Simple Evaluation of Water Permeability of Cover-concrete Using a Water Spray Method

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The near-surface layers of concrete structures (or cover-concrete) play a crucial role in preventing the corrosion of reinforcing bars embedded in the concrete. From the viewpoint of improvement in the durability of reinforced concrete (RC) structures, establishment of on-site testing methods for evaluating the permeability of cover-concrete has become increasingly important in recent years. Therefore, a simple testing method has been developed, called the Water Intentional Spraying Test (WIST), with especial emphasis on the applicability to the inspection of railway RC structures. By using the latest WIST Method-A which is reported in the current paper, it is possible to easily evaluate the cover-concrete quality by visual inspection with the use of a simple implement for spraying a small amount of water.

Keywords: durability of reinforced concrete structures, cover-concrete quality, non-destructive evaluation, water intentional spraying test (WIST)

1. Introduction

Recently, the need for non-destructive evaluation of the quality of near-surface layers of concrete structures, namely, cover-concrete quality, has increased. Because cover-concrete quality significantly affects the durability of reinforced concrete (RC) structures, there has been significant research and development into establishing non-destructive testing methods applicable to actual structures. For example, at the Annual Meeting of the Japan Society of Civil Engineers (JSCE) held every September, in 2008 there was only one presentation with the keyword “cover-concrete quality”, with only a handful of other presentations related to the topic. However, in 2015, there were 10 lectures with “cover-concrete quality” in their title, while there were over 30 examples of research cases and presentations with keywords including quality of near-surface layers, air permeability, or water permeability/absorbability.

The Railway Technical Research Institute (RTRI) has placed importance on applicability of cover-concrete quality evaluation methods to the inspection of actual structures, with particular focus on simplicity, and a unique approach to find a method which (1) does not require an external power source, (2) is labor saving, and (3) space saving. In the past RTRI already proposed a method called “Water Intentional Spraying Test (WIST)” whereby small quantities of water are sprayed onto the surface of dry concrete in order to detect change in intentionally generated surface color (or brightness), as well as water absorption of cover-concrete through quantitative assessment of water flowing down its surface thereby performing a simple evaluation of the cover-concrete quality [1].

This paper reports on the result of a study of a simpler evaluation method based on the water absorption phenomenon found in cover-concrete, and observed when applying WIST to a vertical plane. The paper also describes technical developments for the practical application of WIST.

2. Overview of WIST

In technological terms, WIST is a method for discriminating the behavior of dissipation and/or effluence of small quantities of water sprayed intentionally on the dry surface of concrete, by visual observation or measurement of the reflection/absorption characteristics of visible light, thereby allowing evaluation of water absorption in cover-concrete. It has been shown that the index obtained through measurement of the change in brightness on the surface of concrete enables evaluation of cover-concrete quality. In addition, a method was proposed to evaluate the cover-concrete quality, by taking the “distance covered by water flowing down the surface of the cover-concrete when conducting a WIST test” as an index, based on knowledge obtained from tests on water flowing down the surface of cover-concrete [2], and water absorption as water flows down a vertical plane. Hitherto, it was considered that the phenomenon linked to water flowing down a vertical plane, was simply a side effect of WIST. However, if a method could be found to evaluate cover-concrete quality based on water absorption, which required only visual observation, measurement work would become dramatically more efficient. Accordingly, this paper studied/investigated the water spray method focusing specifically on the phenomena related to water flow and observation of related phenomenon. The phenomena related to water flowing down a vertical plane observed in conventional WIST were then abstracted, and taken to form a new standalone method, (and not construed simply as a side effect of WIST). The WIST method is illustrated in Fig. 1. WIST Method-A (hereinafter, ‘Method-A’) requires only visual observation of water flowing down the surface, to make a simple evaluation; the conventional method using instruments for measurement was renamed WIST Method-B (hereinafter Method-B); to classify into 2 methods. “WIST” hereafter is used as the collective term for both methods.

The cover-concrete quality assessment method is described in more detail in chapter 3, however, briefly, in Method-A, a visual inspection is made, to see if water falls

Fig. 1 Overview of Water Intentional Spraying Test (WIST)

down after spraying. The test is completed at the point in time when water begins to fall down after spraying, and the evaluation is made by counting the number of times water was sprayed until that point in time. In Method-B, a person with, for example, a hand-held measuring device collects detailed data on the change in brightness at the surface of the concrete after water has been sprayed. The evaluation of the cover-concrete quality is based on the number of times the surface was sprayed until saturation of the change in brightness. In the case of dense concrete which does not absorb water easily, the number of times tends to be lower that water has to be sprayed before water begins to flow out and saturation is achieved in the change in brightness. In other words, the higher the quality of the concrete, the sooner both tests – using method A or B – are completed. For example, if water is sprayed at intervals of 60 sec and the test is over after spraying the concrete once or twice, the test can be completed in approximately 2 minutes. On the other hand, the concrete with poor quality would require longer time to complete the test because of the higher rate of absorption, which means water has to be sprayed onto the surface more times.

The basic interval between each spraying was 60 seconds for both WIST methods. The 60 seconds however are not just spent waiting, but allow several spots on the concrete to be evaluated simultaneously using Method-A. Each spot is sprayed approximately every 5-10 seconds, allowing 4-8 spots to be measured during this time.

3. Method for assessing the quality of near-surface layers using WIST

Method-B allows the collection of more detailed information using a measuring instrument than method-A. In method-B, the change in color of the surface of the concrete is measured quantitatively to evaluate the quality of the cover-concrete which darkens when sprayed with water, and then gradually lightens as water is absorbed. The saturation degree of change in brightness defined in (1) was proposed as an evaluation index for the B-Method. This was based on the assumption and experiment results which showed that, the easier the concrete absorbs water,

the larger the quantity of water required to reach brightness saturation:

$$S_B = (L_I - L_E) / (L_I - L_{MIN}) \quad (1)$$

where S_B is the degree of saturation in change in brightness; L_I is the initial value of brightness before water was sprayed; L_E is the brightness at an arbitrary point in time; and L_{MIN} is the lowest brightness at the measuring point.

Method-A however is based on the premise that the distance travelled by water sprayed onto concrete with high absorption will tend to be shorter. Figure 2 shows change in brightness measured with B-Method together with measured distances travelled by the water being sprayed on the concrete in the B-Method evaluation. It shows that as the number of sprayings n increases, so does the degree of saturation in change of brightness S_B while the increased in distance x travelled by the water down the surface, is confirmed. As the supplement, here, we adopted the procedure of setting the repeating time interval of water spray at 120 sec, measuring a change in brightness during 10 sec to 90 sec after water spraying, and measuring the flowing-down distance immediately after that, in order to surely execute measurement of the change in brightness and flowing-down distance after water spraying.

RTRI proposed a method whereby the quality of cover-concrete can be evaluated by the number of times the concrete needs to be sprayed before brightness saturation and flow distance reach predetermined threshold values. For instance, the temporary threshold values for flow distance and brightness saturation were set at 20 mm and 0.9 respectively. Therefore, the assessment could be made using to determine the number of times the concrete had to be sprayed until the flow distance reached 20 mm, while Method-B could be used to determine the number of sprayings required to reach a change in brightness saturation of 0.9. As such, the cover-concrete quality index for WIST can be based on the “number of sprayings”. By using the data in Fig. 2 for example, method-A would give an index of “2” (two sprayings) while method-B would indicate “6”. Since the evaluation index in WIST is based on simple frequency, the understanding of numerical values and phenomena becomes comparatively easy.

Fig. 2 Measurement example of a brightness change with time by Method-B (with flowing-down distance measured collaterally)

4. Investigation into appropriate manner to spray water for WIST method-A

4.1 Overview

The amount of sprayed water per area to be measured will significantly affect the result obtained using the WIST method, therefore it is necessary to adapt the amount of sprayed water, and the spraying apparatus to the spray area, to ensure suitable test conditions. The amount of sprayed water will depend on the performance of the spraying apparatus; therefore apparatus with a predetermined water spraying performance was selected to conduct the tests. The area to be sprayed was originally round, to fit the shape of the brightness measuring instrument used in the B-Method. However, as the target for measuring distance travelled by the water down a vertical plane is not round, it was not necessary to remain with the round shaped area. Accuracy and workability could in fact be improved if another shape was used for the measurement area, therefore investigations were carried out to find the most suitable shape of sprayed area for method-A. Furthermore, as described above, the evaluation is carried out by measuring the distance travelled by water down the surface after spraying, which by definition means that the person carrying out the evaluation must not only spray, but also measure the water trickle. Measurement of the trickling water is done in much the same way as in Method-B with a measuring instrument. Therefore, in order to improve the workability of this method, it was investigated whether this “simultaneous need to measure” stage could be omitted.

In order to implement study simply, we conducted measurement at the wall surface of the actual structure in our research facility. Aging of the concrete is about 5 to 10 years, however, its exact composition (details of materials used, etc.) was unknown. We have not performed detailed study about comparison of the frequency of water spray necessary for flowing-down, etc. Measurements were conducted at places where influence of direct sunlight and rain splashing was small. We carried out the water spraying repeatedly in the pace of once per approximately one second at the same place until flowing-down occurs, and we observed the shape of wet area after occurrence of flowing-down.

4.2 Study of shape formed by water spray at the point of origin of the water flow

In method-B, a jig with an opening in the shape of a true circle (hereinafter referred to as the water spray guide) is used, in order to spray water in a round shape with a diameter of about 60 mm. This guide has an edge with a margin of about 2 mm added to the diameter so that it can be used for measuring change in brightness. The water spray guide is placed against the surface of the concrete at the point to be measured and a conical nozzle is affixed to the tip of the spraying device, in order to control the spray area. Figure 3 shows the configuration and conditions in which the water spray apparatus is used for WIST. In WIST, water spraying and observation for method-A or measurement for method-B are repeated alternately.

The water spray guide also plays an important role as the positioning guide to reproduce the measurement position within a certain range, repeatedly.

If focusing solely on the trickling of water down a vertical plane in Method-A, it is easy to imagine how the vertical flow of water can be affected by the shape of the pattern used to spray the wall. Figure 4 schematically shows the relationship between the water trickle and the shape of the pattern used for water spraying on the vertical plane. Immediately after spraying, the water that is not absorbed by the concrete begins to trickle down (or flowing-down) the surface because of gravity. Water around the edge of the spray pattern however collects towards the center of the bottom of the shape under the effect of surface tension. Therefore, if the circle shape is elongated to form a vertical oval, water will accumulate more easily towards the bottom of the pattern, enhancing the trickle-down effect. Following on, the accumulation effect will be affected by the edges of the shape being straight or curved. Therefore, the shape of the guide was radically changed to a downward pointing triangle to compare the trickle-down effect using this new shape. Four different inverted isosceles triangle guides were tried, with apex angles ranging between 30° and 120°.

Figure 5 illustrates the different guide shapes and flow patterns being compared. Results of the investigation confirmed that the trickle-down effect varied significantly depending on guide shape, while using the same amount of water for spraying. The following findings were obtained:

- (1) Water frequently trickled out from points other than the lowest point of the guide shape, regardless of whether the edge of the spray area was straight or curved.
- (2) The sharper the angle of the bottom most point on the spray area, the easier it was to guide the water to the bottom. However, even in that case, water does not always flow just below.
- (3) When a sprayed area is not a round shape and the bottom tip of its guide shape is not pointing vertically downwards, the direction of the water flow is influenced. Furthermore, the sharper the inverted apex angle, the greater the influence of any shift away from verticality.
- (4) Influence of the positional shift of water spray at alternately repeating water spray and measure-

Fig. 3 Water spray apparatus for WIST

Fig. 4 Relationship between flowing-down phenomenon and shape of water spray

Fig. 5 Example of flowing-down status

ment in WIST becomes larger, when the lower edge part at the shape of water spray has a sharp angle.

Based on the insight obtained from these trials, it was decided that the shape of the lower edge of the area to be sprayed should be curved, as previously used in method-A.

4.3 Investigations into establishing a water spraying method without measurement of the trickle-down distance

With a view to reducing the labor intensity, investigations were carried out to see if it was possible to omit the trickle-down distance measurement phase. This was done following 3 steps:

- (1) No measurement of trickle-down distance.
- (2) Preparation for measurement of trickle-down distance in advance.
- (3) Re-design of the water spray method to allow omission of the trickle-down measurement

Step (1) was based on the following premise: The higher the absorption rate of the concrete, the greater the volume of water required for the trickle-down distance to reach the threshold point. If the applied volume of water is less than the amount of water the concrete absorbs instantaneously, then the trickle-down distance will be 0. If a value of 1 is given to indicate the presence of any trickling, then it is possible to attribute a score of 0 to cases where there is no trickling at all, and a score of 1 to cases where there is some trickling, which can be determined from visual observation alone, omitting the need for any measure-

ment. An example of step (1), where evaluation is carried out by simple visual inspection, is shown in Fig. 6. In concrete with a low water absorption rate, water trickles a distance of almost 10mm, even after the first spraying. That means that subsequent evaluation by measurement of the distance travelled by water trickling down the surface is simple, since the trickle-down is visible straight away. However, in the case of concrete with poor water absorption resistance as shown on the right in Fig. 6, blurring (or bleeding) occurs along the edge of the sprayed area, making measurement of any trickle-down difficult. In cases like the example shown in Fig. 7, where the trickle down of water is extremely slow, the sprayed area actually expands rather than displaying any vertical flow of water. The expansion of the sprayed area occurs very slowly, for example, approximately 1mm every few minutes. This makes it difficult to measure water flowing down the vertical surface accurately. Consequently, it was thought that an evaluation method omitting measurement and based only on presence or absence of water trickling down the vertical surface would not be appropriate.

Approach (2) studied next was a simple method whereby marks of target and guide were put or target objects and tape measures were affixed around the spot on the surface to be evaluated, in order to omit the need for measuring distance travelled by water flowing down the surface. Although this method is simple and can be finished in just a few minutes per measurement area, several problems became clear. One problem was that the point of origin of the trickling water was uncertain, as explained in 4.2. When the lower edge of the sprayed area was a circular arc, the threshold marks for the distance travelled by water flowing down the surface also had to be in concentric circles (not a straight line), etc. In addition, when blurring such as in Fig. 7 occurs, the target mark to measure the distance

Fig. 6 Judgement of presence or absence of the flowing-down

Fig. 7 Expansion of water spray area by blurring

travelled by water must be accurate, however, it was found that this was rather complicated to achieve.

Finally, step (3) was studied. It is based on the idea that the shape of the opening on the water spraying guide should be adjusted, and that a mark should be added simultaneously when water is being sprayed using the excess water from spraying. This approach is described in more detail in the next section.

4.4 Proposal of water spray method suitable WIST method-A

Figure 8 shows proposed new shape for the area to be sprayed and the resulting water patterns. The most distinctive feature of the new shape shown in Fig. 8 (a) is that it the sprayed area is divided into a circular area above and a sickle shaped area below. The crescent-shaped area below indicates the standard flow distance from the rugby ball-shaped area above; this distance is at least 20 mm. This format enables instant visual identification of cases where the trickle-down distance does not reach 20 mm (Fig. 8 (b)), and those which exceed 20 mm (Fig. 8 (c)). It should be noted that cases such as the one shown in Fig. 8 (c), where the water trickles beyond the crescent-shaped area were frequently observed. In cases where the water did not flow easily down the concrete the sprayed area gradually expanded (Fig. 8 (d)).

Findings obtained through method-A based on the shape of the sprayed area in Fig. 8 (a), can be summarized as follows:

- (1) Dividing the sprayed area into an upper and lower part makes it much easier to determine when the water has reached the threshold point flowing down the surface.
- (2) Even though the point of origin of water flowing

Fig. 8 Shape of water spray specialized in the WIST Method-A

down from the sprayed area is not always from the bottom of the shape when the lower edge of the sprayed area forms an arc, a curved lower edge makes it possible to more easily control any shift in position of the spray guide.

- (3) By making the upper edge of crescent-shaped area into a concave arc as well, the flow distance can be determined regardless of where water begins to flow down from the sprayed area above.

Considering the results obtained above, it was decided that a partitioned spray guide would be used for method-A evaluation as shown in Fig. 8 (a).

4.5 Proposal of simplified evaluation method to determine the quality of cover-concrete using frequency of sprayings required in WIST method-A as an indicator

In order to verify method A and the frequency of sprayings could be used as a non-destructive test method to evaluate the quality of near-surface layers in the actual structures, it was applied to a wall specimen of reinforced concrete (hereinafter referred to as the wall specimen). Table 1 and Fig. 9 show the wall specimen. Two wall specimens were made using different demolding conditions, and then set up outside under a roof to avoid direct rainfall. 8 positions on the north-side surface of the specimen sheltered from direct sunlight were measured (left side surface in Fig. 9). The measurement positions were located at

Fig. 9 Wall-formed specimens

Table 1 Outline of wall-formed test specimen

Feature of concrete	Ready-mixed concrete, Nominal strength: 24 MPa, Max. coarse aggregate dia.: 20 mm, Slump: 8 cm, Ordinary portland cement, W/C = 57 %
Dimension, shape	1200 × 1200 × 400 mm, Wall-formed
Demolding condition	One day (specimen W1), 7 days (specimen W2)
Curing condition	Atmospheric exposure at the outdoors
Material age at measurement	About 2 months
Ambient condition at measurement	Outdoor environment in winter (about 10 °C, about 30 %RH)

Fig. 10 Measurement result of wall-formed specimens (WIST Method-A)

Fig. 11 Measurement result of wall-formed specimens (Air permeability test)

around 600 mm from the bottom of the wall specimen. The age of the concrete at the time of measurement was about 2 months. In addition, prior to applying evaluation method-A, the air permeability of the near-surface layers was tested using a Torrent permeability tester [2] in 12 places other than those selected for evaluation.

Figures 10 and 11 show the results of the evaluation under method-A and the air permeability tests for the wall specimen. In the case of the W1 test specimen which was demolded one day after concrete casting, numerical values significantly increased in both the frequency of sprayings and air permeability coefficient, compared with the W2 test specimen which was demolded after seven days. Evaluation of concrete specimens made simultaneously using a different production method revealed that the relative difference

in the air permeability coefficient was easily detectable using method-A. This meant that method-A was indeed an effective means to determine the quality of cover-concrete, based on frequency of sprayings required for water to cover a certain distance falling down the surface of the wall. Air permeability data from the test shown in Fig. 11 showed that measured results from the test specimen and actual structures of about 1,000 mm tended to vary significantly, compared with measured data from small scale specimens. When making the small-sized specimen of 100 mm to 500 mm indoors, comparatively elaborate work is possible, and assuming that unevenness at the work of concrete placing and compaction is small, we consider that its influence has appeared. When evaluating the cover-concrete quality of an actual structure however, it is necessary to take measurements at four to eight locations each time, and to compare the data after checking the variability in measured values.

5. Technology development toward practical realization of WIST Method-A

In order to apply Method-A in practice in railways, it is necessary to adapt it so that it can be used in real-life situations. In concrete terms, this means going further than conducting simple experiments, and producing an actual kit that could be used in the field. A prototype kit for Method-A evaluations was produced accordingly. In the spraying tests, each test area was sprayed repeatedly every 60 seconds, and during the 60 sec intervals, measurements were carried out simultaneously in the different areas in order to increase efficiency. Therefore, the person carrying out the evaluation must be aware of the timing and measurement positions precisely. Initially an ordinary stopwatch was tried and proved to be inadequate. Then, we uniquely developed the application software (hereinafter referred to as app) with a dedicated timer function and announcement function. It is possible to use the application by installing in tablet terminal devices and smart-phones.

Figure 12 shows the prototype test kit for Method-A. The test kit contains a spray, spray guide, timer and accessories. The test kit for the Method-B, includes the same items, with an instrument for measuring the surface colors in addition. Since the spray and spray guide in the kit form the essential pieces required for controlling the 'spraying' for the evaluations, the kit was named 'spray kit' (Fig. 12 (b)). An off-the-shelf manual spray bottle and atomizer were selected to form the kit, however, in order to control the amount of water being sprayed during the WIST evaluation a specially designed conical cup was produced to fit

Fig. 12 Test kit for the WIST Method-A

to the spray head. Furthermore, during the evaluation, the spray nozzle must remain up against the spray guide to ensure the exact amount of water is projected and therefore the opening of the spray guide must match the cone nozzle. 3D printing which has become mainstream over recent years was used to produce the spray guide (Fig. 12(c)). The app which can be used on any type of tablet was then developed (Fig. 12(d)) which can be updated, to keep pace with improvements to the WIST evaluation method. Due to a number of issues regarding the version management and operational guarantees for the application, the app is currently only available for R&D purposes within RTRI. The application contains a timer function, a voice-guided instruction function to assist those carrying out the evaluation and a function for recording results. Thanks to these functions, we can improve correctness of work in WIST compared with WIST which utilizes a stop watch, and also speedy measurement becomes possible. The application enables the simultaneous progression of measurement at eight places in the Method-A, and at two places in the Method-B.

6. Conclusions

This paper proposes a simplified WIST Method-A for the evaluation of cover-concrete quality, which is based on the visual inspection of a small amount of water sprayed on the surface to be evaluated. Technological investigations were also carried out with a view to adapting the test

method for practical use. The following results were obtained:

- (1) A simple and effective method, called Method-A, was proposed based on visual observation of water trickling down a vertical surface, for the evaluation of cover-concrete quality.
- (2) Tests on a full scale specimen wall in outside conditions that simple evaluation of the near-surface layer quality of concrete is possible, by using frequency of sprayings in the WIST as an index.
- (3) A prototype test kit for the Method-A was produced using 3D printing technology, and a dedicated timer application was then developed.

In order to quantitatively clarify the relationship between the frequency sprayings in the Method-A and the different types of physical properties of concrete, further work will be continued on the basis of collected measurement data, and further experimental studies as well.

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