A STUDY OF MIXTURE DESIGN AND QUALITY CONTROL METHODOLOGY FOR HIGH FLY-ASH CONCRETE

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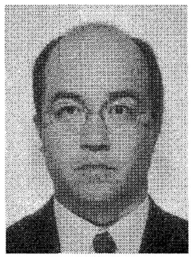
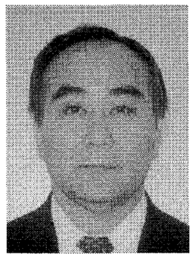
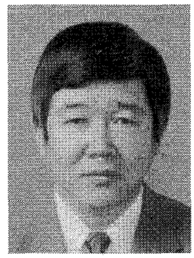

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A mixture of fly ash and cement with a water-to-powder ratio close to the optimum moisture content has the characteristics of a wet powder immediately after mixing. After a few minutes of vibration compaction, however, the wet powder becomes fluidized and can be adequately compacted. By using this fluidization phenomenon in the manufacturing process, the water-to-powder ratio and cement content can be reduced. This in turn improves the quality and cost efficiency of high fly-ash concrete. In this study, the authors investigate methods of mixture design and quality control for such high fly-ash concrete. The work demonstrates that an optimum mixture can be determined through flow tests on fly ash, while the quality of high fly-ash concrete can be controlled in terms of fluidization time.

Keywords : fly ash, high fly-ash concrete, optimum moisture content, vibrating compaction, fluidization phenomenon, mixture design, quality control

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1. INTRODUCTION

As the construction of coal-burning power plants has accelerated in recent years, the production of coal ash is rapidly increasing. Annual output of coal ash, which is 6 million tons in Japan at present, will exceed 10 million tons by 2010 [1].

Against this background, the authors have developed a technology to produce hardened material containing a large amount of raw fly ash [2],[3](and called "high fly-ash concrete"). The authors have also studied the application of this type of concrete to marine structures, where it is likely to find wide use. Such structures include man-made reefs for attracting fish and artificial sandbanks and ridges on the seabed to provide habitat for fish. In carrying out this work, the authors noted that the properties of a mixture of cement and fly ash, which takes the form of a wet powder immediately after mixing when the water-to-powder ratio is close to the optimum moisture content, change under the influence of vibration. Vibration induces fluidization, which enables compaction of the mixture [4],[5],[6]. By making use of this phenomenon, it should be possible to produce high-quality fly-ash concrete economically using large amounts of fly ash, since both the water and cement ratios can be significantly reduced.

To ensure a continuous supply of power, fuel coal of many different kinds from different sources is used at power plants. Coal from various sources is blended before firing to meet the combustion requirements of the plant, and coal mixtures can be broadly classified according to the type of blend. Further, fly-ash quality varies widely according to the type and size of a power plant's boilers and the combustion characteristics of the coal. With such high proportions of fly ash being used in concrete, the quality of the final product depends greatly on the fly ash used [4]. However, to make most effective use of this industrial by-product, the raw fly ash produced by a plant would ideally be used without sorting or blending. To this end, methods of identifying the quality of fly ash and then selecting an optimum mixture need to be developed.

In this study, we investigate a mixture design method applicable to a range of conditions (of fly-ash quality and vibration compaction), and establish quality control methods. In doing this, we analyze the characteristics of vibration compaction and compressive strength of various high fly-ash concrete.

2. STUDY OF MIXTURE DESIGN

2.1 Relationship between water-to-powder ratio and compressive strength

Of the 15 types of fly ash shown in **Table 1**, ten (G to P) were examined to determine the relationship between water-to-powder ratio (W/(C+F)) and compressive strength. Ordinary Portland cement was used in these tests and the cement content was 15% (C/C+F). Compressive strength tests were conducted pursuant to JIS A 1108 standards, using specimens of uniform size measuring 10 cm x 20 cm at an age of 28 days. The specimens were compacted on the table of a large VC testing machine; test conditions were 66.7 Hz vibration frequency, 1 mm (full span) amplitude, and duration of 5 minutes. The mass of each specimen was measured immediately after compaction. Its dry density was also calculated from the form volume and the mix proportion. Curing was standard water curing.

Fig.1 shows the relationships between water-to-powder ratio and compressive strength. As this makes clear, it is not necessarily true that a lower water-to-powder ratio corresponds to higher compressive strength; there is a particular water-to-powder ratio at which the compressive strength reaches a maximum. **Fig.2** shows the relationship between dry density immediately after compaction and compressive strength. There is a strong correlation between dry density and compressive strength: the higher the dry density, the higher the compressive strength. It has already been noted in a previous report on compaction by ramming that there exists an optimum moisture content that maximizes dry density, and this is true also when vibration compaction is adopted [7],[8]. Therefore, the optimum moisture content when vibration compaction is used should be approximately that which yields the greatest compressive strength. This optimum moisture content is the weight ratio of water to powder (C+F) that yields the maximum dry density. In order to distinguish this from the value obtained for the case of ramming compaction, it is specifically referred to as the "optimum moisture content by vibration compaction".

In designing a mixture proportion for high fly-ash concrete, it is desirable to choose water to powder ratio that gives maximum compressive strength. When designing the mixture proportion for maximum compressive strength, it is important to accurately determine the optimum moisture content particular to vibration compaction. The term "optimum moisture content" expresses a soil condition that exists in nature, but is not suitable description for a

Table1 Properties of fly ash

Fly Ash	Density (g/cm³)	Blaine specific surface area (mm²/g)	Optimum moisture Content (wt.%)	Maximum dry density (g/cm³)	Chemical composition (wt.%)							
					Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	NaO	TiO_2
A	2.21	33.5	27.8	1.240	2.7	63.9	28.0	4.6	0.9	0.6	0.3	1.7
B	2.31	24.3	18.2	1.510	0.5	61.6	18.1	4.3	9.6	2.1	1.6	1.0
C	2.24	23.2	21.8	1.411	0.5	64.7	23.0	3.7	4.7	1.3	0.7	1.2
D	2.23	32.2	22.0	1.430	0.9	62.8	26.7	4.0	2.6	0.8	0.6	1.6
E	2.19	34.5	32.0	1.157	1.3	77.2	18.1	2.4	0.4	0.4	0.2	0.9
F	2.17	38.4	25.1	1.340	1.1	61.4	31.5	2.2	0.6	0.3	0.3	1.4
G	2.37	29.6	15.8	1.648	0.6	59.2	18.1	5.0	9.2	1.8	2.2	1.0
H	2.33	30.5	17.0	1.542	1.3	56.1	23.2	5.9	6.3	1.6	1.4	1.5
I	2.24	35.2	22.8	1.432	2.0	58.7	26.5	5.6	2.6	0.9	0.4	1.7
J	2.20	29.4	22.9	1.378	2.4	57.6	28.0	7.7	1.2	0.7	0.2	1.5
K	2.21	26.7	26.0	1.313	1.7	49.6	30.3	5.0	7.0	2.5	0.4	1.4
L	2.25	38.2	25.9	1.330	6.3	52.0	25.6	6.2	3.4	1.3	0.7	1.4
N	2.20	32.5	28.0	1.251	1.1	43.9	41.1	3.7	6.1	0.4	0.2	1.6
O	2.21	31.8	21.8	1.407	1.8	55.8	27.6	3.6	6.5	1.2	0.3	1.1
P	2.20	38.5	29.7	1.239	3.4	69.2	18.6	4.1	1.7	0.6	0.6	0.7

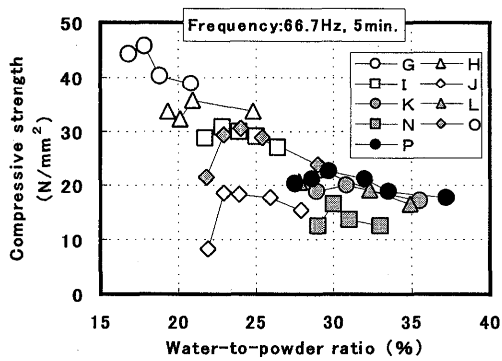

Fig.1 Compressive strength versus water-to-powder ratio

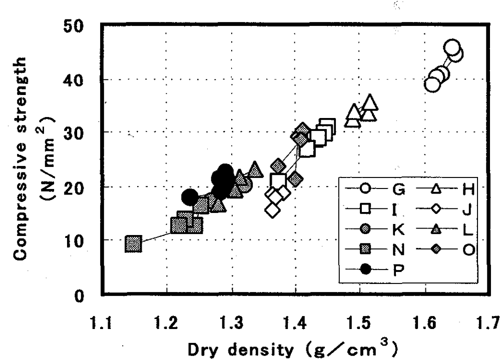

Fig.2 Compressive strength versus dry density

concrete mix. Therefore, the water-to-powder ratio that is equivalent to the optimum moisture content by vibration compaction (and that maximizes the compressive strength) is called here the "optimum water-to-powder ratio."

2.2 Introduction of coefficient to represent water-to-powder ratio

In a previous report on this subject, it was found that there is a strong correlation between water-to-powder ratio yielding a flow value of 140 and the optimum water-to-powder ratio (when compacted at a frequency of 66.7 Hz for 5 minutes). This W140 index is a useful way to estimate the optimum water-to-powder ratio [4],[5]. **Fig.3** shows the relationship between water-to-powder ratio that yields a flow value of 140 and the optimum water-to-powder ratio. This figure demonstrates that the optimum water-to-powder ratio can be estimated fairly accurately for compacting conditions identical to those noted above. However, the optimum water-to-powder ratio does vary with compaction conditions [8], and so it should be selected according to compacting conditions. In actual production, some minor adjustments will be needed to respond to the specific local characteristics of vibration compaction, as described later in this report.

The authors considered it reasonable to introduce a dimensionless coefficient to represent the water-to-powder ratio, thus eliminating the need to consider the various optimum values depending on compaction. The water-to-powder ratio that gives a flow value of 140 is defined as the standard water-to-powder ratio, because it has a strong correlation with optimum water-to-powder ratio. In the previous report, a limit water-to-powder ratio was defined as the value at which fluidization would occur just occur with a five-minute vibration time (fluidization time): the "critical water to powder ratio." It was noted that there is also a strong correlation between this value and the optimum water-to-powder ratio [8]. Fluidization time in this context means the time for which continuous vibration is applied to the wet powder before its behavior becomes that of a viscous liquid, as observed visually and measured through vibration compaction tests [8].

As shown in **Fig.4**, there is a strong correlation between the water-to-powder ratio equivalent to a flow value of 140 and the critical water-to-powder ratio. Thus, the critical water-to-powder ratio can also be used as an index in the selection of optimum water-to-powder ratio. As already noted, this critical water-to-powder ratio is for the condition that vibration is at a frequency of 66.7 Hz, while it is constant all kinds of fly ash. Vibration should be provided by the same vibrating table.

Taking into account the considerations above, coefficient α is proposed in this report as representing the water-to-powder ratio equivalent to a flow value of 140 and the critical water-to-powder ratio:

$$\alpha = \{(W/(C+F) - Wlim\} / (Wf140 - Wlim) \quad (1)$$

Where, W/(C+F) is water-to-powder ratio, Wlim is the critical water-to-powder ratio at a vibration frequency of 66.7 Hz, and Wf140 is the water-to-powder ratio equivalent to a flow value of 140.

In equation (1), the water-to-powder ratio is equal to Wlim when $\alpha = 0$ and to Wf140 when $\alpha = 1$. Therefore, within the compacting conditions covered in this study, the coefficient α of optimum water-to-powder ratio should lie between 0 and 1. The next step is to examine whether coefficient α is a suitable coefficient for use in selecting the optimum water-to-powder ratio.

In the relationship between water-to-powder ratio and dry density [8]. (**Fig.5**), dry density was divided by maximum dry density to provide a normalized value. Similarly the water-to-powder ratio was converted into the coefficient α so that the relationships among values could be analyzed. **Fig.6** shows the ratios of coefficient α and dry density against maximum dry density. Although the distributions of values are somewhat non-uniform in the figure, depending on the different qualities of the fly ashes, the value of coefficient α at the optimum water-to-powder ratio (αopt) is within the range 0.16-0.27. The value of α, which is the optimum water-to-powder ratio for vibration at a frequency of 66.7 Hz and for 5 minutes, is the mean, or 0.23. **Fig.7** shows the relationship between optimum water-to-powder ratio and estimation errors when αopt is 0.23. While the estimation error in water-

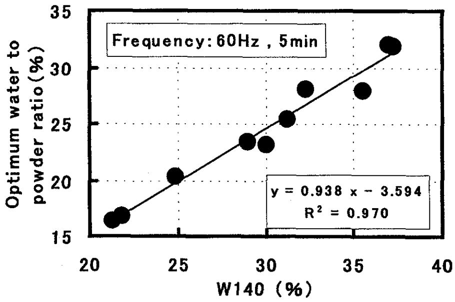

Fig.3 Optimum water-to-powder ratio versus W140

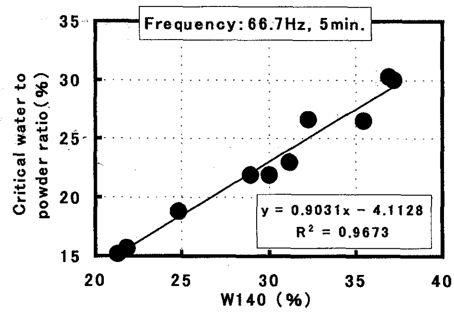

Fig.4 Critical water-to-powder ratio versus W140

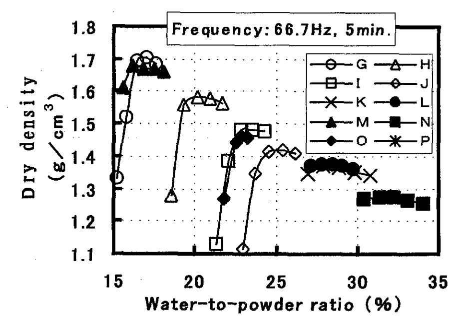

Fig.5 Dry density versus water-to-powder ratio

to-powder ratio is approximately ±0.5%, this value does not depend on the magnitude of optimum water-to-powder ratio. Further, even if these discrepancies appear in **Fig.1** and **Fig.5**, in practice they have negligible effect on dry density and compressive strength. Therefore, the optimum water-to-powder ratio is close to the same α value regardless of the quality of the fly ash. If α opt is given, the optimum water-to-powder ratio (Wopt) is given by:

$$Wopt = Wlim + \alpha opt \cdot (Wf140 - Wlim) \qquad (2)$$

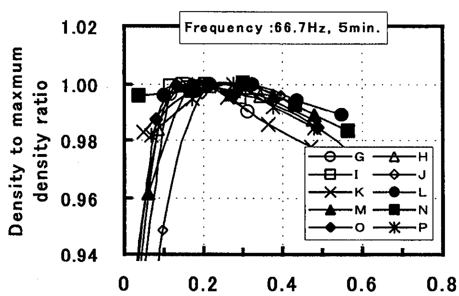

Fig.6 Dry density to maximum dry density ratio versus α

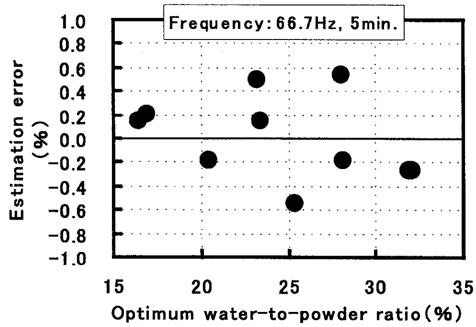

Fig.7 Estimation error versus optimim water-to- powder Ratio

2.3 Methods of selecting optimum water-to-powder ratio in response to vibration conditions

The value α opt = 0.23 yields the optimum water-to-powder ratio under conditions where the vibration frequency is 66.7 Hz, the amplitude is 1 mm (full span), and the vibration time is 5 minutes. The value of α opt must be properly defined for each set of vibration conditions. A further investigation was carried out to establish a selection method for α opt according to vibration conditions. The value of α opt was calculated for various conditions, based on the relationship between vibration frequency, time of vibration, and optimum water-to-powder ratio [8]. **Fig.8** shows the relationship between vibration time and α opt for different vibration frequencies.

The value of α opt is approximately constant at a frequency of 33.3 Hz regardless of vibration time. However, at both 50.0 Hz and 66.7 Hz, the longer the vibration time, the smaller the value of α opt. As the vibration frequency increases and vibration time becomes longer, the values of α opt and/or optimum water-to-powder ratio decrease. With given additional external force (vibration energy), the mixture can be compacted at a lower water-to-powder ratio. Thus, the vibration energy for each vibration condition was calculated to determine its relation with α opt.

The vibration energy acting upon a unit volume of a specimen is obtained by solving the following equation [9] :

$$E = m \cdot \alpha_{max}^{2} \cdot t / ((2\pi)^2 \cdot f) \qquad (3)$$

Where, E is vibration energy (J/l), f is vibration frequency (l/S), t is vibration time (s), amax is maximum acceleration (m/s^2), and m is the density of the specimen (kg/l).

Fig.9 shows the relationship between vibration energy and α opt. Depending on vibration frequency, some results appear somewhat inconsistent. These inconsistencies may have resulted from errors in measuring the optimum water-to-powder ratio and from loss of energy at high frequencies. In practice, the value of α opt that gives the optimum water-to-powder ratio can be forecast from the calculated vibration energy.

As indicated in **Fig.8** and **Fig.9**, the optimum water-to-powder ratio as represented by α opt may include a discrepancy of up to about 0.05 depending on the quality of the fly ash. With a vibration frequency of more than 50

Hz to ensure that the fly ash is fluidized by the vibration [8], however, the value of α opt is between 0.1 and 0.4. The discrepancy is rather large compared with this possible range of α opt, although still small compared with the variation in optimum water-to-powder ratio resulting from the use of different fly ashes (15-30%). In this study, no compaction tests with variables as parameters were conducted except in the case of the fly ash O. Further studies on whether the relationships indicated in **Fig.9** are applicable to other fly ashes need to be carried out in future.

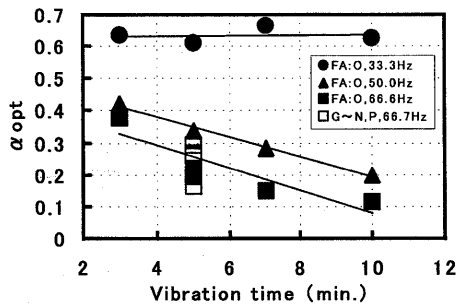

Fig.8 α opt versus vibrarion time

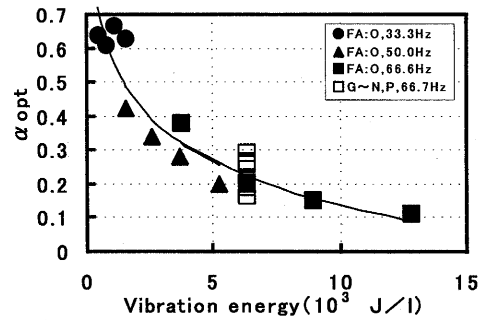

Fig.9 α opt versus vibrarion energy

2.4 Study of cement content selection

As discussed in 2.1, since the optimum water-to-powder ratio varies significantly with the source and quality of the fly ash, the cement content of a mixture must be defined according to the optimum water-to-powder ratio such that a hardened mass of required performance is produced economically. There are varying requirements for the hardened mass depending on the actual application. In this study, however, the features and requirements of compressive strength are addressed to define the cement content in a mixture that satisfies those qualities, as compressive strength represents the required performance for the fly ash products.

Using the 15 fly ashes indicated in **Table 1**, the compressive strength of each material was tested for a constant cement content (C/(C+F): 15%) but differing water-to-powder ratios. Since the compressive strength decreases as the water-to-powder ratio falls below the optimum value, the water-to-powder ratio was changed between the optimum ratio and the ratio that yields a flow value of 140. Another test for compressive strength was conducted for 6 different fly ashes (B, C, D, E, F, and N) by changing the cement content to either 10% or 20%. Ordinary Portland cement was used for all tests. Compressive strength measurements were carried out according to the JIS A 1108 standard at an age of 28 days; specimens were cylinders measuring 10 cm in diameter and 20 cm in height. The specimens were compacted on the table of a large VC testing machine, and the test conditions were a 66.7 Hz vibration frequency, 1 mm (full span) amplitude, and a duration of 5 minutes.

Fig.10 shows the relationship between water-to-powder ratio and compressive strength when the cement content is kept constant (at C/(C+F): 15%). Though the distribution of the test results is non-uniform according to the type of fly ash used, the water-to-powder content and compressive strength correlate almost linearly. In practice, the compressive strength can be forecast on the basis of the calculated water-to-powder ratio [4].

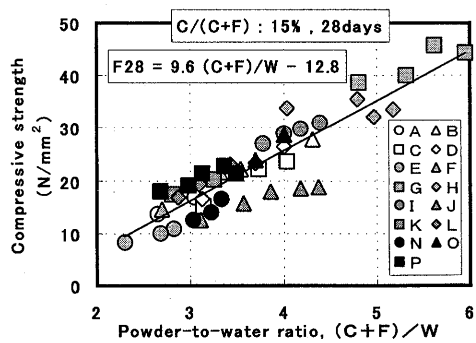

Fig.10 Compressive strength versus powder-to-water ratio

Fig.11 shows the relationship between cement content and compressive strength. As indicated, cement content and compressive strength are almost linearly correlated ratio [4]. Using these test results, we calculated the cement content that yields the standard compressive strength (defined here as 20 N/mm^2) and analyzed how variations in the cement content relate to the compressive strength.

Fig.12 shows the relationship between cement content and compressive strength. A single straight line can be drawn through these points regardless of the type of fly ash. This suggests that the optimum mixture proportion can be selected according to fly ash quality as described below.

First, we estimate the compressive strength when the cement content is 15%, based on **Fig.10** and the optimum water-to-powder ratio. Then the cement content is adjusted according to the discrepancy between the target strength and the estimated strength.

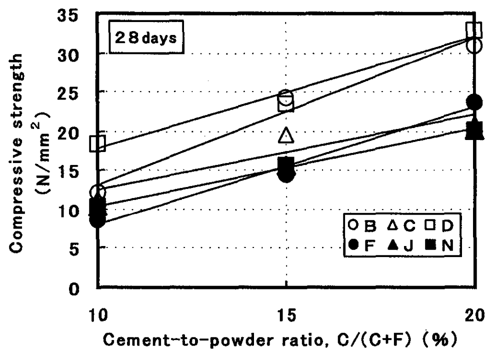

Fig.11 Compressive strength versus cement-to-powder ratio

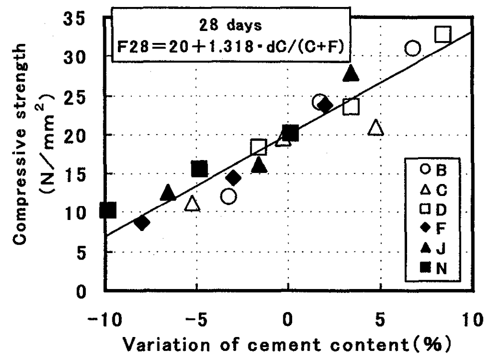

Fig.12 Compressive strength versus variation of cement content

2.5 Proposed design method for mixture proportion

As outlined in sections 2.1-2.4, the process described below can be used to set up an ideal mixture. **Fig.13** is a flow chart of the mixture design process.

(1) Set-up of vibration conditions
Prepare the conditions for vibration compaction, taking into account the production facilities and their efficiency.

(2) Select α opt value
Calculate the vibration energy provided by the vibration conditions, then select the optimum value of coefficient α opt. **(Fig.9)**

(3) Quality tests on fly ash
Using fly ash actually supplied, calculate the relationship between water-to-powder ratio and flow value. Measure the water-to-powder ratio that yields a flow value of 140. Measure the density of the fly ash according to JIS R 5201.

(4) Assumption of critical water-to-powder ratio
Choose an assumed value of critical water-to-powder ratio (Wlim) (see **Fig.4**) based on the water-to-powder ratio (WF140) that yields a flow value of 140.

$$Wlim = 0.903 \cdot Wf149 - 4.11 \qquad (4)$$

(5) Calculation of optimum water-to-powder ratio
Calculate the optimum water-to-powder ratio (Wopt) using WF140, Wlim, and α opt.

$$Wopt = Wlim + \alpha opt \cdot (Wf140 - Wlim) \qquad (5)$$

(6) Calculation of cement content
Forecast the compressive strength (at an age of 28 days, F28C: 15) for a cement content of 15%, taking into account the water-to-powder ratio. Adjust the cement content (C/(C+F)) to obtain the target compressive strength (F28), filling the discrepancy with the forecast strength.

$$F28_{C:15}=9.31\cdot(C+F)/W-11.8 \quad (6)$$
$$C/(C+F)=15-(F28-F28_{C:15})/1.318 \quad (7)$$

(7) Designing mixture proportion
Select the mixture proportion based on the factors of water-to-powder ratio, cement content, and the densities of the cement and fly ash.

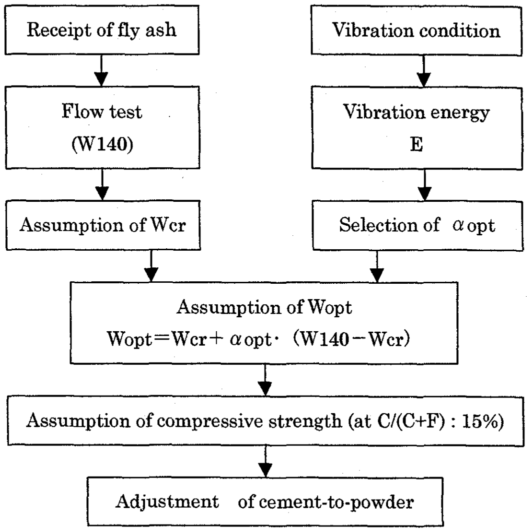

Fig.13 Flow for selection of mix proportion

Using this method, flow tests and density measurements can be used as the basis for rapid mixture design according to the quality of the fly ash. However, the values obtained may include certain errors and discrepancies. Such disparities are a result of a lack of data on vibration compaction for different types of fly ash under varying vibration conditions. Another cause of error is that material strength depends on the quality of the fly ash. Though such errors and discrepancies can be taken into account in actual application of this method, more data should be accumulated so as to improve the equations. Further, all the equations used are based on the precondition that ordinary Portland cement is used. Different cement materials should be tested and more data accumulated in this area as well.

3.QUALITY CONTROL BY FLUIDIZATION TIME

By following the procedure described in section 2 above, it is possible to design a mixture proportions that achieves the required characteristics of compressive strength for given vibration compaction conditions. However, the characteristics of vibration compaction will need to be adjusted in each case to correct for errors and discrepancies induced by the non-uniform quality of fly ash.

One clue that indicates a way to deal with this adjustment is provided by the study carried out on the characteristics of vibration compaction. Fluidization time and the dimensionless value obtained by dividing the water-to-powder ratio by the optimum water-to-powder ratio are related by a constant regardless of the type and quality of the fly ash. (See **Fig.14**) This means that fluidization time might be a characteristic value of use in evaluating the characteristics of vibration compaction ratio [8]. **Fig.14** indicates that the water-to-powder ratios can be adjusted to give the same fluidization time for any fly ash if compaction is carried out under the same vibration conditions. To look into this, we studied and evaluated quality control methods based on fluidization time.

Note that vibration compaction tests are used to evaluate the characteristics of the water-cement/ash mixture, while fluidization time is a test value used to evaluate the consistency of the water-cement/ash mixture. This test value is similar to the VC value that represents the vibration time until mortar uplift is observed on roller-compacted dam concrete.

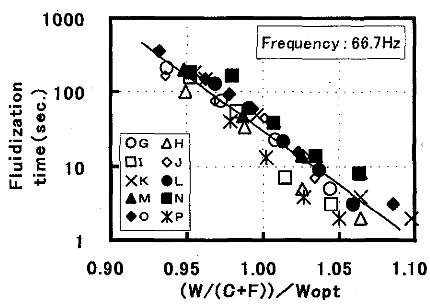

Fig.14 Fluidization time versus (W/(C+F)) / Wopt

3.1 Selecting optimum fluidization time

Fig.15 shows the relationship between water-to-powder ratio and fluidization time for different vibration frequencies.

By dividing these water-to-powder ratios by the optimum water-to-powder ratios, we obtain the desired relationship with fluidization time. **Fig.16** shows this relationship for a constant vibration frequency of 66.7 Hz and varying durations. Likewise, another vibration test in which the duration was kept constant at 5 minutes and the frequency was changed gives the relationship shown in **Fig.17**. Based on these tests, this optimum fluidization time was calculated for various vibration conditions to determine the relationship with vibration energy when the water-to-powder ratio equals the optimum water-to-powder ratio in **Fig.16** and **Fig.17**. That is, when the ratio of water-to-powder ratio to optimum water-to-powder ratio is 1.

Fig.18 shows the relationship between vibration energy and optimum fluidization time. Certain anomalies are present, depending on the frequency. However, the optimum fluidization time can be approximately determined from the vibration energy. In other words, an optimum fluidization time can be set for a particular vibration energy. These test data are also relevant to mixture proportioning. For example, if a longer vibration time is acceptable, the mixture can be designed so that the water-to-powder ratio is low and fluidization time is long. If a short vibration time is required, the water-to-powder ratio must be higher so as to give a shorter time till fluidization.
The optimum fluidization time is the target value for quality control during production. This is similar to the use of a target VC value when roller-compacting dam concrete.

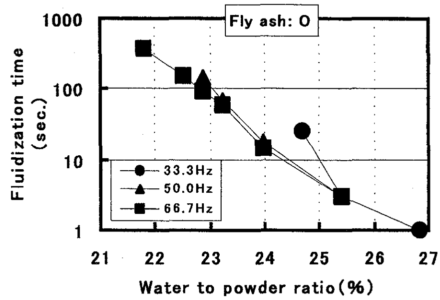

Fig.15 Fluidization time versus water-to-powder ratio

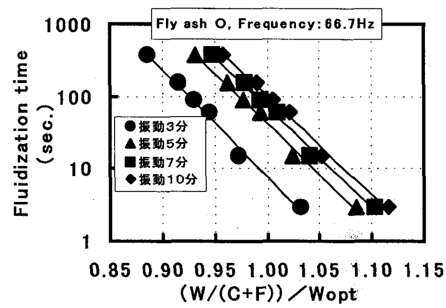

Fig.16 Fluidizatin time versus (W/(C+F)) /Wopt

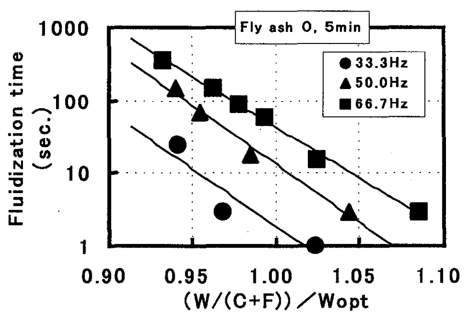

Fig.17 Fluidizatin time versus (W/(C+F)) /Wopt

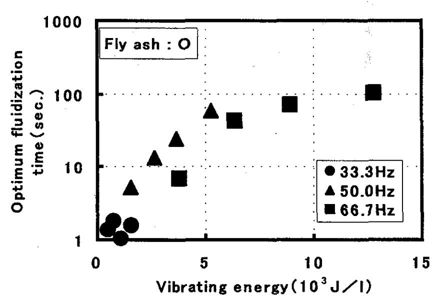

Fig.18 Optimum fluidization time versus vibration energy

3.2 Mixture proportioning when production begins

The desired compacting conditions (optimum fluidization time) may not be achievable by adjusting the mixture, as a result of errors and discrepancies in measuring the optimum water-to-powder ratio. It is assumed that such failures result mainly from discrepancies in the calculation of the critical water-to-powder ratio and the optimum water-to-powder ratio.

It is known from **Fig. 14** that the relationship between the dimensionless value of water-to-powder ratio to optimum water-to-powder ratio and the fluidization time is constant regardless of the quality of the fly ash. Consequently, actual values of critical water-to-powder ratio and optimum water-to-powder ratio can be predicted from measured values of fluidization time when production first begins. The following is the procedure for such a prediction when the vibration frequency is 66.7 Hz.

Assume first that the optimum fluidization time is To, the water-to-cement/ash ratio in the mixture is (W/(C+F)), and the fluidization time at the start of production is T.

The water-to-powder ratio is linearly proportional to the optimum water-to-powder ratio and the fluidization time, so the following equations can be written:

$$\log(T)=16.2-14.7\cdot(W/(C+F))o/Wopt \quad (8)$$
$$\log(T\lim)=16.2-14.7\cdot W\lim/Wopt \quad (9)$$

Where Tlim is the fluidization time for the critical water-to-powder ratio (300 seconds).

From equation (5) and (6), the optimum water-to-powder ratio (Wopt) and critical water-to-powder ratio (Wlim) are calculated as follows:

$$Wopt=14.7\cdot(W/(C+F))_0/(16.2\text{-}\log(T)) \quad (10)$$
$$W\lim=\frac{(16.2-\log(T\lim))}{(16.2-\log(T))}\cdot(W/(C+F))o \quad (11)$$

As discussed above, by measuring the fluidization time, corrections can now be made for discrepancies in the calculated optimum water-to-powder ratio and critical water-to-powder ratio.

3.3 Minor corrections to mixture during production

In the production of high fly-ash concrete, the mixture is varied for each lot, as each lot has some variation in quality. Temperature and other factors might also affect the quality. Minor corrections to be made with regard to fluidization time during production can be characterized as described below.

Fig.19 shows the relationship between α and fluidization time, as calculated using various types of fly ash, for a vibration frequency of 66.7 Hz. Although there is some non-uniformity in the distributions for different fly ash types, a straight line can be drawn through the data. Required corrections to the water-to-powder ratio to correct for changes in the fluidization time are not expected to be excessive during production, since the line is effectively constant regardless of the type of fly ash. Thus, small adjustments can be made to the value of α opt to bring the fluidization time closer to the optimum. The method of correcting α for a vibration frequency of 66.7 Hz is as described below.

In designing the mixture, the coefficient α opt is set and the optimum fluidization time is made To. Assume that the fluidization time is actually found to be T. For fluidization time To, the coefficient is α opt, as α is linearly correlated with the logarithm of fluidization time, so the following equation is derived.

$$\log(T)=2.36-3.86\cdot\alpha opt \quad (12)$$
$$\log(To)=2.36-3.86\cdot(\alpha opt+d\alpha) \quad (13)$$

Then α opt is obtained from equations (13) and (14) as follows:

$$\alpha=(\log(To)-\log(T))/3.86 \quad (14)$$

In this way, as a part of the test process for quality control, fluidization time is measured to allow for minor corrections to the mixture such that its required characteristics of vibration compaction are achieved.

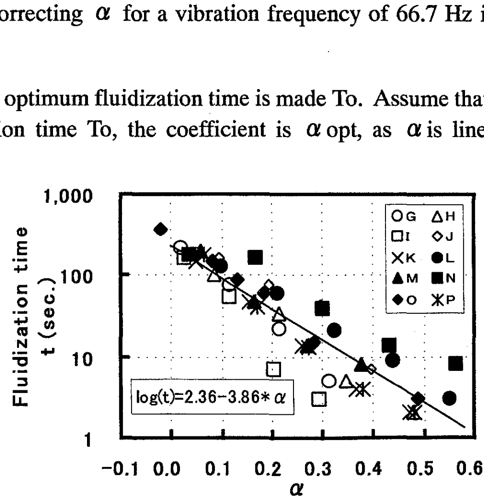

Fig.19 α **versus fluidization time**

4.CONCLUSIONS

In this study we attempt to establish a mixture design method and a quality control method for the production of high fly-ash concrete by a process involving the vibration-induced fluidization of the fly ash/cement mix at the optimum water-to-powder ratio. The findings of the study are summarized as follows:

(1) We propose the use of coefficient α as a measure of water-to-powder ratio. This coefficient is the ratio of water-to-powder ratio that yields a flow value of 140 to the critical water-to-powder ratio.

(2) The relationship between vibration energy and α opt, or the optimum water-to-powder ratio, is represented by a single curve regardless of the vibration frequency. The value of α opt can e determined from the vibration energy.

(3) The time taken for a wet powder to fluidize under vibration compaction can act as a useful index in evaluating the characteristics of this form of compaction. An optimum fluidization time for the optimum water-to-powder ratio can be defined by calculating the vibration energy applied to the concrete.

(4) The mixture can be adjusted so as to match the optimum fluidization time. This makes use of the finding that the water-to-powder ratio is correlates linearly with the optimum water-to-powder ratio and the logarithm of fluidization time.

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