mixing from the electrical power required to drive the empty mixer.

The mixer was loaded with different volumes of each type of material in case of mixing single material. In case of binary mixtures (coarse fine, fine + powder, coarse + powder), the mixer was loaded with 30 liters of coarser particles at the beginning (ratio between solid volume of fine particles and total solid volume or $V_{sf}/V_{st}=0$) and finer particles were gradually added in order to obtain a different combination of mixture. The mixer was loaded until V_{sf}/V_{st} was approximately 0.5 because the full capacity of the mixer could be reached. The experiment of the same material was repeated by loading finer particles to the mixer first ($V_{sf}/V_{st}=1.0$) and gradually adding coarser ones until V_{sf}/V_{st} was approximately 0.5. The same

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Table 1 Properties of materials used in this study

Size (mm)	Coarse1 (G20)	Coarse2 (G13)	Fine (Sand)	Powder (Slag)
15.0-20.0	20 %	—	—	—
10.0-15.0	77 %	48 %	—	—
5.0-10.0	3 %	52 %	—	—
2.5-5.0	—	—	20 %	—
1.2-2.5	—	—	30 %	—
0.6-1.2	—	—	20 %	—
0.3-0.6	—	—	15 %	—
0.15-0.3	—	—	7 %	—
<0.15	—	—	8 %	100 %
av. dia[a] (mm)	10.15	7.65	0.22	(0.00525)
Unit weight (kg/l)	1.55	1.54	1.82	1.05
Specific gravity	2.70	2.70	2.63	2.90

Table 2 Mix proportion for mixture of three types of material

No.	Coarse,G20 (kg)	Fine,Sand (kg)	Powder,Slag (kg)
Mix 1	46.5	36.0	31.5
Mix 2	46.5	24.0	25.0
Mix 3[b]	46.5	44.5	15.9

Notes:

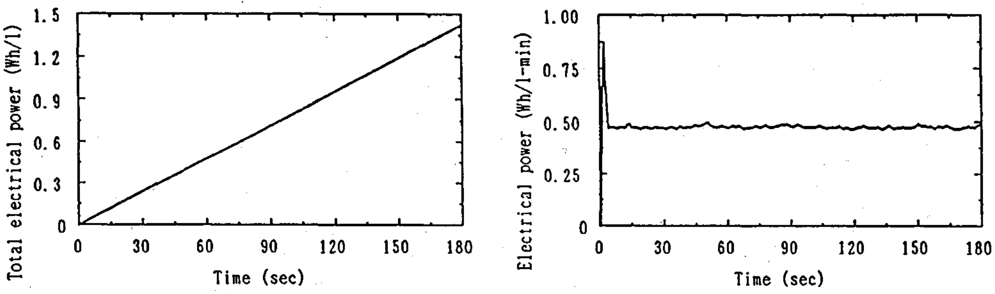
(a) Calculated from the equation recommended by Ref.[4] as:

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

where p_i is solid volume fraction of the ith size group and d_i is (2/3) of the upper seive opening

( ) Calculated from "Blaine Value" of 3940 cm^2/g

(b) All materials were loaded simultaneously into mixer



(a) Total electrical power consumption (b) Electrical power consumption per unit time

Fig.1 Mixing time and electrical power consumption per unit solid volume

loading method was also applied to the case of mixing of three types of materials (coarse+fine+powder). Three different mix proportions were tested as shown in **Table 2**. However, for analysis in this system, the solid volume of fine particles (V_{sf}) was defined as the summation of the solid volume of fine particles and powder.

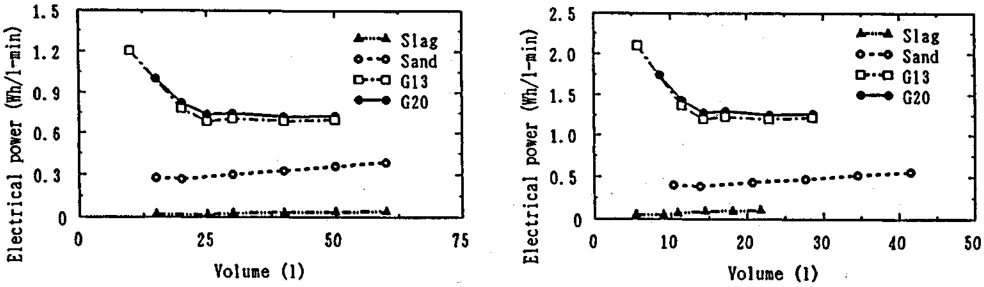
3. EXPERIMENTAL RESULTS AND DISCUSSION

The mixing of solid particles is a purely mechanical operation since there is no particulate motion equivalent to the molecular diffusion of gas and liquid. The relative movement of the particles can not occur without an energy input to the mixture in order to destroy the structure of particles and allow the particles to change their positions. Once movement begins, the particles may randomize or segregate depending on the type of movement imposed to the system (type of mixer), mix proportion and also the physical characteristics of the constituent such as size, shape, density, elasticity, etc..

An energy input to the mixture in this study can be measured by considering the electrical power consumption of the mixer during mixing. Actually the electrical power is consumed by several aspects such as interparticle friction, collision, etc.. In this study, however, interparticle friction is believed to consume the highest energy since the energy consumption by different materials at the same mixing weight were not the same. It was found that the relation between total electrical power consumption per unit solid volume (Wh/l) with time is always linear, in other words, the electrical power consumption during mixing is almost constant as shown in **Figs.1**(a) and **1**(b) respectively. From the relation shown in **Fig.1**(a), the electrical power consumption per minute of certain material and mixing volume can be calculated from the slope of this relation.

(1) Mixing of single material

The experimental results are shown in **Figs.2**(a) and **2**(b). Among the solid particles, it was found that coarse particles (G20 and G13) consumed the largest electrical power while powder (slag) consumed the least. The unit of the vertical axis, "Wh/l-min", means the energy required to mix the unit solid volume of a certain type of material for one minute. It can be observed that when the bulk volume (volume of void is included) of material inside the mixer is approximately 25 to 50 liters or about a half to full designed capacity, the electrical power consumption is almost constant as shown in **Fig.2**(a). From this observation, the bulk volume of material in mixer during mixing is controlled to



(a) Bulk volume, V (b) Solid volume, Vs

Fig.2 Electrical power consumed by each type of material

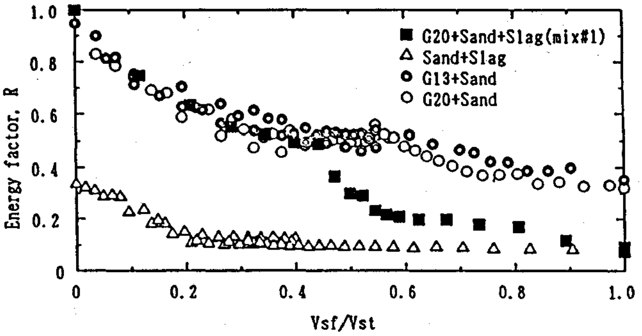


Fig.3 Energy factor of mixture with different mix proportions

vary within 25 to 50 liters for all the experimental cases in order to avoid any unexpected scattering of the results.

Since the electrical power consumption during mixing of each single material depends on many factors such as particle size, shape, surface texture etc., no accurate model to estimate the electrical power consumption during mixing has been proposed. It seems to be reasonable to obtain these values from experimental approach.

(2) Mixing of mixture

As shown in **Fig.3**, all the experimental results were plotted in the same figure. The horizontal axis is solid volume ratio of fine particles and the total solid volume in mixture. The vertical axis is "energy factor, R" obtained by normalizing the electrical power consumption per unit solid volume of mixtures by that required by coarse particles alone. In these experiments the value of 1.298 Wh/l−min is used which is the average value for G20. It can be clearly seen that once finer particles were added to the system of coarser particles (V_{sf}/V_{st} from 0.0~0.5) electrical power consumption decreased. On the other hand, if coarser particles were added to the system of finer particles (V_{sf}/V_{st} from 1.0~0.5) an adverse effect can be observed from the gradual increase in the electrical power consumption. This phenomenon can be observed in all the cases of mixture except in the case of mixing of coarse particles and powder (G20 + Slag and G13 + Slag) as shown in **Fig.7**(c) and 7(d). This is mainly because of the effect of segregation due to size difference (rather than density). Therefore, the coarse particles could not be dispersed properly when they were added to the system of powder. However, when powder was added to the system of coarse particles a reduction in the electrical power consumption can be observed.

The reduction of the electrical power is caused mainly by the higher fluidity of mixture due to the entrapment of finer particles in between the coarser particles. This entrapment is caused by a mechanism so called "interparticle percolation"[5], the penetration of the smaller particles through the large paticles simply due to gravity or subjected to some relative movement. Therefore, the interparticle friction can be changed from completely coarse-coarse interaction to a combination of coarse-coarse, coarse-fine and fine-fine interaction (**Fig.4**). When the amount of fine particles exceeds certain value, the mixture will behave just in the same manner with the fine particles in between them. This may be due to the interparticle friction controlled mainly by fine-fine interaction (see also **Fig.5**).

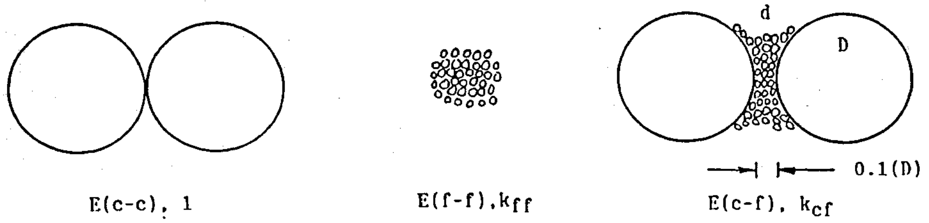
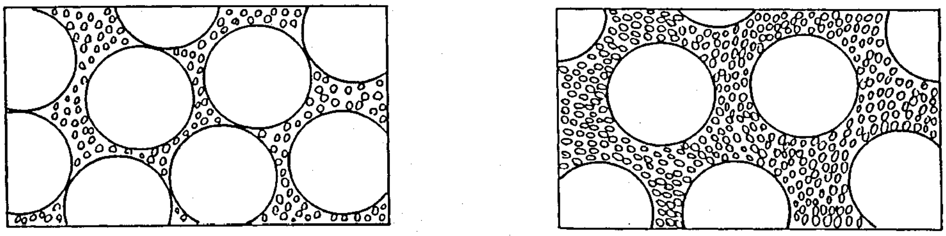


Fig.4 Model for interparticle friction



(a) Mixture with rich amount of coarse particles (b) Mixture with rich amount of fine particles

Fig.5 The possible arrangement of particles in the mixture of coarse and fine particles

4. PROPOSED METHOD TO PREDICT THE ELECTRICAL POWER CONSUMPTION FOR MIXING OF SOLID PARTICLES

(1)Binary Mixture

As mentioned previously, the electrical power consumption during mixing of solid particles is consumed mainly by the interparticle friction. The possible types of interparticle friction are discussed in 3.2. In order to predict the electrical power consumption, it is assumed that the total electrical power during mixing can be considered as the summation of the electrical power required by each type of interparticle friction existing in the mixture. This can be represented as follows :

$$E_m = n_1 E(c-c) + n_2 E(c-f) + n_3 E(f-f) \cdots (1)$$

where

E_m = electrical power required for mixture per unit solid volume
$E(c-c)$ = electrical power required for coarse-coarse interaction per unit solid volume
$E(c-f)$ = electrical power required for coarse-fine interaction per unit solid volume
$E(f-f)$ = electrical power required for fine-fine interaction per unit solid volume
n_1 = solid volume fraction corresponding to coarse-coarse interaction
n_2 = solid volume fraction corresponding to coarse-fine interaction
n_3 = solid volume fraction corresponding to fine-fine interaction

Normalizing the electrical power required by mixture by that required by coarse-coarse interaction alone we can obtain the equation for "energy factor, R" as a function of "energy factor, k" which corresponding to the energy required by each type of interparticle friction as in the following :

$$\frac{E_m}{E(c-c)} = R = n_1 k_{cc} + n_2 k_{cf} + n_3 k_{ff} \cdots\cdots\cdots (2)$$

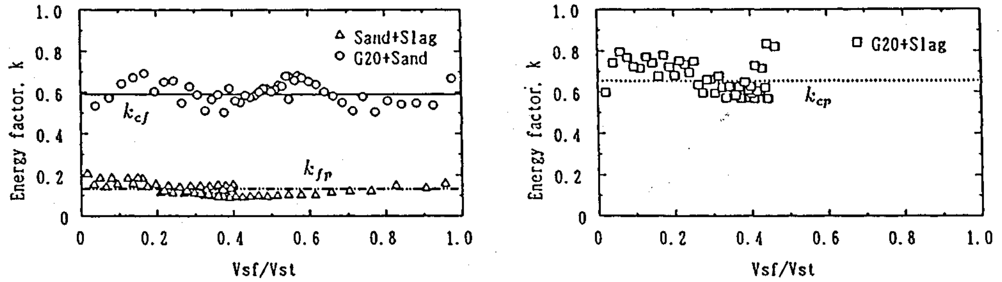
where

R = energy factor corresponding to the energy required by mixture
k_{cc} = energy factor corresponding to the energy required by coarse-coarse interaction (equal to 1.0)
k_{cf} = energy factor corresponding to the energy required by coarse-fine interaction
k_{ff} = energy factor corresponding to the energy required by fine-fine interaction

In order to predict the electrical power required by the mixer, the idealized state of mixture during mixing is considered. This state can be changed according to the mix proportion as shown in Figs.5(a) and 5(b). It should be kept in mind that this idealized state of mixture may not be attained after the mixing process, because the force of attraction between solid particles does not exist. In the case of mixture with rich amount of coarse particles, segregation of fine particles to the bottom of the mixer usually takes place.

Besides considering the idealized state of mixture during mixing the following assumptions are also considered.

1. All particles are sphere.



(a) k for coarsel-fine and fine-powder (b) k for coarsel-powder

Fig.6 Energy factor, k corresponding to the interaction between particles

2. When the amount of fine particles in mixture is enough to coat all the surface of coarse particles, no contribution of coarse-coarse interaction to the electrical power consumption ; $n_1=0$
3. When the amount of fine particles in mixture is not enough to coat all the surface coarse particles, no contribution of fine-fine interaction to the electrical power consumption ; $n_3=0$
4. The fine-fine interaction can be developed by excessive fine particles defined as the rest of fine particles from the amount required to coat all the surface of coarse particles ; n_3
5. The coarse-coarse interaction can be developed by excessive coarse particles defined as the rest of coarse particles from the amount which can be coated by fine particles ; n_1
6. The electrical power consumed by the coarse-fine interaction is constant for all mixing volume. This interaction can be contributed to the electrical power consumed by mixture of coarse particles and fine particles required to coat their surface ; n_2
7. The amount of fine particles required to coat the surface of coarse particles is defined as the amount of fine particles needed to entrap in between coarse particles and to separate the coarse particles apart up to a distance of 10 % of diameter of coarse particle.

Consider diameter of large and small particles as D and d, where D≫d. Surface area of a large particle is πD^2. The area occupied by each small particle adhering to a large particle will be the projection area of $\pi\frac{d^2}{4}$. Therefore the number of small particles adhering to each largeone in a monolayer is $\frac{4D^2}{d^2}$ or approximately $k\frac{4D^2}{d^2}$ in k layers. According to assumption (7) the number of layers can be estimated as :

$$k=\frac{0.1D}{2d}=0.05\frac{D}{d}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(3)$$

Therefore, the solid volume of fine particles required to coat all the surface of coarse particle can be calculated. By utilizing all the above assumptions, the equation to predict the electrical power consumption during mixing or energy factor of binary mixture can be written in a bilinear relation as in the following equations :

$$R=\frac{V_{sc}+V_{sf1}}{V_{st}}k_{cf}+\frac{V_{sf2}}{V_{st}}k_{ff}\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

when no excessive coarse particles exist

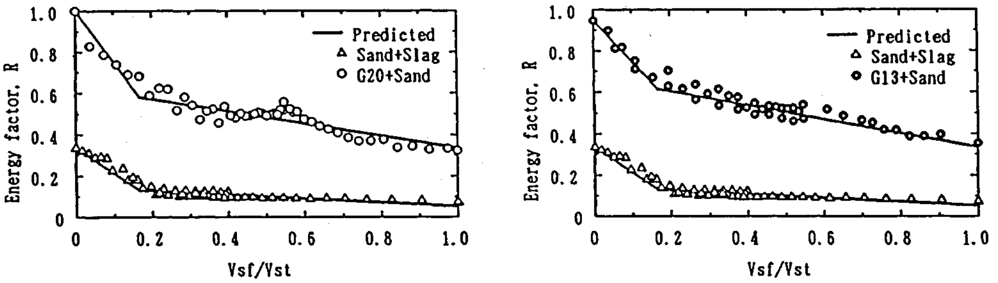
$$R=\frac{V_{sf}+V_{sc1}}{V_{st}}k_{cf}+\frac{V_{sc2}}{V_{st}}\cdots\cdots\cdots\cdots\cdots\cdots\cdots(5)$$

when no excessive fine particles exist

where

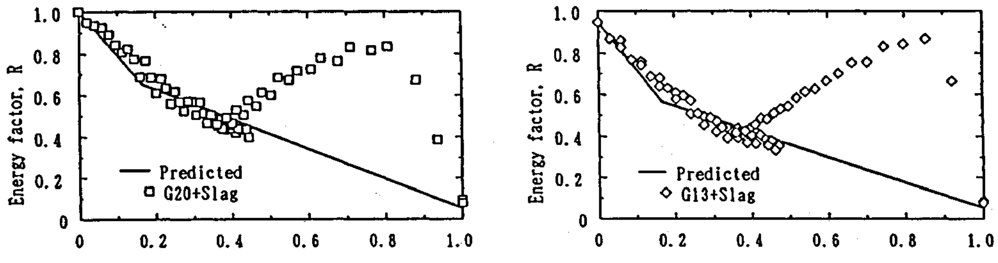
V_{sc}= solid volume of coarse particles
V_{sc1}= solid volume of coarse particles which can be coated by fine particles
V_{sc2}= solid volume of excessive coarse particles
V_{sf}= solid volume of fine particles
V_{sf1}= solid volume of fine particles required to coat all the surface of coarse particles
V_{sf2}= solid volume of excessive fine particles
V_{st}= total solid volume

By applying the same way of thinking, the equation for mixture of coarse-powder as well as fine-powder can be written in the same manner as shown in equations (4) and (5) by simply considering the larger particles as coarse particles and the smaller one as fine particles. The energy factor, k for the corresponding particle interaction such as coarse-fine (k_{cf}), fine-powder (k_{fp}) and coarse-power (k_{cp}) can be calculated by substituting the experimental results to equations (4) and (5). It can be found that these interactions are almost constant for all mix proportions as shown in **Fig.6**. According to the assumption (6), the average values are used as the representatives. The results of the calculated energy factor made by adopting the above equations are shown in **Fig.7**. From **Fig.7**(c) and 7(d) which represent the mixing of



(a) coarse1-fine and fine-powder

(b) coarse2-fine and fine-powder



(c) coarse1-powder

(d) coarse2-powder

Fig.7 Comparision between predicted energy factor, R and the experimental results

coarse particles and powder. Segregation of coarse particles was detected during mixing when coarse particles were added to the system of powder and the energy consumption was much larger that predicted value. This implies that the idealized state of mixture can not be obtained if the difference between predicted electrical power required during mixing and the experimental one is quite large.

(2) Mixture of three types of material (coarse-fine-powder)

By the same concept as for binary mixture, the electrical power required during mixing of three types of material can be estimated by the following equation :

$$\frac{E_m}{E(c-c)}=R=n_1k_{cc}+n_2k_{cf}+n_3k_{ff}+n_4k_{cp}+n_5k_{pp}+n_6k_{fp}+n_7k_{cfp} \cdots\cdots (6)$$

where

n_1, n_2, n_3, k_{cc}, k_{cf} and k_{ff} are the same as the case of binary mixture

n_4= solid volume fraction corresponding to coarse-powder interaction

n_5= solid volume fraction corresponding to powder-powder interaction

n_6= solid volume fraction corresponding to fine-powder interaction

n_7= solid volume fraction corresponding to coarse-fine-powder interaction

k_{cp}= energy factor corresponding to the energy required by coarse-powder interaction

k_{pp}= energy factor corresponding to the energy required by powder-powder interaction

k_{fp}= energy factor corresponding to the energy required by fine-powder interaction

k_{cfp}= energy factor corresponding to the energy required by coarse-fine-powder interaction

By assuming that the mixture of three types of material can be obtained by adding powder to the system of binary mixture of coarse and fine particles. Considering all the assumptions as in the case of the binary mixture, then equation (6) can be simplified. The possible combinations are shown in **Fig.8**. From equation (6), all the binary interaction such as k_{cf}, k_{cp}, k_{fp} can be obtained from the previous section. However, k_{cfp} is still unknown. Since the electrical power consumption has been observed to be reduced significantly when powder was added to the binary mixture of coarse and fine particles (see also **Fig.3**). Then k_{cfp} is assumed as :

$$k_{cfp}=\beta * k_{cf} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

where β=non-dimensional reduction factor

The value of β can be defined by considering the following system

$$\boxed{\begin{array}{c} V_{sf} \\ \hline V_{sc} \end{array}} + \boxed{\begin{array}{c} V_{sp}= \\ V_{sp1}+V_{sp2} \end{array}} = \boxed{\begin{array}{c} V_{sp1} \\ \hline V_{sc} \end{array}} + \boxed{\begin{array}{c} V_{sp2} \\ \hline V_{sf} \end{array}}$$

From the above diagram, on the left hand side, considering the binary system consists of V_{sc} and

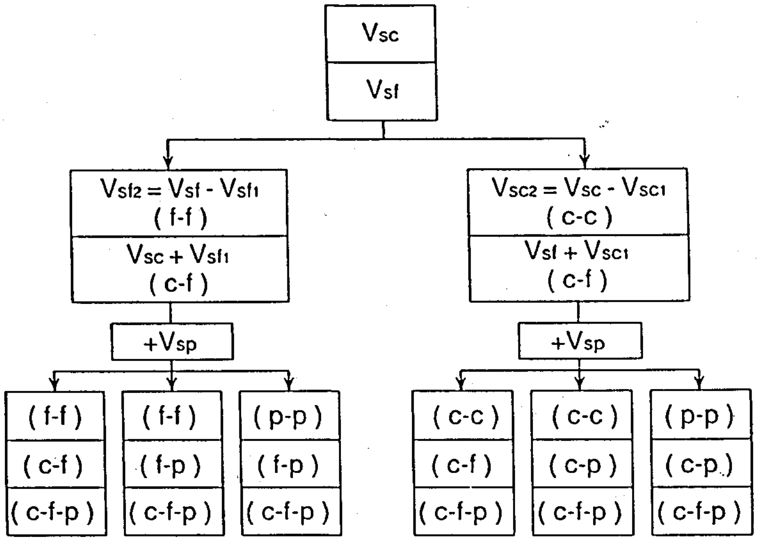


Fig.8 Possible combination of mixture among coarse-fine-powder

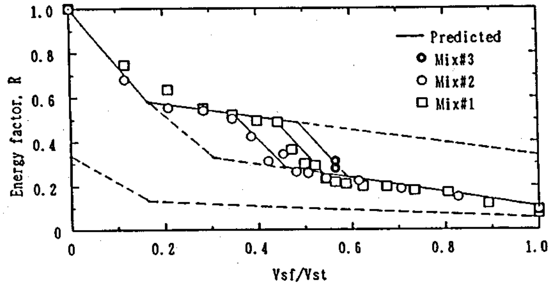


Fig.9 Mixture of coarse-fine-powder

V_{sf}, the amount of V_{sf} is exactly equal to the amount required to coat all the surface of V_{sc}. Then powder with an amount of V_{sp} which is exactly equal to the amount required to coat all the surface of V_{sc} (V_{sp1}) and V_{sf} (V_{sp2}) is added to form mixture of three type of materials. This system is devided to become two independent sub-systems, coarse-powder and fine-powder systems, as shown in the right hand side of the diagram. Then β is defined as :

$$\beta=\frac{V_{sc}+V_{sp1}}{V_{sc}+V_{sf}+V_{sp}}k_{cp}+\frac{V_{sf}+V_{sp2}}{V_{sc}+V_{sf}+V_{sp}}k_{fp}\cdot\cdot(8)$$

Three different mix proportions as in **Table 2** were tested. In **Fig.9**, a comparison between the experimental results and the predicted curves obtained from equations (6)~(8) is shown. Fair agreement can be observed.

5. CONCLUSIONS

1. The linear relation between total electrical power consumption per unit solid volume and time can be observed for all the experimental cases of solid mixing.
2. Among the solids, the largest electrical power is consumed by coarse particles, the least is consumed by powder while the electrical power consumed by fine particles is in between.
3. The electrical power consumption per unit solid volume during mixing can be reduced significantly by the addition of fine particles.
4. The electrical power required during mixing of binary mixture can be empirically obtained by summarizing all the power required by each type of interparticle friction existing in mixture namely, coarse - coarse, fine - fine or coarse - fine interaction.
5. The electrical power required by mixture of coarse-fine-powder can be estimated by the same idea as for binary mixture associated with the value of k_{cfp} which represents the interparticle friction of coarse-fine-powder.

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骨材,粉体の混合時における消費電力量

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本研究は，コンクリートの練りまぜ機構に関する研究を実施する第1段階として，水をのぞいたコンクリートの構成材料である粗骨材，細骨材,粉体の混合について検討したものである，これらの固体材料を混合する場合には，外部から機械的なエネルギーを加えることが必要であることから，ミキサで消費される電力量を指標とした．これらの単一材料および混合物の消費電力量を実験から求めるとともに，粗骨材と細骨材，細骨材と粉体，粗骨材と粉体の混合時消費電力量の推定方法を提案した．また，粗骨材，細骨材,粉体の3種類の材料を混合する場合の消費電力量の推定方法についても提案した．