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EFFECT OF MIX PROPORTION AND ELECTRIC POWER CONSUMPTION OF MIXER ON PROPERTIES OF CONCRETE

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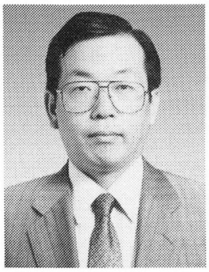

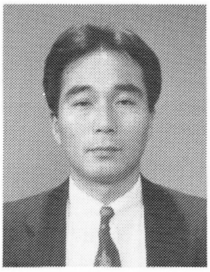
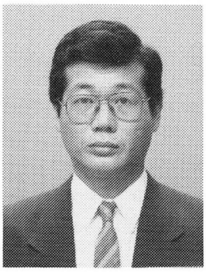

Taketo UOMOTO Tsugio NISHIMURA Tadashi WATANABE Kyoichi TANAKA

SYNOPSIS

Although the material used and mix proportions of concrete are the same, generally mixed concrete has different properties, when different types and volumes of concrete mixers are used. To obtain the same concrete properties, a previous paper[2] clarified that concrete has to be mixed with the same total electric power consumption per unit volume of concrete (EPC). The purpose of this paper is to clarify whether the method can be used in the case of concrete with different mix proportions. The experimental results with 14 mix proportions show that although mix proportion has some effect on the relation between EPC and concrete properties, the relationship is almost the same. Based on these test results, 0.5wh/l is proposed as the most appropriate value of EPC for mixing normal concrete. A method for estimating the properties of concrete at certain mixing time is also proposed.

Keywords : mixer, mixing time, mix proportion, electric power consumption, properties of concrete

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1. Introduction

Concrete mixing operation should be designed so that the quality of concrete produced is optimized. However, the current JIS A 1119, which sets forth a standard method of efficiency testing for batch mixers, is designed for consideration of macroscopic indicators of the degree of mixing, such as coarse aggregate content and mortar content. Thus, the quality of concrete is not considered. Concrete mixers today are designed and manufactured for maximum efficiency in concrete production with a view to achieving macroscopic uniformity in the shortest possible mixing time [1].

However, quality indicators such as slump and compressive strength of concrete can change substantially, even if the degree of mixing of materials put into mixers has fallen within the tolerance specified in JIS A 1119, depending on the subsequent mixing operation. Variation in slump is particularly pronounced [2][3][4]. It tends to increase as mixing progress of mixing and then decrease again after having reached a peak.

The purpose of this study is to determine experimentally the effect of maximum coarse aggregate size, unit water content, water-cement ratio, and type of admixtures and the content in concrete, and to investigate the electric power consumption per unit volume of concrete on mixers during mixing operation.

2. Outline of Experiment

2.1 Mixers

Two types and three models of concrete mixers shown in Table 1 were used in this experiment : pan-type mixers F and M with a designed capacity of 100 liters, and a horizontal biaxial mixer with a capacity of 90 liters. The pan-type mixer M was equipped with torquemeters on the shafts supporting rotating blades so that forces acting during concrete mixing could be measured directly.

Table 1 Types of mixers

Mixer type	Designed capacity (liters)	Revolution speed (m/sec)
Pan-type F	100	2.65
Pan-type M	100	2.00
Horizontal biaxial type	90	1.07

2.2 Mix Proportions of Concrete

Mix proportions of concrete are shown in Table 2. A total of 14 mix proportions were designed using maximum coarse aggregate sizes of 10 mm, 20 mm and 40 mm, water-cement ratios of 40%, 55% and 70%, and unit water content of 165 kg/m^3, 175 kg/m^3 and 185 kg/m^3 (slump for a mixing time of 120 seconds being about 5 cm, 10 cm and 15 cm). Some of the mix proportions were plain concrete, and others contained admixtures (air-entraining agent, water-reducing agent, or superplasticizer). Quality of materials for concrete used is shown in Table 3.

Table 2 Mix proportions of concrete

No.	Mixer	Max. size of coarse aggregate (mm)	Water-cement ratio W/C(%)	Fine aggregate ratio s/a(%)	Unit content(kg/m^3) Water W	Cement C	Fine aggregate S	Coarse aggregate G	Admixtures(×C%) AE	WR	SP
1	Pan F	10	55	54	213	387	926	798	-	-	-
2		20	55	47	196	356	839	957	-	-	-
3		40	55	40	182	331	737	1117	-	-	-
4		10	55	52	198	360	883	824	0.025	-	-
5		20	55	45	182	331	794	981	0.025	-	-
6		40	55	38	169	307	691	1140	0.025	-	-
7	Pan M Hor.	20	40	48.1	165	413	836	930	-	-	-
8		20	40	48.1	165	413	836	930	-	0.25	-
9		20	40	48.1	165	413	836	930	-	-	0.5
10		20	40	48.1	165	413	836	930	-	-	0.7
11	Pan M	20	40	46.7	175	438	789	930	-	-	-
12		20	55	49.6	175	318	889	930	-	-	-
13		20	70	50.9	178	254	934	930	-	-	-
14		20	40	45.1	185	463	742	930	-	-	-

Pan:Pan type mixer, Hor.:Horizontal biaxial mixer
AE:Air-entraining agent, WR:Water-reducing agent, SP:Superplasticizer

Table 3 Quality of materials for concrete

Material	Quality	No. of mix proportions
Cement	Normal portland cement	No.1-No.14
Fine aggregate	Gravel from FUJI River,Specific gravity=2.62, Absorption=1.32%,Fineness modulus=2.78	No.1-No.6
	Gravel from OHI River,Specific gravity=2.62, Absorption=1.67%,Fineness modulus=2.60	No.7-No.14
Coarse aggregate	Crushed stone from KASAMA Area Specific gravity=2.65,Absorption=0.68%	No.1-No.6
	Crushed stone from CHICHIBU Area Specific gravity=2.70,Absorption=0.62%	No.7-No.14
Air-entraining agent	Natural resin type	No.4-No.6
Water-reducing agent	Polyol complex	No,8
Superplasticizer	Aromatic-sulphonate high condensate	No.9,No,10

2.3 Mixing Method

Mixing method is shown in Fig. 1. As a first step, fine aggregate, cement, and coarse aggregate are placed in alternate layers while the mixers were not in operation. Then, water and admixtures were fed into the mixer so that they were distributed uniformly. The mixers were activated soon after the ingredients were fed. The conditions of coarse aggregate and fine aggregate were adjusted so that coarse aggregate was in the saturated surface-dry state, and fine aggregate had surface moisture ratios of 0-1%.

Standard mixing periods of 20, 60, 120, 180, 300, and 1,000 seconds were used, and six batches were prepared for each mix proportion. The mixing volume per batch was set at 70% of the designed capacity of the pan-type mixer M and 100% of the other mixers.

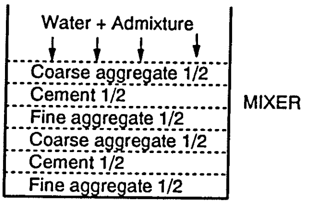
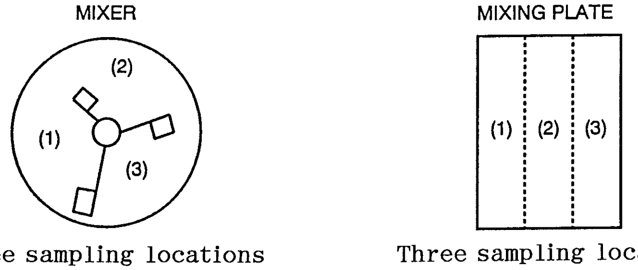


Fig.1 Mixing method

2.4 Measurement Items

As an indicator of power consumed by the mixers, electric power consumed by the motors during mixing operations was measured. For the pan-type mixer M, torque was also measured, from time to time.

The quality of mixed concrete was evaluated by slump (JIS A 1101), air content (JIS A 1128), and compressive strength at the age of 28 days (JIS A 1108). As shown in Fig. 2, specimens were taken at three locations in each of the pan-type mixers. As for the horizontal biaxial mixer, specimens were taken at three locations in a mix discharged onto a mixing plate. In either case, remixing was not conducted before sampling. Three test cycles were conducted for each batch, and the average of the measurements was taken as the quality indicator for each batch. Compressive strength was tested using three specimens taken at three different.



Three sampling locations in the mixer
(a) Pan-type mixer

Three sampling locations in the mixing plate
(b) Horizontal biaxial mixer

Fig.2 Sampling locations of concrete for quarity test

3. Power Consumed by Mixers in Operation

Work performed by a mixer can be measured by the power required to perform the work. In the chemical industry, the unit called power is often used as a measure of the mixing characteristics and efficiency of mixers [5]. Power can be measured by the force acting directly on mixer blades, that is, torque. To measure power easily, electric power consumed by a mixer motor is often measured as a substitute indicator of the power.

Figure 3 shows the relationship between the cumulative electric power consumption per unit volume of concrete (hereafter called the mixer power consumption) and the cumulative torque (cumulative power) for concrete mixes No. 7 to No. 14 mixed in the pan-type mixer M. The mixer power consumption was

obtained by subtracting the cumulative electric power consumption during the dry run of the mixer from that during mixing operation and converting the difference thus obtained into the value per unit volume of concrete (Wh/l). The cumulative torque (kg·cm·h/l) per unit volume of concrete was obtained similarly.
As is evident from the figure, the mixer power consumption is in proportion to the cumulative torque, irrespective of the differences between the concrete mixers. Thus it can be concluded that the mixer power consumption of mixer motors can be used as a substitute indicator of the power.

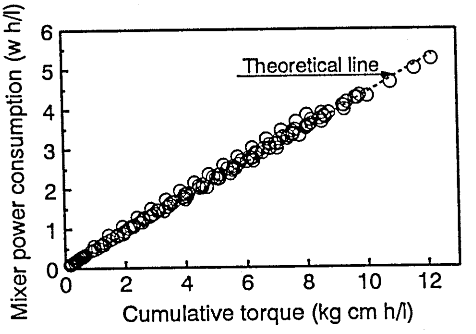


Fig.3 Relationship between cumulative torque and mixer power consumption (Pan-type mixer M, Mix No.7-No.14)

4. Relationship between Mixer Power Consumption and Concrete Quality

It is seen that as long as concrete of identical mix proportions is used, a uniform quality of concrete can be achieved by maintaining the same mixer power consumption during mixing, irrespective of the type and capacity of the mixer used [2]. In this study, the effect of differences in mix proportions was examined.

Figures 4 to 9 show the effect of the maximum coarse aggregate size, water-cement ratio, unit water content, the type and quantity of admixtures used, and the type of mixer on the quality of concrete produced. The bscissas represent the mixer power consumption. The markers plotted in the figures represent measurements corresponding to different mixing periods, and the lines connect their averages.

As is clearly seen from these figures, all mix proportions show tendencies similar to those confirmed in previous studies [2]. That is, slump increased as the mixer power consumption increased, and then it decreased after having reached a peak. Air content, in the case of plain concrete, decreased and compressive strength increased as the mixer power consumption increased.

The phenomenon of consistency of change in slump and other factors during in the mixing process was observed with all types of cement [6]. The phenomenon was also observed with concrete containing blast furnace slag powder, which it inactive, in place of cement [7]. Therefore, the quality of concrete produced would depend largely on the dispersibility of cement.

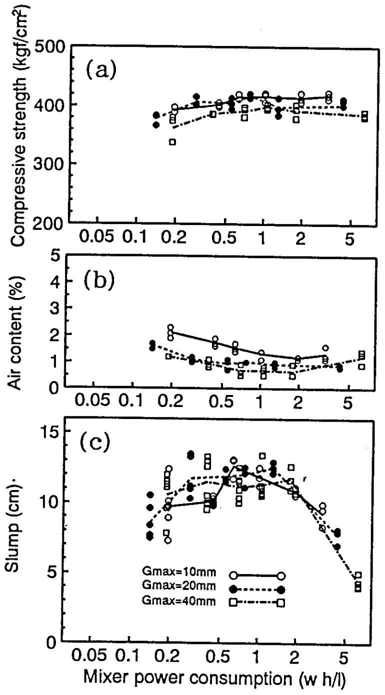


Fig.4
Effect of maximum coarse aggregate size (Plain concrete, Pan-type mixer F)

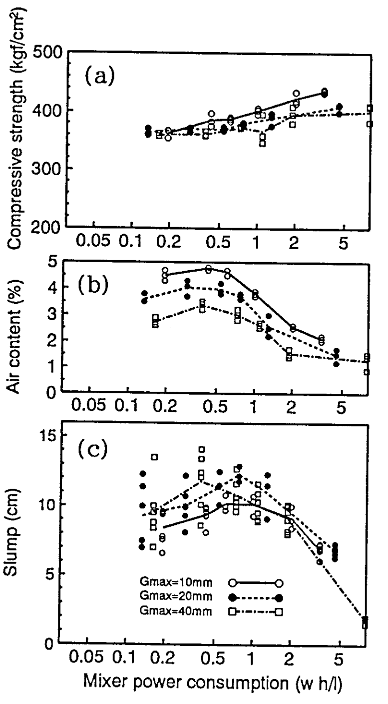


Fig.5
Effect of maximum coarse aggregate size (AE concrete, Pan-type mixer F)

As shown in Figs. 4 to 9, patterns of the concrete quality curves vary with mix proportions. In order to investigate their tendencies, Fig. 10 shows the mixer power consumption corresponding to the maximum slump, Fig. 11 shows the rate of decrease in the air content of plain concrete with the increase of the mixer power consumption, and Fig. 12 shows the rate of increase in compressive strength with the increase of the mixer power consumption for each mix. The mixer power consumption corresponding to the maximum slump was determined through regression between slump and the logarithm of the mixer power consumption using a quadratic curve. The rates of increase in air content and compressive strength were obtained as the gradients of lines obtained from a linear regression using the logarithm of the mixer power consumption. The compressive strength was determined using values of the mixer power consumption of 0.05 Wh/l or more.

4.1 Effect of Maximum Coarse Aggregate Size and Air-Entraining Agent

As shown in Fig. 10(a), the mixer power consumption corresponding to the maximum slump became smaller as the maximum coarse aggregate size increased. The mixer power consumption for concrete containing the air-entraining agent was about 15% lower than that for plain concrete.

The tendency of the mixer power consumption, corresponding to the decrease in maximum slump as the maximum coarse aggregate size increases, agrees with the results of the test using a horizontal biaxial mixer with a mixing capacity of 3 m^3 [8]. This means that mixing efficiency increases due to the effect of

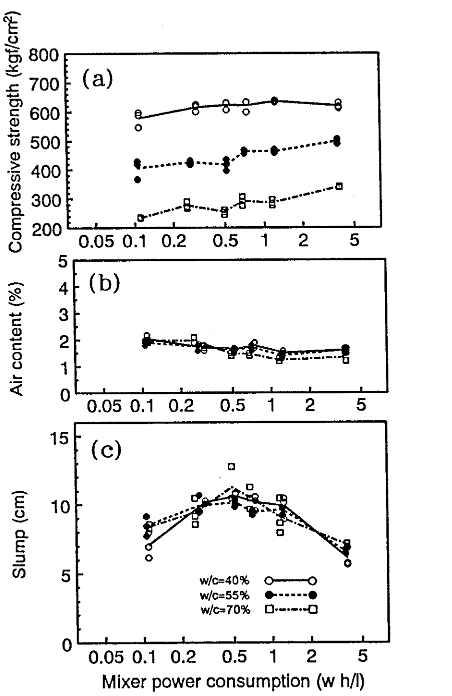


Fig.6 Effect of water-cement ratio (Pan-type mixer M)

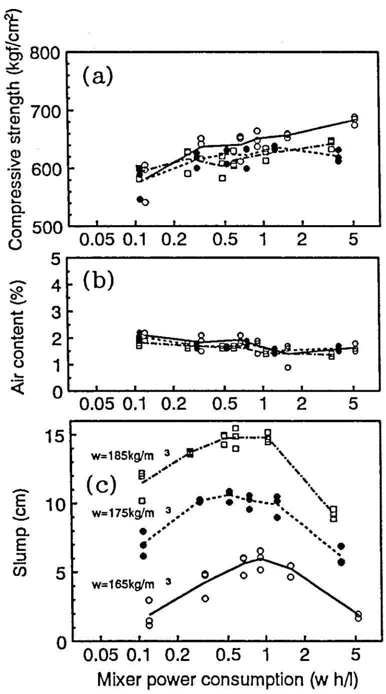


Fig.7 Effect of unit water content (Pan-type mixer M)

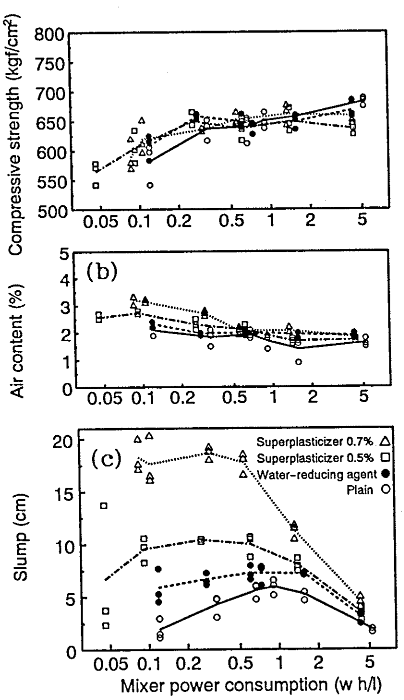


Fig.8 Effect of admixture (Pan-type mixer M)

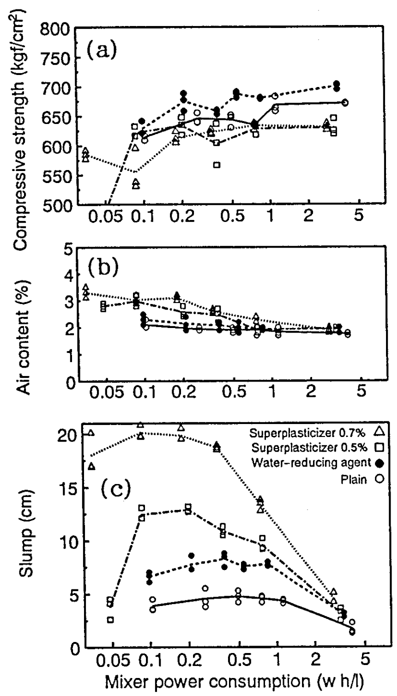


Fig.9 Effect of admixture (Horizontal biaxial mixer)

larger-size aggregate, and coarse aggregate is thought to promote dispersion by a milling dispersion mechanism. That is, as in ball mills and roll mills, coarse aggregate effectively disperses cement particles coagulated due to the effect of evenly distributed water.

The air content curves (in Fig. 4(b) and Fig. 5(b)) for plain concrete and concrete containing the air-entraining agent (AE concrete) are different. The air content of plain concrete decreased monotonously as the mixer power consumption increased. In contrast, the air content of AE concrete peaked early at 0.3-0.5 Wh/l and decreased after that.

The compressive strength increased gradually as the power consumption increased (Fig. 4(a) and Fig. 5(a)), and its rate of increase tended to lower as the maximum coarse aggregate size increased (Fig. 12(a)). One of the causes for this is the decreases in air content.

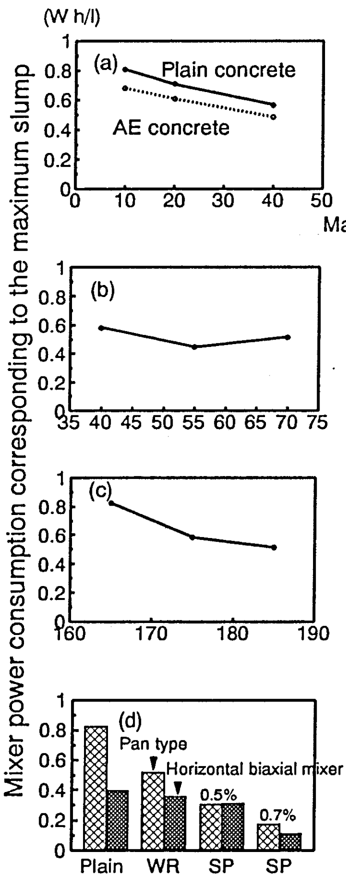


Fig.10
Mixer power consumption corresponding to the maximum slump

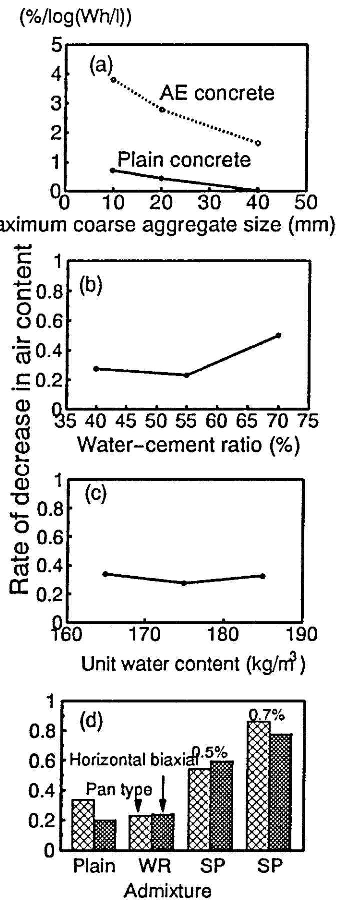


Fig.11
Rate of decrease in air content of plain concrete with increase of mixer power consumption

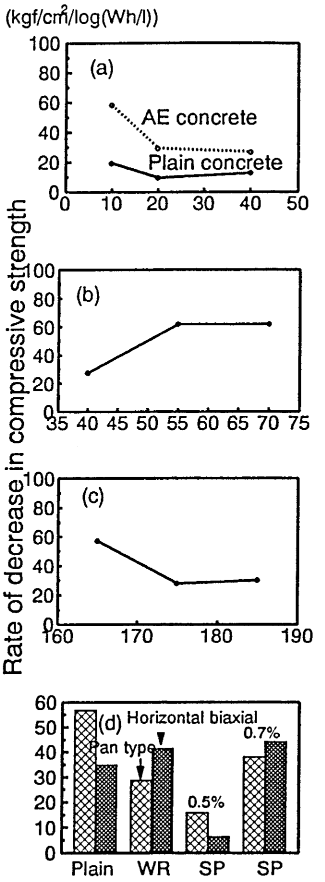


Fig.12
Rate of decrease in compressive strength with increase of mixer power consumption

4.2 Effect of Water-Cement Ratio

As Fig. 6 indicates clearly, the slump curves and the air content curves agree substantially in spite of differences in the water-cement ratio. The mixer power consumption corresponding to the maximum slump is about 0.5 Wh/l, as shown in Fig. 10(b).

4.3 Effect of Unit Water Content

As shown in Fig. 10(c), the mixer power consumption corresponding to the maximum slump for higher unit water contents tends to be slightly lower than that for lower unit water contents. The rate of decrease in air content remains almost constant, irrespective of the unit water content (Fig. 11(c)). The rates of increase in the compressive strength of the mixes with unit water contents of 175 kg/m^3 and 185 kg/m^3 remain almost constant, but that of 165 kg/m^3 is higher.

4.4 Effect of Water-Reducing Agent and Superplasticizer

It was observed that superplasticizer greatly affected changes in concrete quality due to increases in the mixer power consumption. The effect on slump was particularly pronounced. As slump was increased by the addition of superplasticizer, the mixer power consumption corresponding to the maximum slump showed a tendency to decrease sharply, as shown in Fig. 10(d).

It is thought that chemical action caused by superplasticizer disperses cement particles, thus maximizing slump at early stages of the mixing process. This means that similar phenomena occur when concrete is mixed using cement paste that has been mixed well in a special high-speed mixer [9]. The dispersibility of cement particles is thought to have a considerable effect on slump.

As shown in Figs. 8 and 9, for all the mix proportions variation in concrete quality was greater when the mixer power consumption was about 0.2 Wh/l or below. In particular, the use of superplasticizer resulted in increased the variation in concrete quality even when the mixing period was close to the maximum slump.

5. Discussion of Methods for Evaluating Concrete Quality during Mixing and Their Applications

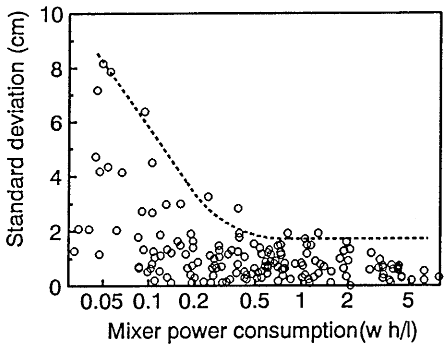
The slump, air content, and compressive strength of concrete, which are major indicators of concrete quality, change with increase in mixing time, that is, the mixer power consumption. The quality indicators of concrete vary depending on the type of the mixer used even when materials, mix proportions, and mixing time are identical.

With this in mind, the authors looked at the mixer power consumption during mixing as an indicator of changes in the uniformity of the quality of concrete produced, and attempted to develop a method for evaluating changes in quality indicators, taking account of the type of mixer and mix proportions.

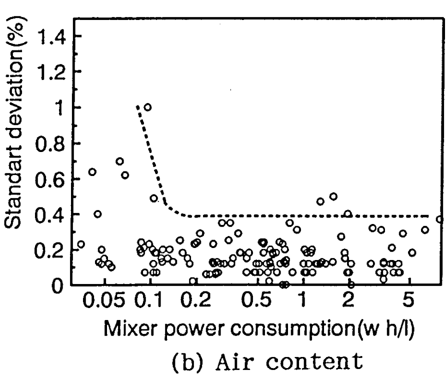
In considering the above, the results of the test conducted in this study and the results of a previous test[2] were used (the testing methods being identical). The test conditions for the above tests and the conditions considered here are as follows:
-Type of mixer: tilting mixer; biaxial mixer 901; pan-type mixer
-Mixing method: see Fig. 1.
-Mixing time: 10-1,000 sec
-Maximum coarse aggregate size: 10, 20, 40 mm
-Water-cement ratio: 40, 55, 70%
-Slump: 6-19 cm (maximum values recorded in the mixing process)
-Air content: 0.9-4.8%
-Admixtures: plain, AE agent, AE water-reducing agent

5.1 Uniformity of Concrete Quality

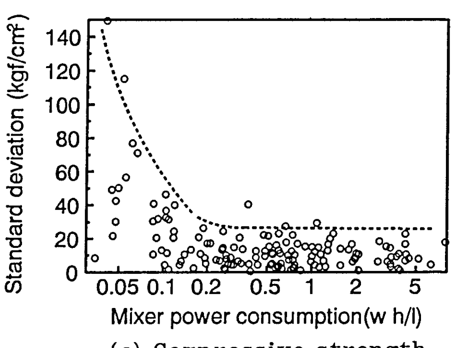
Figure 13 shows how the standard deviations of the slump, air content, and compressive strength of concrete change according to the mixer power consumption. The standard deviations were calculated from the values of quality indicators for specimens taken at three locations in each mixer. In the figure, the approximate upper limits of plots are marked with dotted lines.



(a) Slump



(b) Air content



(c) Compressive strength

Fig.13 Relationship between mixer power consumption and standard deviation of concrete quality

As the above figure indicates, the standard deviations of all quality indicators are very high at the early stages of the mixing process, and they tend to decrease as the mixer power consumption rises. The standard deviations of air content and compressive strength at mixer power consumption of 0.1-0.2 Wh/l remain steady in the ranges of 0-30 kgf/cm^2 and 0-0.4%, and their variations do not become smaller by further mixing. The standard deviation of slump remains steady in the range of 0-1.5 cm, and the corresponding mixer power consumption of about 0.3 Wh/l is higher than that for air content and compressive strength. Thus, variation in slump is considered to be an important indicator of the uniformity of the quality of concrete being mixed.

From the above, it can be concluded that unless the mixer power consumption is kept at or above about 0.9 Wh/l throughout the mixing process, irrespective of the type of mixer or mix proportions used, the quality of concrete being mixed varies widely. If mixing is performed at lower mixer power consumption, the quality of concrete is likely to vary widely among batches.

5.2 Evaluating Changes in Quality Indicators

(1) Slump Variation Curves

Slump variation curves show peaks at certain values of the mixer power consumption, irrespective of mix proportions. Except in cases where superplasticizer was added, slump variation curves shows similar tendencies.

Figure 14 shows the relationship between the mixer power consumption and the relative slump, which is defined as the ratio of the measured slump (average of measurements taken at three locations) to the maximum slump for each mixing period. The relationship is based on the results of the test conducted in this study except for those obtained from the cases where superplasticizer was not added, and the results of a previous test [2]. The maximum value of slump used here was estimated through regression of the relationship between the mixer power consumption and slump using a quadratic curve. Shown below are results obtained by performing a regression of plotted values and adjusting in the direction of the axis of ordinates so that the maximum value of the relative slump thus obtained becomes 100 (points and lines shown in Fig. 14 have been adjusted similarly.).

$$Sl_r = 95.74 - 29.071 \log P - 49.63(\log P)^2 \quad \text{-------} \ (1)$$

where Sl_r : relative slump (ratio of slump Sl to maximum slump Sl_{max} for each mixing period=$(Sl/Sl_{max}) \times 100$)

P : mixer power consumption (Wh/l)

As seen from the figure, when the mixer power consumption is 0.3 Wh/l or above, the relationship between the relative slump and the mixer power consumption shows a distinct correlation. It can be expressed by the quadratic curve defined by equation 1 and is plotted roughly within $\pm$10%. The mixer power consumption corresponding to the maximum slump is 0.5 Wh/l.

(2) Air Content Variation Curves

The air content of plain concrete also shows a tendency to decrease with the increase of the mixer power consumption for all mix proportions. The rate of decrease varied depending on mix proportions, but the air content tended to remain almost constant when the mixer power consumption was higher than a certain level. This applies to AE concrete as well.

Considering this, the authors calculated a relative air content (air content at a mixer power consumption of 1 Wh/l=100) for plain concrete and AE concrete in each test case. Figures. 15(a) and (b) show the relationship between the relative air content and the mixer power consumption in each test case. A quadratic curve was used in the regression for plain concrete, and a cubic curve for AE concrete. By adjusting the results thus obtained using a similar method so that the relative air content for the mixer power consumption of 1 Wh/l is 100 as in the case of the relative slump, the following regression formula can be obtained:

(a)Plain concrete

$$Air_r = 100 - 15.7\log P + 15.7(\log P)^2 \quad \text{--------} \quad (2)$$

(b)AE concrete

$$Air_r = 100.3 - 102.9\log P - 3.6(\log P)^2 + 93.3(\log P)^3 \quad \text{--------} \quad (3)$$

where Air_r : relative air content (air content at a mixer power consumption of 1 Wh/l=100)
P : mixer power consumption (Wh/l)

As Figs. 15(a) and (b) indicate, the curves for plain concrete for mixer power consumption of about 0.5 Wh/l or above shows a strong correlation between mixer power consumption and relative air content. The relationship for AE concrete also shows a strong correlation, though it is based on a small number of measurements, and the relative air content peaks at a mixer power consumption of about 0.3 Wh/l.

(3) Compressive Strength Variation Curve

The compressive strength increased as the mixer power consumption increased, and similar tendencies were observed at all the mix proportions. The rate of increase in compressive strength varied depending on the mix proportions, but it was within the range of 10-60 kgf/cm^2 when the mixer power consumption was 1 Wh/l.

On the basis of the test results obtained under this study and the results of the test conducted previously, the relative compressive strength (compressive strength at the mixer power consumption of 1 Wh/l=100) was determined by a method similar to that used for the air content. Figure 16 shows the relationship of the relative compressive strength with the mixer power consumption. By performing a regression for the mixer power consumption of 0.05 Wh/l and adjusting the results thus obtained so that the relative compressive strength corresponding to the mixer power consumption of 1 Wh/l is 100 as in the case of the relative air content, the following regression formula can be obtained:

$$CS_r = 100 + 9.407\log P \quad \text{-------} \quad (4)$$

where CS_r : relative compressive strength (compressive strength at a mixer power consumption of 1 Wh/l=100)
P : mixer power consumption (Wh/l)

As is clearly shown in Fig. 16, there is a strong correlation between the relative compressive strength and the mixer power consumption. Plotted values are within ±10% of the values given by the regression formula.
Thus, it can be said that under the test conditions employed in this study, changes in concrete quality can be expressed by means of the mixer power consumption using quality indicators for concrete in the forms of the relative slump, relative air content, and relative compressive strength, even if mix proportions for concrete, mixing time, and the type of mixer vary. If the above equations, 1 to 4, are used, the quality of concrete corresponding to any mixer power consumption can be predicted by checking the quality of concrete being mixed at a certain mixer power consumption. It is possible, for example, to estimate the maximum slump from the slump Sl and the relative slump Sl/Sl_{max} of concrete mixed at the mixer power consumption p. It is also possible to estimate slump at any mixer power consumption.

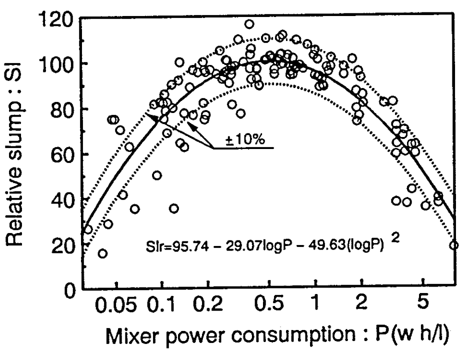
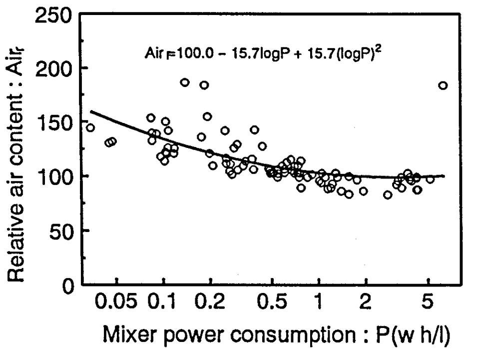


Fig.14 Relationship between mixer power consumption and relative slump



(a) Plain concrete

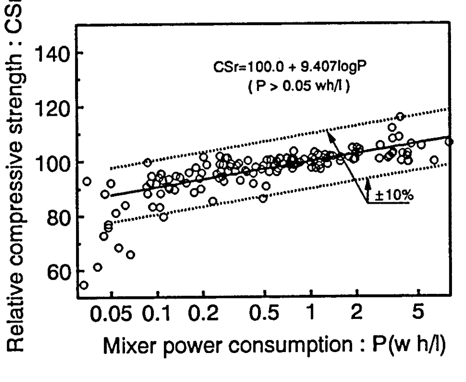
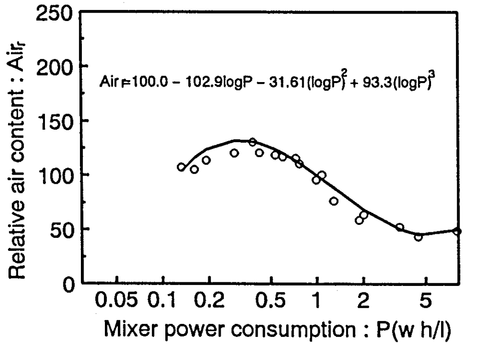


Fig.16 Relationship between mixer power consumption and relative compressive strength



(b) AE concrete

Fig.15 Relationship between mixer power consumption and air content

It is believed, therefore, that this method has the following applications:

(1) Defining Mixing Conditions Suitable for Mix Proportions
Mixing conditions for particular mix proportions can be optimized by meeting the following requirements: (1) slump must be maximized, (2) air content for AE concrete must be maximized, and (3) compressive strength should be as high as possible. Minimized variation in quality also contributes to quality control.

It can be said from Figs. 14 to 16 that no mixer power consumption can meet all the above three requirements simultaneously for optimized mix proportions. There are some cases, however, where a well-balanced combination of quality indicators is required, and others where only certain quality indicators are considered important. Mixing conditions in such cases can be determined by use of Fig. 12, which shows variation in the quality of concrete being mixed, and equations 1 to 4, which define the quality variation curves.

(2) Quality Control Indicators
When forced-action mixers are used, usually a mixing period of 120 seconds is applied to small mixers for laboratory use and 30-60 seconds for large mixers in concrete plants. However, the quality of concrete obtained using the mixers is not the same. This is not only due to the use of different mixing periods but also the use of different mixer power consumption. It was confirmed that in the case where horizontal biaxial mixers were used, the quality of concrete produced in a small 100 liter mixer for laboratory use and that of concrete produced in a large $3m^3$ mixer in a concrete plant became equal when the mixer power consumption was kept at the same level.

Therefore, the results of this study indicate that if concrete of the same quality is to be produced in different mixers using the same mix proportions, it is necessary to perform mixing at the same mixer power consumption. It is thought that the quality of concrete is better controlled by the mixer power consumption than by mixing time.

(3) Indicators of Mixing Efficiency and Performance
It is thought that the efficiency and performance of mixers can be compared by the time required for mixing, by mixing concrete in different types of mixers for periods that make the mixer power consumption equal and checking quality indicators and variation in quality during the process. If concrete is mixed in different types of mixers at the same mixer power consumption, the quality of concrete produced becomes almost the same. Thus, mixers requiring less time for mixing have higher efficiency and superior performance.

6. Conclusions

In this study, changes in concrete quality in the mixing process were studied using electric power consumed by mixers as an indicator. From the test conducted in this study, the following conclusions have been drawn:

(1) The quality of concrete being mixed varies with mixing time, irrespective of the maximum coarse aggregate size, water-cement ratio, unit water content, use of air-entraining agent, water-reducing agent, and superplasticizer.

(2) The slump of concrete being mixed increases with time at any mix proportion, and it decreases after having reached a peak. The mixing period and the mixer power consumption that maximize slump may vary depending on mix proportions. Particularly, a significant effect was observed when superplasticizer was added to increase slump.

(3) The air content of plain concrete being mixed increases with time, but the air content of AE concrete being mixed increases at early stages of the mixing process and then decreases. The compressive strength of concrete being mixed increases with time at any mix proportion.

(4) Curves expressing the variations of slump, air content, and compressive strength according to mixing time have been analyzed, and a quantitative evaluation method using the mixer power consumption, as well as the type of mixer and mix proportions, as an indicator of concrete quality has been proposed. By checking the quality of concrete mixed at a certain mixer power consumption using the proposed method, concrete quality that can be achieved at a particular mixer power consumption can be predicted. Thus, the method is useful in determining mixing conditions best suited to particular mix proportions, controlling concrete quality, and evaluating mixing efficiency.

(5) In order to maintain optimum control of concrete quality, taking account of mix proportions and variation in quality when superplasticizer is not used, it is necessary to use a mixing period that maximizes slump and air content. Under the test conditions employed in this study, that requirement was met at a mixer power consumption of about 0.5 Wh/l.

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