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Development of a Simple Quantitative Method for Evaluating Concrete Separation Resistance

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Abstract

Concrete is tested using slump testing, but slump testing is a method for evaluating concrete consistency, and it is thus difficult to directly evaluate concrete separation resistance by this method. Generally, it is common to perform slump plate tamping after slump testing, and observe concrete deformation to evaluate the concrete separation resistance, but this method is not quantitative. This research proposes a simple method for evaluating concrete separation resistance, based on compaction completion energy, by confirming the presence of circles on the top of a concrete sample after performing hammer tamping used in air volume measurement until the slump flow of a sample reaches 47cm after slump testing. This paper is an extended version of the author’s previous publication (Maruya et al. 2013).

1. Introduction

Concrete workability is believed to depend on many factors, such as consistency and separation resistance. In the past, concrete workability has been indirectly evaluated through slump testing, a method for evaluating consistency (Tamura et al. 2003). When there are few varieties of aggregates and admixtures, there are few factors which affect concrete separation resistance, so the consistency determined via slump testing is sufficient for indirect workability evaluation. However, concrete has grown more diverse and admixtures more multifunctional, due to the depletion of high quality aggregates and the usage of more varied admixtures. Because of this, it is difficult to evaluate concrete freshness based purely on slump testing.

There have been many reports of concretes with identical slumps but differing material separation resistances (JCI 2009). Because of this, while it has been possible in the past to decide based on prior experience that a certain level of slump indicated a certain level of material separation resistance, and to supply concrete based on this judgment, this approach will be less feasible in the future.

Several methods have been proposed for testing concrete freshness (Fujishiro et al. 2006; JSCE 2007; Hughes 1961; Browne et al. 1977), but most require new equipment, making it difficult for them to achieve greater penetration as inspection methods used in worksites.

At worksites, it is common to perform slump plate tamping after slump testing, and observe concrete deformation to evaluate the concrete separation resistance, but, with this method, it has not been clarified to what extent a slump plate should be tamped and what provides the evaluative criterion. While we tried to make this testing method quantitative by recourse to the frequency of slump plate tamping, the test results had large errors depending on tamping tools, the environment underneath the slump plate, and the persons performing the tamping. This research proposes a simple method for evaluating concrete separation resistance, based on compaction completion energy, by confirming the presence of circles on the top of a concrete sample after performing hammer tamping used in air volume measurement until the slump flow of a sample reaches 47cm after slump testing. Here compaction completion energy refers to the energy required by concrete in a formwork to reach from its apparent bulk density to the theoretical density according to its mix proportion. Therefore, in this study, the sufficiently compacted state of concrete is defined as the state of concrete compacted up to the theoretical density.

This (proposed) testing method is applied to plain concrete in its fresh state whose coarse aggregate has the maximum dimension of 25 mm or less and whose slump ranges from 5 to 15 cm, made by using sand and gravel specified in Attachment A to JIS A 5308 or gravel and crushed stone specified in JIS A 5005.

2. Compaction completion energy evaluation method

This research considers concrete separation resistance from the perspective of concrete compaction completion energy. Figure 1 shows the test apparatus used to measure concrete compaction completion energy. It is com-
posed of a vibration table with two opposed eccentric rotation motors that vibrate with a specific amplitude, a computer for recording data, and a control panel for adjusting the vibration table frequency, controlling acceleration. First, slump testing is performed in test containers with a diameter of 24mm, which are placed on the vibration table and vibrated. When this is performed, the amount of sample surface settlement, vibration table acceleration, and vibration table frequency are covered. The level of concrete compaction can be thought of as indicating the ease of deformation to ideal density for the concrete mixture based on the apparent bulk density of the concrete in the mold before compaction, based on the concrete’s consistency.

The amount of compaction is taken to be the ratio of the cylinder volume (based on the height of the highest point of the sample in the cylindrical container) to the true concrete sample volume. This is defined as the amount of compaction, $\gamma$. The amount of compaction $\gamma$ can be expressed using eq. \ref{eq:compaction} (Linag et al. 2006).

$$\gamma = \frac{H_0}{h} \times 100 = \frac{m}{\rho \times A \times h} \times 100$$  \hspace{1cm} (1)$$

where, $\gamma$: amount of compaction (%), $H_0$: height of the sample when compacted to the theoretical weight per unit volume of the concrete based on its composition (mm), $h$: height of sample at a given compaction time (mm), $m$: sample mass (kg), $\rho$: sample weight per unit volume (kg/L), and $A$: cylindrical container bottom surface area (mm²).

Equation \ref{eq:compaction} indicates the deformation progress curve. The coefficients in the formula are based on the schematic view.

$$\gamma = C_i + (C_f - C_i)[1 - \exp(-bE^d)]$$  \hspace{1cm} (2)$$

where, $\gamma$: concrete compaction for compaction energy $E$ (%), $C_i$: initial compaction (%), $C_f$: achievable compaction for infinite compaction energy (%) (compaction is always possible for stiff concrete, so $C_f$ is considered to be 100%), $b$, $d$: experimental constants.

The compaction energy can be determined using eq. \ref{eq:compactionenergy} (Kokubu et al. 1996).

$$E_t = \frac{\rho a_{\text{max}}^2 t}{4\pi^2 f}$$  \hspace{1cm} (3)$$

where, $E_t$: amount of compaction energy received by concrete in $t$ seconds (J/L), $t$: compaction time (s), $a_{\text{max}}$: maximum acceleration (m/s²), $f$: frequency (s⁻¹), $\rho$: sample’s weight per unit volume (kg/L).

In this study, a compaction of 99.5% can be considered to be sufficient for compaction completion, and the amount of energy needed to reach a compaction of 99.5% is defined as the compaction completion energy (E99.5), as shown in Fig. \ref{fig:compaction}.  

### 3. Materials used and concrete composition

A 55% water to cement ratio was used, with a unit water volume of 155 kg/m³, and a 40.5% fine aggregate percentage. The standard composition shown in Table \ref{tab:composition} was used to produce concrete with a target slump of 8 cm and a target air volume of 4.5%. Table \ref{tab:materials} shows the materials used.

### Table 1 Concrete composition.

| admixture | W/C (%) | s/a (%) | Water | Cement | Fine Aggregate | Coarse Aggregate | AE Water Reducing Agent C×% |
|-----------|---------|---------|-------|--------|---------------|-----------------|-----------------------------|
| Standard  | 55      | 40.5    | 153   | 278    | 769           | 452             | 673                         | 0.25                        |

### Table 2 Materials used.

| Type              | Quality                                                                 |
|-------------------|--------------------------------------------------------------------------|
| Cement (C)        | Ordinary Portland cement: Density 3.16g/cm³                               |
| Fine Aggregate S  | Chiba Prefecture Kimitsu City Mountain Sand: Surface drydensity 2.65g/cm³, water absorption ratio 1.56% |
| Coarse Aggregate G1 | Aomi Crushed Rock Lime (GMAX13mm): Surface dry density: 2.66g/cm³, water absorption ratio 0.60% |
| Coarse Aggregate G2 | Aomi Crushed Rock Lime (GMAX20mm): Surface dry density: 2.65g/cm³, water absorption ratio 0.60% |
| Admixture (Ad)    | AE Water Reducing Agent (Standard Type), AE                              |

![Fig. 1 Compaction test apparatus.](image)
4. Consideration of flow conditions of concrete which has received compaction completion energy

Fine aggregate percentages, water / cement ratios, slumps, etc. were changed from the standard composition to produce various mixtures with different freshness. Then the compaction completion energy of each mixture was measured by the method described in the section 2 and shown by the mixtures in Table 3. Each mixture was placed on the vibration table, without its settlement plate or settlement plate holding frame. Slump testing was performed, and then, as shown in Fig. 3, vibration equivalent to the compaction completion energy of each mixture was applied, and the slump and slump flow were measured after vibration. The amount of energy imparted was controlled by controlling the compaction time. The vibration table frequency was 35 Hz and acceleration was 13.5 m/s².

The measured compaction completion energies and vibration table frequencies for each mixture, and the acceleration received by the concrete were input into eq. 3, and the compaction time needed to apply compaction completion energy to each mixture using the vibration table was calculated. Table 3 shows measurement results and the compaction completion energy of each mixture. As the table shows, changes in the freshness of concrete resulted in different compaction completion energies, which indicate the ease of compacting the concrete. These differences varied from 0.8 to 11.4 J/L. In terms of vibration time, this is 3.2 to 32.2 seconds.

Figure 4 shows the relationship between the vibration time, slump flow for each mixture to which compaction completion energy was imparted. As the figure shows, although vibration times, which indicate the compaction completion energy, varied widely, from 3.2 to 32.2 seconds, the slump flow of each concrete sample after vibration was essentially the same, with slump flows of approximately 47 cm. This indicates that even if their composition is different, concrete samples to which compaction completion energy has been imparted have roughly the same slump flows.

The amount of concrete compaction completion energy indicates the ease of deformation to ideal density for the concrete mixture based on the apparent bulk

Table 3 Concrete compositions and measurement results.

| admixture | Target Slump (cm) | W/C (%) | s/a (%) | Unit Amount (kg/m³) | AE Water Reducing Agent Cx% | Slump (cm) | Compaction Completion Energy (J/L) | Vibration Time (s) | After Vibration Slump Flow (cm) |
|-----------|-------------------|---------|---------|--------------------|-----------------------------|------------|----------------------------------|------------------|-------------------------------|
| Standard  | 8                 | 55      | 40.5    | 153                | 278                         | 676        | 452                              | 673              | 0.25                          | 8.5 | 1.66 | 5.5 | 45.8 |
| s/a change| 55                | 40.5    | 35.0    | 153                | 278                         | 665        | 494                              | 735              | 0.25                          | 10.7 | 2.60 | 8.1 | 49.0 |
| W/C change| 55                | 40.5    | 45.0    | 153                | 278                         | 855        | 518                              | 622              | 0.25                          | 10.5 | 1.73 | 5.7 | 48.8 |
| Slump change| 55                | 40.5    | 45.0    | 153                | 278                         | 1045       | 843                              | 642              | 0.25                          | 5.2  | 4.16 | 12.4 | 48.7 |
| 8         | 55                | 55      | 44.5    | 153                | 278                         | 342        | 509                              | 0.25             | 8.9                          | 1.27 | 4.5  | 48.2 |
| 12        | 40.5              | 55      | 44.5    | 153                | 278                         | 295        | 441                              | 662              | 0.25                          | 11.2 | 1.03 | 3.8 | 46.7 |
| 15        | 44.5              | 60      | 44.5    | 153                | 278                         | 300        | 817                              | 607              | 0.25                          | 16.7 | 0.80 | 3.2 | 46.5 |

Fig. 2 Schematic view of deformation progress curve.

Fig. 3 Condition of sample before and after vibration.

Fig. 4 Slumps and slump flows of concrete samples after vibration.
density of the concrete in the mold. Therefore, disre-
garding minor variations in concrete density, the con-
crete in a form after compaction has the same dimen-
sions. Figure 4 and the data in Table 3 show that the
shapes of concrete sample flow to which compaction
completion energy has been imparted are the same, even
without forms.

Therefore, regardless of how many times tamping is
performed, and the tool used to perform the tamping,
the amount of energy used to produce a slump flow of
47 cm after sample slump testing can be taken as the
sample’s compaction completion energy.

As the definition of compaction completion energy
indicates, compaction completion energy is the mini-
imum amount of energy necessary for concrete compac-
tion. To compact concrete, the amount of energy one
must impart to it must be equal to or greater than the
compaction completion energy. Concrete separation
occurs if concrete is subjected to excessive vibration.
Therefore, in selecting a concrete mixture, it is neces-
sary to choose at least one which does not separate even
if it is subjected to vibration equivalent to the compac-
tion completion energy.

Therefore, if, during the course of tamping a slump plate in order to reach a concrete
sample slump flow of 47 cm (that is, during the course of imparting compaction completion energy) there is
crumbling, separation, or water leakage, as shown in
Fig. 5, the material separation resistance can be consid-
ered insufficient.

5. Considering a Method for Evaluating
Separation Resistance based on Sample
Conditions after Tamping

The considerations of the previous section made it clear
that concrete separation up to compaction completion
energy can be confirmed by confirming whether or not
there is crumbling, etc., when tamping a sample to a
slump flow of 47 cm after slump testing. However, even
if there is no crumbling, etc., when tamping to 47 cm, it
does not necessarily indicate that the mixture is optimal
for the compaction completion of concrete (JCI 2009).
If the concrete has low viscosity, compaction comple-
tion energy becomes greater as the impact of coarse
aggregate meshing becomes significant. On the other
hand, if concrete viscosity is too high, not only does
compaction completion energy become greater due to
the viscosity, but also bubbles tend to remain on the
surface of the concrete. It is necessary to choose a mix-
ture with a viscosity that is optimal for compaction.
Therefore, a method must be considered for evaluating
optimal mixtures. Ishii et al. (2008) pointed out that
whether or not there are circular shapes in the top of a
sample after tamping testing can be used as an indicator
of concrete separation resistance.

Considering concrete material separation as the sepa-
ration of mortar and coarse aggregate, material separa-
tion resistance can be considered to be primarily gov-
erned by the mortar's plastic viscosity. In the case of
concrete, whose mortar composition has a high plastic
viscosity, when an impact is applied, the viscosity pre-
vents the top of the sample from being affected a great
deal, with only the bottom of the sample deforming.
However, when the level of plastic viscosity is low, de-
formation will occur at the top of the sample as well,
meaning that circular deformations on the top surface of
the sample will disappear. Based on this, it is possible to
evaluate material separation resistance based on how
much the top of a sample retains circular shapes.

In order to quantitatively evaluate the separation re-
sistance of concrete, the hammer used in air volume
measurement was used to strike slump plates after
slump testing to flows of 32 cm, 37 cm, 42 cm, 47 cm,
and 52 cm, and the change in the upper circle shape in
conjunction with flow change was observed. Figure 6

Fig. 5 Examples of separation after tamping.

Fig. 6 Changes in circular shape in upper surface as a result of tamping (Standard Composition).
shows an example of a mixture with a standard composition after tamping.

The concrete compositions used in the testing were determined as follows, based on actual composition selection conditions. First, fine aggregate percentage changes were envisioned, using as a starting point for testing samples the standard composition of the previous section, keeping a constant W/C but changing s/a values to 43.5%, 42.0%, 40.5%, 39.0%, and 37.5%.

In order to avoid the influence that coarse aggregate meshing gives for the result of the examination, the volume of coarse aggregate was kept constant. The mortar’s viscosity was changed by changing the volume of fine aggregate by adding paste volume.

Next, the unit water volume was adjusted, keeping the W/C constant and changing the s/a for individual samples to 43.5%, 42.0%, 40.5%, in mixtures with slumps between 8 cm and 10cm. Testing was then performed on these mixtures. Table 4 shows the compositions and experiment results.

Values were assigned to indicate whether or not a circle remained present as slump flow changed after tamping: samples with circles present on their upper surfaces after tamping were represented by a value of 1, while those without circles present were represented by a value of 0. Figure 7 shows experiment results for samples with a constant W/C and s/a of 43.5%, 42.0%, 40.5%, 39.0%, and 37.5%. Figure 8 shows the experiment’s results after slump alignment. As Fig. 7 shows, the standard composition mixture retained a circular shape on top until the slump flow reached 47 cm, but the circle was gone once the slump flow reached 52 cm. Mixtures with smaller s/a showed more separation than the standard composition mixture, with circles disappearing before the flow reached 47 cm. Conversely, mixtures with larger s/a maintained circular shapes on their surface even after the flow reached 47 cm. In other
words, this means that the standard composition retained circular shapes on its upper surface until the amount of energy imparted to it reached compaction completion energy, but once this amount of energy was exceeded, the circles disappeared. Circles did not disappear for mixtures with greater s/a even after their flows passed 47 cm, but mixtures with a tendency for separation lost their circular shapes even before compaction completion energy had been imparted to them. Figure 7 shows that the same results held even when the unit water volume was adjusted to produce equal slumps. This indicates that it is possible to evaluate the change in concrete separation resistance due to changes in s/a by confirming whether or not there are circular shapes present in the upper surfaces of samples after tamping them to a flow of 47 cm after slump testing.

In order to confirm the influence of differences in paste viscosity, samples were created by maintaining constant fine aggregate percentages and coarse aggregate volumes, while varying unit cement volumes by ±10 kg and ±20 kg. After slump testing, these samples were tamped to a flow of 47 cm. Table 4 and Fig. 9 show the compositions and experiment results. As Fig. 9 shows, compositions with greater paste viscosity due to greater volumes of cement retained the circular shapes even when their slump flows exceeded 47 cm, but compositions with less cement and therefore less viscosity lost their circular shapes before their slump flows reached 47 cm. As the data in Table 4 shows, the test results did not change even when the unit water volume was adjusted to a slump of 8 cm to 10 cm. This indicates that this evaluation method can also be used to evaluate paste viscosity changes.

In order to confirm the impact of different unit water volumes, the amount of water of the standard composition was adjusted by ±5, ±10, ±15, and ±20 kg/m³, and the presence or absence of circular shapes on the tops of the samples was checked. Table 4 and Fig. 10 show the compositions and experiment results. As Fig. 10 shows, compositions with 5 kg/m³ less water retained their circular shapes to a slump flow of 47 cm, just as the standard composition sample did, but the other compositions with concrete viscosities lowered by adding water lost their circular shapes before their slump flows reached 47 cm, and compositions whose viscosity was increased by decreasing their water volume retained their circular shapes beyond slump flows of 47 cm. This indicates that this method can be used to evaluate concrete viscosity changes if the change in unit water volume is 5 kg/m³ or greater.

The procedure of the method for evaluating concrete material separation resistance is shown below and in Fig. 11.

A) Fill a slump cone with sample as in slump testing, and carefully even out the upper surface of concrete with a trowel or similar tool.

B) In order to enable clear evaluation of the properties of the upper surface of the sample, color it in reddish
violet by spraying phenolphthalein solution on it. This colored part is called the colored surface.

C) Gently lift the slump cone up vertically as in slump testing. Measure the slump at this moment.

D) Strike a slump test plate with a wooden hammer to deform the concrete sample through the vibration of the plate until slump flow reaches 47 cm. If crumbling, separation, or water leakage occurs in the sample during this deformation process, the mixture is determined to have insufficient material separation resistance. If a circular rim on the colored surface at the top of sample is retained at the stage where slump flow has reached 47 cm as a result of sample deformation, the concrete is determined to have appropriate separation resistance. If the circular rim is broken, the concrete is determined to have insufficient separation resistance.

E) Strike the plate further to deform the concrete until slump flow reaches 52 cm. If the circular rim is broken during this deformation process, the concrete is determined to be in a state with excessive separation resistance. If the circular rim is retained even at the stage where slump flow reaches 52 cm as a result of deformation, the concrete is determined to be in a state with excessive separation resistance.

6. Conclusions

This study considered a method for evaluating concrete material separation resistance by using the hammer used to perform air volume measurement to strike a slump plate after slump testing, and check if the circular shape was retained as the sample reached a slump flow of 47 cm. The following conclusions were reached.

(1) When an amount of energy equivalent to a concrete sample’s compaction energy is applied after slump testing, the slump flow will expand to approximately 47 cm. Therefore, the amount of energy needed to achieve a slump flow of 47 cm can be considered the compaction completion energy.

(2) It appears that performing tamping on a sample until it reaches a slump flow of 47 cm after slump testing, and checking for the presence of a circular shape on the top of the sample, can be used to evaluate concrete material separation resistance. If the circular shape has disappeared, the sample's material separation resistance is low.

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