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STUDY OF DISCHARGE EFFICIENCY FROM TRUCK AGITATOR

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Truck agitators are generally used to transport fresh concrete after mixing at a concrete plant. In placing the concrete at a construction site, the discharge efficiency from the truck agitator influences construction efficiency and concrete quality. In this report, we observe the flow of fresh concrete in the agitator, which has hitherto been impossible to observe, with the help of visualization techniques. We also investigate the influence of blade spiral pitch angle and rotational speed on discharge efficiency.

Results demonstrate that the agitator has an optimum angle for discharge efficiency, and that if the sliding resistance between concrete and blade surface is higher, discharge efficiency is lower.

Keywords : truck agitator, similarity law, discharge efficiency, blade, visualization technique

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1. INTRODUCTION

After mixing at a concrete plant, fresh concrete is generally transported to the construction site in a truck agitator. If the discharge efficiency of the truck agitator is poor, a number of problems arise, as follows.

1) Placing the fresh concrete takes excessive time.
2) The quality of the fresh concrete changes during placing.
3) Air mixes with the fresh concrete as it is pumped.
4) The blades and inner drum surface of the agitator suffer excessive wear.
5) Undischarged fresh concrete hardens inside the agitator, and removal is time-consuming.

This has led to recent demands for improvements in discharge efficiency, especially to prevent the fresh concrete hardening.

At the user end, discharge efficiency can be improved by increasing the rotation of the agitator, while the maker can attempt to improve discharge characteristics. In this respect discharge efficiency depends on the form of agitator in the drum, and of the blades welded to the inner surface of the drum. The drum shape cannot be changed freely, since the Japan Automobile Body Industry Association regulates of that. So to improve discharge efficiency, the blades must be made more suitable for discharge. Many blades have been designed to achieve this type of improvement, but they have not been investigated theoretically. Designs have largely depended on observations and the experience of the designer. Blade shape, in theory, be decided based on the flow conditions of fresh concrete in the agitator, but this is impossible to observe as things stand.

In this paper, we describe experiments in which we observed the flow of fresh concrete in the agitator and quantified discharge efficiency with the help of a newly developed visualization technique [1]–[4]. We were able to clarify the factors that have negative effects on discharge efficiency and investigate the following characteristics :

1) Relation between blade spiral pitch angle and discharge efficiency
2) Relation between rotational speed of the agitator and discharge efficiency

2. SUMMARY OF EXPERIENCE

2.1 Agitator Construction and Discharge Mechanism

The interior of an agitator is illustrated in Fig. 1. Two spiral blades are welded to the inner surface of the drum with a 180–degree phase angle. When the agitator rotates, the blades force the fresh concrete inward and agitate it. When the agitator rotates in the opposite direction, the blades push the fresh concrete toward the outlet and discharge it. Figure 2 illustrates how the agitator discharges the fresh concrete.

2.2 Equipment for Visualization Experiment

We designed equipment that would give a visualization of the situation in order to observe and quantify the flows of fresh concrete in the drum. This equipment comprises a model agitator, a model of fresh concrete, an image analyzer, and other systems.

Photo 1 shows the model agitator. This is a model of the type of agitator fitted to a 10–ton chassis. The scale is 1/5, and the

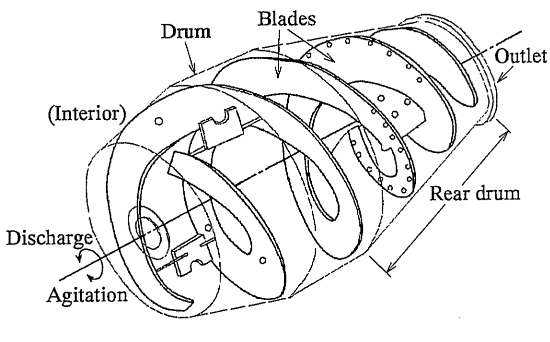


Fig.1 Illustration of agitaor interior

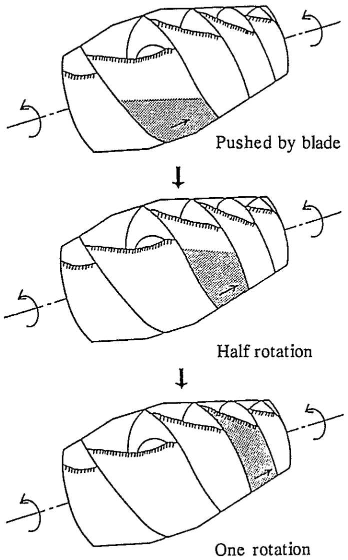


Fig.2 Discharge motion of fresh concrete

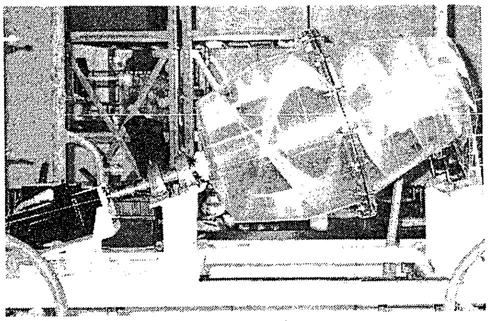


Photo 1 Model agitaotr

model consists of the drum, a drive motor, and a frame. The drum is made of colorless, transparent acrylic resin, which allows observations of the flows of model concrete inside. The drive motor has a rating of 100 watts, and its rotation is reversible. Rotational speed can be control freely between 0 and 24 rpm.

We assumed that the fresh concrete consists of two phases : coarse aggregates and mortar. On this basis, we made the model fresh concrete. It is a mixture of artificial light aggregates (of particle size 5–10 mm and specific gravity 1.45) as coarse aggregates and a high–polymer resin solution as the mortar. The consistency of the model concrete is controlled by adjusting the consistency of the solution and the ratio of light aggerates to model mortar. (This is known as the volume ratio here.) The consistency of the resin solution can be controlled by adding water to the high–polymer resin.

The consistency of the model mortar is defined by its flow time (according to the criterion of Japan Society of Civil Engineering JSCE–1986 : The flowing test of the injected mortar for prepacked concrete.) The flow time is the time taken for all model mortar to flow out from a filled P–type funnel. The relationship between model concrete, consisting of resin solution and light aggregates, and real fresh concrete will be mentioned later.

The image analyzer comprises CCD cameras for filming the flow of model concrete in the model agitator, a video tape recorder for recording and playing back the images, and ancillary equipment.

2.3 Experimental Method for Discharge Efficiency

Two main factors are considered in the discharge efficiency experiments on model concrete using this visualization equipment : blade spiral pitch angle and rotational speed. An outline of how discharge efficiency is affected by each factor is given below.

(1) Influence of spiral pitch angle

In this experiment, we used model agitators with spiral pitch angles of 11.3, 12.8, 14.9, 16.0, 18.0, and 20.0 degrees. The spiral pitch angle is the angle between the blade welding line and a perpendicular from the rotational axis of the agitator (see Fig. 3). When the spiral pitch angle is large, the spiral pitch (representing the blade spacing) is large and the angle of attack of the blade surface is easy. The experiment is illustrated in Fig. 4. The model agitator is placed horizontally and is charged with 40 *l.* (equivalent to 5 cubic meters in the real agitator) of model concrete. The rotational speed of model agitator is set to 3 rpm, which is the speed at which a real agitator usually discharges fresh concrete. The number of rotations [revs] of the model

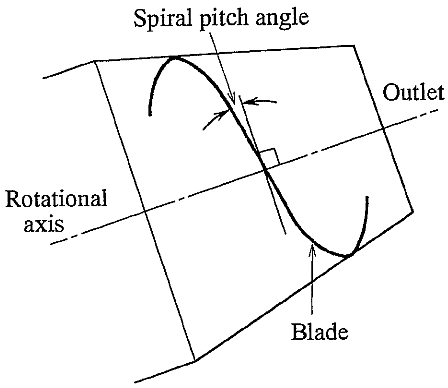


Fig.3 Spiral pitch angle

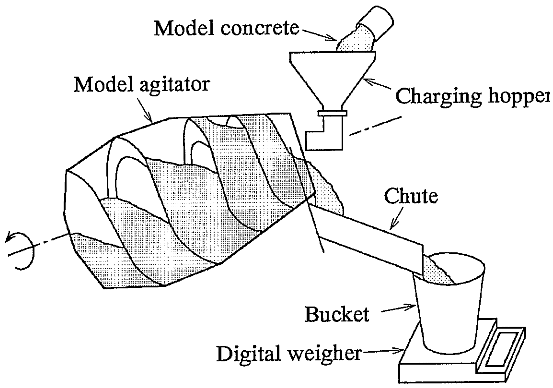


Fig.4 Experimental method for discharge efficiency

agitator required to complete the discharge is measured along with the weight of discharged concrete. The discharge rate [l] is then calculated. The number of rotations divided by the discharge is defined as the rotations to discharge a fixed quantity of concrete [rev/l]. A small value means that the discharge efficiency is good. If the model concrete fails to fully discharge after two rotations, we assume that the discharge is completed even if some model concrete remains in the agitator.

The model agitator was also inclined at 12 degrees (with the outlet side raised) for further tests of discharge efficiency. We compared the discharge efficiency in the horizontally condition and in the inclined condition, and investigated the influence of the rate of concrete sliding over the blade surface on the discharge efficiency.

(2) Influence of rotational speed

In this experiment we use a the model agitator with a spiral pitch angle of 12.8 degrees. It is placed horizontally and charged with 40 l of model concrete. As the model concrete is discharged at rotational speeds of 1.5, 2.0, 3.0, 4.0, and 6.0 rpm, we measure the time to finish the discharge [s], the number of rotations [rev], and the discharged amount [l]. Using these values, we clarify the relationship between time, number of rotations to discharge, and the discharge ratio (the ratio of the amount discharged to the amount charged) to the rotational speed. Incidentally, in this study, we represent the discharge efficiency by the number of rotations or the discharge ratio, rather than by using the number of rotations to discharge a fixed quantity of concrete. In investigating the influence of rotational speed, if the latter measure were to be used, the discharge efficiency would be incorrectly estimated, because, at high rotational speeds, discharge efficiency may be low. Because that the total number of rotations needed to discharge is large even if the number of rotations to discharge a fixed quantity of concrete is small, and that the reduced concrete is many for that the many concrete adheres to the inner surface of the drum.

3. INVESTIGATION OF SIMILARITY

This approach is that of a reductive model. The aim is to make a reductive model that reflects the real world, allowing the results for the reductive model to be applied to the real thing. Therefore, we fix our eyes upon two rheological constants, the yield point and the plastic consistency, that control concrete flow conditions. On this basis, we investigate how closely the model simulates the real world. Pi–numbers relating these rheological constants are the Bingham number and the Hedstrom number, which is the Bingham number multiplied by inertia. These numbers are defined as follows [5].

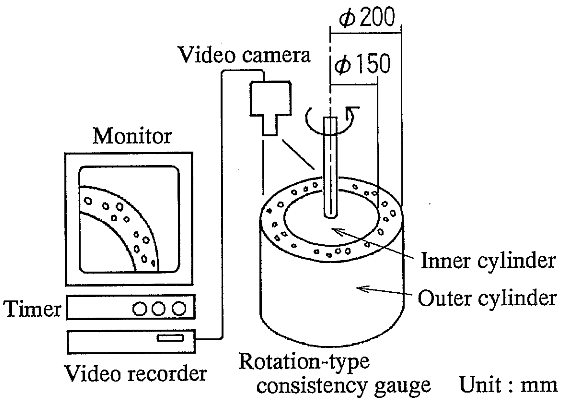


Fig.5 Measurement of rheology constants

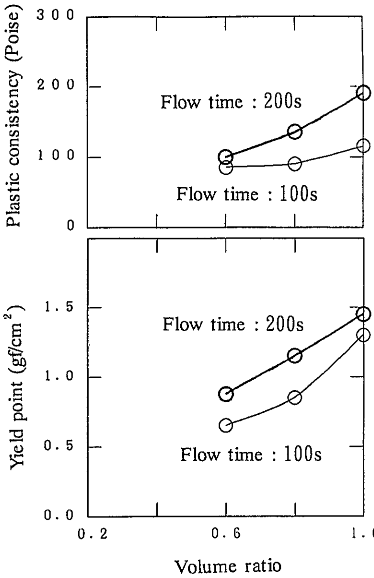


Fig.6 Ryeology constant of model concrete

$$\text{Bingham number : Bi} = \frac{\tau\, l}{\mu\, v} \qquad (1)$$

$$\text{Hedstrom number : He} = \frac{\rho\, \tau\, l^2}{\mu^2} \qquad (2)$$

where, τ : yield point μ : plastic consistency
ρ : density v : velocity l : length

Where the situation in question is a flow problem in a pipe, such as concrete being transported by a pump [4], the Bingham number is usually adapted as the main pi–number, since the concrete has no free surface. However, in case of concrete flow in an agitator, as in this study, we believe it is more appropriate that the Hedstrom number be used as the main pi–number, since the concrete does have a free surface.

We therefore investigate the similarity of the model concrete to real concrete by calculating the Hedstrom numbers. First, the rheological constants of some model concretes with different flow times and volume ratios were measured from a video image by the one–point method using a double–cylinder inner rotation type of consistency gauge. An outline of this measurement is shown in Fig. 5. We recorded the flow conditions of the model concrete on its free surface with a video tape recorder, and measured the angular velocities of tracer grains floating on the free surface from the video images. Using the torque and angular velocities of tracer grains measured in this experiment, we plotted the consistency curve and calculated the plastic consistency and yield point diagrammatically. Here, to calculate the rheological constants, we used six kinds of model concrete with flow times of 100s or 200s and volume ratios of 0.6, 0.8, or 1.0 [6]. Results are shown in Fig. 6. The plastic consistency μ' and the yield point τ' of the model concrete are found to be the following. (The characters added " ' " mean the physical values of model concrete.)

$$\mu' = 100 \sim 200 \text{ Poise}$$
$$\tau' = 0.70 \sim 1.50 \text{ gf/cm}^2 \qquad (3)$$

The plastic consistency μ and yield point τ of concrete have been given different values by many workers using various methods. According to Kikkawa' s measurements [7], the values for concrete with a slump value of 10 to 15 cm and incorporating water gravel are as follows.

$$\mu = 250\sim400 \text{ Poise}$$
$$\tau = 1.4\sim1.9 \text{ gf/cm}^2 \tag{4}$$

By substituting value (4) into equation (2), the Hedstrom number He of real concrete can be obtained as follows.

$$\begin{aligned} He &= \frac{\rho\times(1.4\sim1.9)\times l^2}{(250\sim400)^2} \\ &= (1.19\sim2.24)\times10^{-5}\times\rho l^2 \end{aligned} \tag{5}$$

The relationships between model concrete density and real concrete density, and between model agitator length and real agitator length are as follows.

$$\rho' = \rho/2, \quad l' = l/5 \tag{6}$$

By substituting value (3) and equation (6) into equation (2), the Hedstrom number He' of the model concrete is found to be

$$\begin{aligned} He' &= \frac{(\rho/2)\times(0.70\sim1.50)\times(l/5)^2}{(100\sim200)^2} \\ &= (0.075\sim0.140)\times10^{-5}\times\rho l^2 \end{aligned} \tag{7}$$

Thus the ratio of the two Hedstrom numbers is about 16. When this Hedstrom number ratio diverges from 1, the concrete sliding and adhesion phenomena in the model experiment are different from the real situation. In short, this Hedstrom number ratio is a measure of how well the phenomena in the model experiment simulate the real phenomena.

4. DETERMINATION OF MIXING CONDITIONS FOR THE MODEL CONCRETE

It is necessary to decide on mixing conditions for the high–polymer resin solution and the artificial light aggregates to ensure that the model concrete corresponds to real concrete of the prescribed consistency. It would be difficult to fix the mixing conditions through slump tests, so we need to use another type of consistency test. We choose to fix the mixing conditions by comparing the discharge efficiency of real concrete with various slump values and of model concrete made under various mixing conditions with the number of rotations needed to discharge a fixed quantity of concrete. In short, we aim to find a correspondence in a limited physical property; that is, the flow conditions of concrete in the discharge process. If the number or rotations needed to discharge a fixed quantity of concrete are equal, we can consider that the consistency of the model concrete mixed under a certain conditions corresponds to that of fresh concrete with a certain slump value.

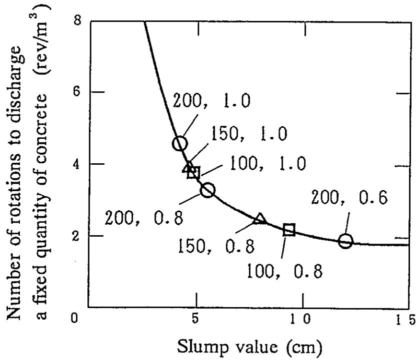


Fig.7 Number of rotations needed to discharge a fixed quantity of various model concretes

We investigated the discharge of a fixed quantity of model concrete made with various flow times and various volume ratios. Figure 7 shows the results, along with corresponding

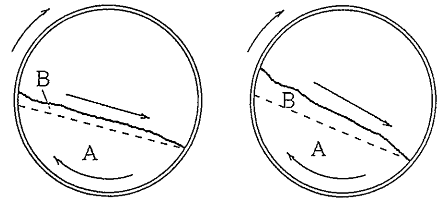
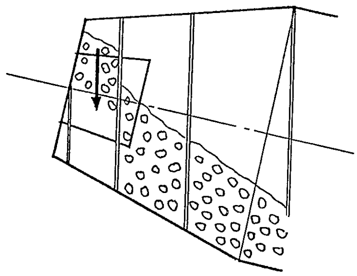


Fig.8 Appearance of model concrete flow in the section direction



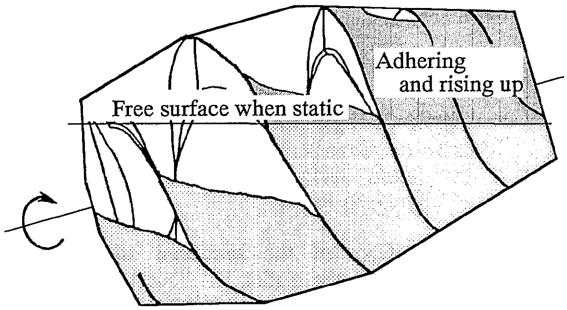


Fig.9 Process of adhering and rising up

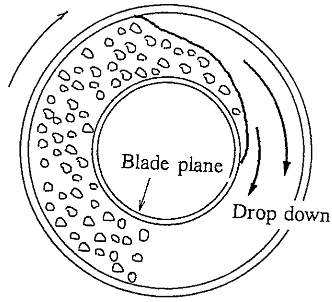


Fig.10 Rearward motion of concrete

slump values of the real concrete. The solid line in the figure shows rotation number for the discharge of a fixed quantity of concrete for the real concrete and the real agitator, while the data points represent flow time and volume ratio for various model concretes. Model concrete of flow time 200s and volume ratio 0.8 corresponds to concrete with a slump value of 5.5cm. Model concrete with a flow time of 200s and a volume ratio of 0.6 corresponds to concrete with a slump value of 5.5cm.

In the subsequent discharge efficiency experiment, only these two types of model concrete are used. Qualitatively, a model concrete with a long flow time or a large volume ratio corresponds to a low slump concrete.

5. FLOW CONDITIONS IN THE DISCHARGE PROCESS

We observed the flow of model concrete during the discharge process in detail, by naked eye and with the video camera. This quickly demonstrated that the following two phenomena harmed the discharge efficiency of model concrete [5] :

1) The effect of the concrete sliding speed over the blade surface
Figure 8 shows how the model concrete flows across a section through the agitator. In region A, if the sliding resistance of the concrete over the blade surface is high, the concrete rises up as the agitator rotates. We call this effect "adhering and rising up". Figure 9 shows how "adhering and rising up" takes place using a side view of the agitator. In region B in Fig.8, the concrete flows down the slope made as the agitator rotates. Concrete with a long flow time and large volume ratio slides slowly over the blade surface as a result of its low fluidity, so it rises further up the drum. The concrete which rises in this way flows back toward the center of the agitator, because of the inclined rotational axis. As a result, the discharge efficiency is lower. Figure 10 shows how the concrete flows backward from the discharge outlet. During the discharge of concrete with a flow time of 200s and a volume ratio of 0.8, i.e. low slump concrete, it was also observed that the concrete rose up near the

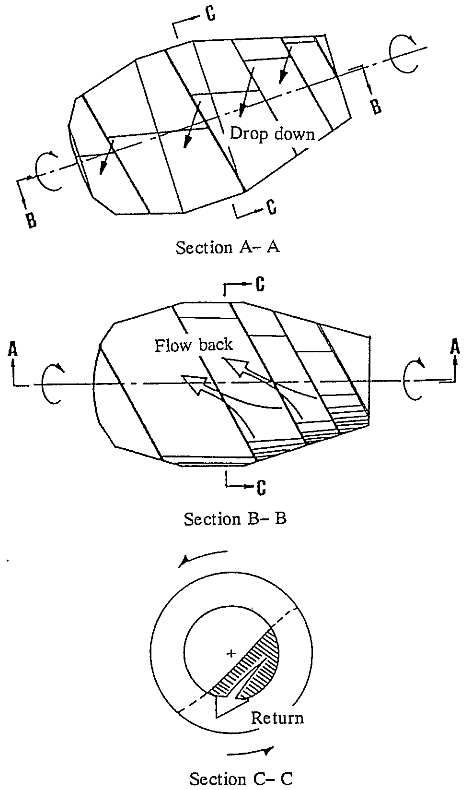


Fig.11 Concrete flow near outlet

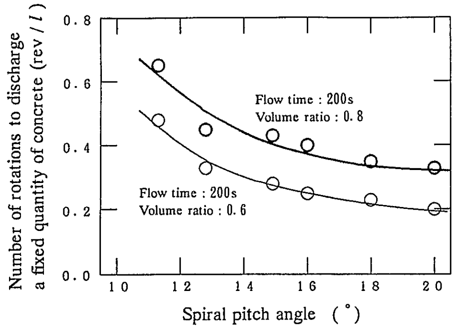


Fig.12 Relation between spiral pitch angle and number of rotations needed to discharge a fixed quantity of concrete

top of the agitator and dropped down under gravity. Clearly, if the sliding speed over the blade surface is lower, the discharge efficiency is lower.

2) The effect of the sectional area of flow route near the outlet

Near the outlet of the agitator, the inside of the drum tapers because the drum is a conoid. In this area, the blade spiral pitch becomes smaller. There is also a blade plane though which to charge the concrete. As a result, the sectional area of the flow route near the outlet is smaller than at any other position. Figure 11 shows how the concrete flows near outlet. Though the concrete in the center of the agitator is carried close to the outlet in large amounts, the agitator is unable to pass it through the outlet because of the small cross-sectional area, and the concrete rises upward before dropping back inside the agitator.

To improve the discharge efficiency of a truck agitator, it is clearly important to increase the sliding speed of the concrete over the blade surface and to increase the sectional area of the flow route through the outlet.

6. EFFECT OF SPIRAL PITCH ANGLE

We measured the number of rotations needed to discharge a fixed quantity of concrete from model agitators in which the drums had blade spiral pitch angles ranging from 11.3 to 20.0 degrees. Figure 12 shows the result. Regardless of the type of model concrete, the agitator with the small pitch angle needed the least rotations to discharge a fixed quantity of concrete. The discharge efficiency of such a blade is considered good. When the blade spiral pitch angle is large, the sectional area of the flow route near the outlet is greater, because the blade pitch is large. This also has the effect of increasing the distance moved by the concrete in one rotation of the agitator.

In the case of an agitator with a spiral pitch angle of about 12 degrees, the number of rotations to discharge a fixed quantity of concrete is much affected to the spiral pitch angle, but in case of about 18 degrees, it is not much. It is the cause that the sliding speed of the concrete over the blade is small because the large spiral pitch angle makes easy the incline of blade surface. In short, a large spiral pitch angle has a positive effect on discharge efficiency in that the sectional

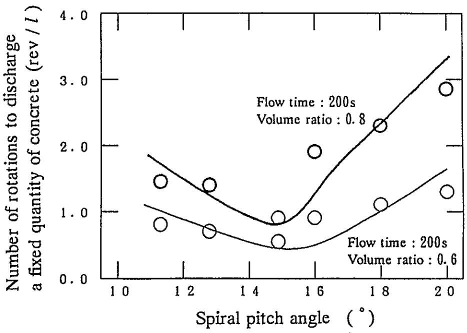


Fig.13 Discharge efficiency in inclined condition

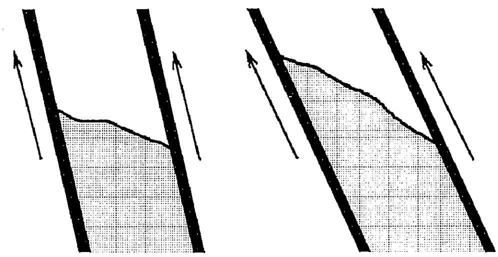

(a) Horizontal condition (b) Inclined condition

Fig.14 Condition of concrete during discharge

area of the flow route is large, but it also has a negative effect because the blade surface has an easy angle. Therefore, in case of an agitator with a larger spiral pitch angle, it is assumed that the discharge efficiency is worse, and therefore an agitator probably exists of which the spiral pitch angle is optimum for discharge efficiency.

To confirm this, we set up the model agitator on an incline, and examined it for the discharging efficiency. The result is shown in Fig. 13. The discharge efficiency in this inclined condition is considerably worse as compared with that in the horizontally condition, even for the same spiral pitch angle. Further, in the horizontal case, the spiral pitch angle giving the minimum number of rotations for a fixed discharge is more than 12 degrees (Fig. 12), while in the inclined case, it is about 15 degrees (Fig. 13). This clarifies that if the angle of incline is larger, the spiral pitch angle for making the least number of rotations to discharge a fixed quantity of concrete is smaller. Figure 14 illustrates the concrete position in the inclined and horizontal cases during discharge. In the horizontal case, the free surface of the concrete is almost flat. On the other hand, in the inclined case, it is steeply inclined such that the concrete adheres to the blade surface and flows with the blade.

If we focus attention upon the concrete as it slides over the blade surface during the discharge process, it appears that discharging the agitator in the inclined condition is equivalent to discharging an agitator with a larger spiral pitch angle in the horizontal condition; the sliding speed of the concrete over the blade surface is smaller and the discharge efficiency is lower.

In the horizontal condition, it is found that the most efficient spiral pitch angle for discharge is more than 20 degrees, but in the inclined condition the number of rotations needed to discharge a fixed quantity of concrete from a 15-degree agitator is smallest. Thus it is shown that an agitator with an optimum spiral pitch angle exists.

In other words, increasing the sectional area of the flow route near the outlet by making the spiral pitch angle larger means causing a lower sliding speed of the concrete over the blade surface, so there is a trade-off effect. As a result, the blade spiral pitch angle, which influences the discharge efficiency, has an optimum value because of these two relations : the increase in discharge amount arising from an increase in the sectional area of the flow route and the decrease resulting from reduced sliding speed over the blade surface.

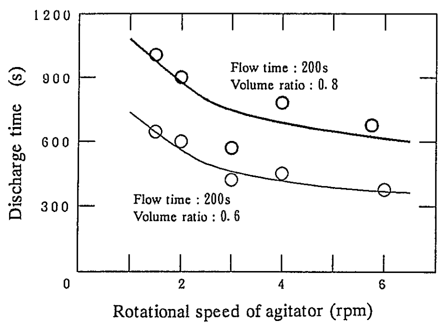


Fig.15 Relationship between rotational speed of agitator and discharge time

7. EFFECT OF ROTATIONAL SPEED

Figure 15 shows the relationship between the rotational speed of the agitator and the discharge

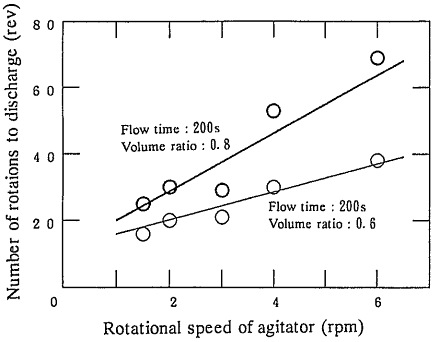


Fig.16 Relationship between rotational speed and number of rotations needed to discharge

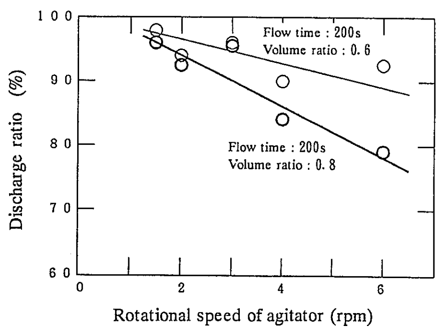


Fig.17 Relationship between rotational speed of agitator and discharge ratio

time. The discharge time is short at high rotational speeds. Figure 16 shows the number of rotations needed to make a discharge. Many rotations are needed to discharge when the rotational speed is high, and as the rotational speed increases, the discharge becomes less smooth. The concrete is pushed by the blade toward the outlet by sliding over the blade surface or on the inner surface of the drum. Yet the drum itself rotates, so when the rotational speed is high, the rotational speed of the drum is faster than the sliding of the concrete over the blade surface. The concrete then adheres and moves with the rotation of agitator, failing to slide over the blade surface toward the outlet. Figure 17 shows the relationship between discharge ratio and rotational speed. When the rotational speed is high, the discharge ratio is low and some concrete fails to be discharged because it adheres to the drum or the blade.

In short, the discharge ratio falls if a high rotational speed is chosen to get a good discharge speed, while the discharge speed falls if a low rotational speed is chosen to get a high discharge ratio. To achieve a short discharge time without a detrimental effect on the discharge ratio, it is advisable to vary the rotational speed during discharge, e.g. use a high rotational speed until most of the concrete is discharged, and then reduce the speed to get a high discharge ratio.

8. SUMMARY

In this study of the discharge efficiency of concrete from an the agitator, we made the process visible by using a model agitator and investigated the influence of blade spiral pitch angle and drum speed on discharge efficiency. The results were used to find factors which influence the discharge efficiency. Results were as follows:

(1) Observations of the flow condition of concrete during the discharge process demonstrate that the factors which have a detrimental effect on discharge efficiency are the sliding of concrete over the blade surface and the limited sectional area of the flow route near the outlet.

(2) Measurements of the number of rotations needed to discharge a fixed quantity of concrete for various discharge conditions and blade spiral pitch angles clarified that an agitator with a large spiral pitch angle has good discharge efficiency because the sectional area of the flow route near the outlet is larger. On the other hand, it had a negative effect in that the sliding speed of the concrete was reduced because the angle of the blade is easier. In short, it was demonstrated that an optimum spiral pitch angle for the discharge of concrete exists.

(3) An investigation of the influence of rotational speed on discharge time and discharge ratio showed that the discharge ratio falls at higher rotational speeds, while the discharge speed falls at a low rotational speed. To obtain a short discharge time without causing the discharging ratio to fall, it is advisable to change the rotational speed than to keep a constant rotational speed throughout the discharge.

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