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Determination of Partial Depth Repair Size for Spalling of Jointed Concrete Pavements Using the Impact Echo Method

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Abstract: When spalling occurs at a concrete pavement joint, partial depth repair (PDR) is implemented by removing the damaged part of a slab and filling the space with repair materials. However, re-repair is frequently also required because additional distress develops at the boundary of the repaired area due to improper PDR size in addition to poor quality of materials and construction methods. For the sustainability of pavement structures, it is necessary to study the PDR size based on the mechanical theory. Therefore, in this study, the PDR size for spalling was suggested based on the results of laboratory and field tests conducted using the impact echo (IE) method. The dynamic modulus estimated in the laboratory using the IE and forced resonance methods were compared for concrete specimens subjected to repetitive freeze–thaw cycles. In addition, the correlations of the dynamic modulus estimated by the methods with the compressive strength and absorption coefficient were analyzed. As a result, the IE method, for which vibration could be estimated on the same side of the specimen where impaction was applied, was selected for use on the pavement surface. Furthermore, the short-time Fourier transform technique was used instead of the fast Fourier transform, which has been commonly used for nondestructive methods, to minimize the noise in the field and, consequently, to estimate the dynamic modulus more accurately. The dynamic modulus was estimated according to the distance from the spalling end using the IE method at the Korea Expressway Corporation test road to identify the damaged range in the slab based on the severity of spalling. The dynamic modulus, compressive strength, and absorption coefficient tests were conducted in the laboratory for specimens cored from the concrete slab where the field test was performed. Finally, the PDR size was suggested according to the severity of spalling based on the damaged range in the slab, as determined by the field test and laboratory test results.

Keywords: jointed concrete pavement; partial depth repair; spalling; impact echo; short-time fourier transform; sustainable pavement structure

1. Introduction

The spalling that occurs at the joint of a concrete pavement deteriorates and propagates with time and, as a result, lowers pavement performance and riding comfort of the road users. In most cases, engineers have implemented partial depth repair (PDR) to repair spalling distress [1]. PDR is a method of cutting and removing a concrete slab up to a certain distance from the end of the spalling distress and filling the space with repair materials. The PDR can also be used to repair other distress types such as durability cracking. However, this study focused on the repair of spalling distress.

Most criteria for PDR identically designate 75 mm from the end of spalling as the minimum repair length in both the parallel and perpendicular directions of the joint and 50 mm as the minimum repair depth, as shown in Table 1 [2–6]. However, the basis of the
PDR size has not been clearly provided for any criterion. The sounding test is occasionally performed by qualitatively evaluating the noise generated by hammering or dragging steel chains on the surface of a concrete pavement in case the criteria cannot be used because of uncertain pavement conditions [7]. Additional distress can propagate from the damaged and unrepaired end of spalling, as shown in Figure 1, due to the penetration of water and other substances when the PDR size, which is determined by the criteria with an unclear basis or a qualitative evaluation method, is smaller than the actual range of the damage. Therefore, the existing methods greatly impair the sustainability of pavement structures. To solve this, to make the pavement structure sustainable, PDR should be implemented up to the point where the damage does not exist.

Table 1. Criteria on PDR Size.

| Repair Size   | MnDOT * [4] | FHWA ** [2] | KEC *** [3] | MoLIT **** [5] | MoLIT **** [6] |
|---------------|-------------|-------------|-------------|----------------|----------------|
| Distance from End of Spalling (mm) | 75          | 75          | 75          | 75             | 75             |
| Min. Depth (mm) | 50          | 50          | 50          | 40–50          | 50             |

* Minnesota Department of Transportation; ** Federal Highway Administration; *** Korea Expressway Corporation; **** Korean Ministry of Land, Infrastructure and Transport.

Figure 1. Propagation of Spalling Caused by Improper PDR Size: (a) 2011, (b) 2013, (c) 2015, (d) 2016.
Both destructive and nondestructive tests can be used to identify the range of damage developed around spalling distress. The destructive test is a method in which the existence of damage is evaluated by conducting laboratory tests for specimens cored around the spalling. However, a relatively longer time is required for coring specimens, and the location of coring can cause additional distress due to the destruction of the pavement. The nondestructive test is a method for identifying the material properties of concrete slabs by performing tests on the pavement surface around the spalling. This method offers advantages over the destructive test because it requires a shorter time and does not destroy the pavement.

Impact echo (IE) and forced resonance (FR) methods have commonly been used as nondestructive tests to determine the range of damage that developed around spalling [8]. The methods use the same approach to convert the first-order resonant frequency, which is obtained by applying vibration to the dynamic modulus. However, the FR method cannot be used for extensive structures such as road pavements because the forced vibration generated on one side of the target object is measured on the opposite side. In contrast, the IE method can be used for road pavements because the vibration generated by the impact of a steel ball using a rebound hammer on one side of the target object is measured at the same location. The dynamic modulus is used as an index indicating the durability of concrete pavements in FHWA [9] and MoLIT [10]. Therefore, the dynamic modulus was judged to be appropriate for use as a damage indicator of concrete.

In this study, three test steps were performed to determine the PDR size for spalling distress developed in concrete pavements using the IE method. First, the applicability of the IE method was determined by conducting laboratory tests on concrete specimens, for which their durability was lowered by repetitive freeze–thaw cycles. In addition, the damage range in the slab was determined according to the spalling severity by performing field tests using the IE method. Finally, the damage range in the slab was verified, and the PDR size was suggested according to the severity of spalling by conducting laboratory tests for the specimens cored from the slabs where field tests were performed.

2. Laboratory Tests for Applicability of IE Method

Laboratory tests were conducted to identify whether the soundness of a concrete pavement slab could be evaluated in the field using the IE method. The dynamic modulus of concrete specimens subjected to repetitive freeze–thaw cycles was measured using the IE and FR methods. Furthermore, compressive strength and absorption tests were conducted to investigate their correlation with the dynamic modulus.

2.1. Test Method

The standard size of the specimens for the compressive strength and dynamic modulus tests was 100 mm in diameter and 200 mm in height according to ASTM C 39 [11] and ASTM C 1548 [12]. Moreover, specimens for absorption tests should have a sectional area of over 5000 mm² and a height of 25 mm according to ASTM C 1585 [13]. Therefore, 13 cylindrical concrete specimens with a diameter of 100 mm and height of 200 mm were fabricated according to ASTM C 192 [14] to satisfy the size criteria. The mixture proportions were designed as shown in Table 2, according to the standard for the quality of expressway construction materials [15]. After mixing the cement, fine aggregates, and coarse aggregates in a mixer for 30 s, water, an air-entraining agent, and a high-performance air-entraining water-reducing agent were added and mixed for an additional 1 min. The concrete mixture was placed in cylindrical molds in three layers, each of which was compacted using a tamping rod. The concrete specimens were covered with a plastic sheet and kept in a room with constant temperature and humidity of 20 °C and 65%, respectively, immediately after flattening their top surface.
Table 2. Mixture Proportions of Concrete Specimens [6].

| Max. Coarse Aggregate Size (mm) | Slump (mm) | Air Content (%) | Water Cement Ratio | Fine Aggregate Percentage | Unit Weight (kg/m³) | Admixture |
|--------------------------------|-----------|-----------------|-------------------|---------------------------|--------------------|-----------|
|                                 |           |                 | Water             | Cement                    |                    | Entraining Agent | Water Reducer |
| 25                              | Less than 40 | 5–7             | 40                | 40                        | 155                | 388       | 649       | 1052         | 0.14 (132 mL) | 2.71 (2557 mL) |

The specimens were demolded one day after the concrete placement. The specimens were cured in water at 20 °C for 13 days after demolding. After curing, the specimens were frozen and thawed repetitively for 300 cycles according to ASTM C 666 [16] in a freeze–thaw tester, with the temperature varying between −23 and 6 °C. The temperature of the specimens themselves varied between −18 and 4 °C during freeze–thaw cycles. Laboratory tests were conducted at 0, 100, 200, and 300 freeze–thaw cycles (14, 23, 33, and 43 days of concrete age). The dynamic modulus test using the IE and FR methods, absorption test, and compressive strength test were sequentially conducted for three specimens at each cycle (0, 100, 200, and 300 cycles). A thermometer installed at the center of the specimen measured the concrete temperature.

2.1.1. Dynamic Modulus Test Conducted Using IE Method

A voltage transducer was placed at the center of the top of each specimen after straightening three specimens in turn at each freeze–thaw testing cycle, as shown in Figure 2a. The location 30 mm from the voltage transducer on top of the specimens was impacted three times for each specimen using a Schmidt hammer. The vibration generated by the impact was obtained as time–voltage data using a voltage transducer, as shown in Figure 3a. The time–voltage data were transformed into time–acceleration data by utilizing Equation (1) and using an oscilloscope, as shown in Figure 3b [17].

\[
A = A_{max} - (A_{max} - A_{min}) \times \frac{V_{max} - V_{measured}}{V_{max} - V_{min}}
\]

where

- \( A \): acceleration (m/s²),
- \( A_{max} \): maximum acceleration (4900 m/s²),
- \( A_{min} \): minimum acceleration (−4900 m/s²),
- \( V_{max} \): maximum voltage (12 V),
- \( V_{min} \): minimum voltage (7 V), and
- \( V_{measured} \): measured voltage (V).

As shown in Figure 3c, the time–acceleration data were transformed into frequency–domain data, which were expressed by the relation between the frequency and amplitude using a fast Fourier transform (FFT) through an oscilloscope. The frequency at which the amplitude reached its first peak was determined as the first-order resonant frequency, as shown in Figure 3d.

FFT and short-time Fourier transform (STFT) are the representative techniques of the discrete Fourier transform, which rapidly transforms the time–acceleration data into frequency–domain data [18,19]. FFT is a technique that transforms the entire time–domain data into the entire frequency–domain data simultaneously by conducting a Fourier transform. In contrast, STFT transforms the entire time–domain data into the entire frequency–domain data by conducting Fourier transforms for the data in each time domain divided by the window function and then combining the transformed data in the entire frequency domain. When the Fourier transform is conducted at the same time for the entire time domain using FFT, the noise caused by factors such as the sound, vibration, and pavement structure affects the entire time domain; therefore, the accuracy of the analysis results may decrease [20–23]. In contrast, when the Fourier transform is conducted for each
divided time domain and the data are combined in the frequency domain using STFT, the size of the time domain affected by a certain noise is minimized. As a result, the accuracy of the analysis results may increase [24]. Furthermore, if there is an excessive amount of data composing the local signal in each divided time domain, many types of noise may also be included in the local signal. In contrast, if the amount of data composing the local signal is too small, important data may be excluded from the local signal. Therefore, through trial and error, it was determined that 128 data points would constitute the local signal in each divided time domain in this study.

Figure 2. Laboratory Tests for Concrete Specimens: (a) Dynamic Modulus Test Using IE, (b) Dynamic Modulus Test Using FR, (c) Compressive Strength Test, (d) Absorption Test.
Figure 3. Procedure for Detecting 1st Resonance Frequency: (a) Time-Voltage, (b) Time Acceleration, (c) Frequency Domain, (d) Detection of 1st Resonance Frequency.

The time–acceleration data obtained by impacting a specimen three times were transformed into the frequency domain using FFT and STFT techniques, respectively. The first peak of the amplitude in the frequency domain was determined to be the first-order resonant frequency, as shown in Figure 4. The first peaks of amplitude were found at three frequencies by the FFT technique, as shown in Figure 4a, whereas the first peaks were found at the same frequency, consistent with the STFT result, as shown in Figure 4b. Therefore, it was verified that the disadvantage of FFT can be complemented by conducting STFT using the Solver function of Microsoft Excel. As a result, a more accurate elastic wave velocity can be estimated using Equation (2) with the first-order resonant frequency obtained by the STFT technique [25]. The correction factor was determined according to the shape of the test object. In this study, the correction factor was 0.96, because the concrete slab is a plate shape.

\[
C_p = \frac{2f}{a \times T}
\]

where
- \(C_p\): velocity of P-wave (m/s),
- \(f\): first-order resonant frequency (Hz),
- \(a\): correction factor (0.96), and
- \(T\): thickness (height of the specimen in this study, m).
The elastic wave velocity estimated by the first-order resonant frequency is related to the elastic modulus, Poisson’s ratio, and density of the concrete. Therefore, the dynamic modulus of the concrete specimens was predicted using the elastic wave velocity, Poisson’s ratio, and density, as shown in Equation (3) [25].

$$E = \frac{C_p^2 \rho (1 + \nu)(1 - 2\nu)}{1 - \nu}$$  \hspace{1cm} (3)

where

- $E$: dynamic modulus (MPa),
- $\nu$: Poisson’s ratio,
- $\rho$: density (kg/m$^3$).

In general, the dynamic modulus predicted using Equation (3) does not coincide exactly with the actual dynamic modulus because common values are used for the Poisson’s ratio and density in most cases. Moreover, the dynamic modulus can be lowered according to the age of the concrete due to the degradation in durability. Therefore, the relative
dynamic modulus (RDM) calculated using Equation (4) was used instead of the dynamic modulus of the concrete specimens.

$$E_{RL} = \frac{E_n}{E_0} \times 100$$ (4)

where

- $E_{RL}$: RDM obtained by laboratory test (%),
- $E_n$: dynamic modulus at n freeze–thaw cycles (MPa), and
- $E_0$: dynamic modulus at 0 freeze–thaw cycles (MPa).

The RDM was defined as the ratio of the dynamic modulus obtained at each freeze–thaw testing cycle when the durability of the concrete specimens decreased to that obtained at zero freeze–thaw cycles when the concrete specimens had suitable conditions.

### 2.1.2. Dynamic Modulus Test Conducted Using FR Method

The dynamic modulus test was conducted for concrete specimens subjected to repetitive freeze–thaw cycles using the FR method according to ASTM C 1548 [12]. The forced vibration was generated by operating the oscillator on which a concrete specimen was placed, as shown in Figure 2b. The vibration transmitted through the specimen was obtained as the time–voltage data using a voltage transducer installed at the top of the specimen. The time–voltage data were transformed into time–acceleration data using an oscilloscope, as in the case of the IE method. The time–acceleration data were transformed into frequency–domain data by the FFT technique using an oscilloscope to detect the first-order resonant frequency. The dynamic modulus was predicted using Equation (5) and utilizing the first-order resonant frequency [12]. Consequently, the RDM was calculated using Equation (4).

$$E = 400 \times 10^{-5} \times \frac{L}{a} \times W \times f^2$$ (5)

where

- $L$: length of specimen (mm),
- $a$: area of top or bottom of specimen (m$^2$), and
- $W$: weight of specimen (kg).

### 2.1.3. Compressive Strength Test

The compressive strength test was conducted for the concrete specimens subjected to repetitive freeze–thaw cycles according to ASTM C 39 [11]. Compressive loading was applied to a concrete specimen by letting the loading plate down with 1.0 MPa/s velocity, as shown in Figure 2c. The compressive strength was calculated by dividing the maximum load, for which the testing machine indicated when the concrete specimen was destroyed, by the sectional area of the specimen.

### 2.1.4. Absorption Test

The absorption test was conducted for the concrete specimens subjected to repetitive freeze–thaw cycles according to ASTM C 1585 [13]. Constant moisture conditions were developed by drying the concrete specimens in a room with a constant temperature and humidity of 20 °C and 50%, respectively, for two weeks immediately after removing them from the freeze–thaw testing equipment. The mass of the concrete specimens was measured once a day during the drying period to check whether the change in the mass fell below 1.0 g during the period showing a constant moisture condition. The upper part of the specimens was soaked to a depth of 10 mm in water at 20 °C after coating the sides of the dried specimens with paraffin to repel water, as shown in Figure 2d. The increase in the mass of the concrete specimens was measured at 10 min, 30 min, 1 h, 6 h, and 24 h after soaking in a 1.0 g unit. The increased mass of the concrete specimens was defined
as the weight of the absorbed water, and the absorption coefficient was calculated using Equation (6) [13].

$$w_t = \frac{\Delta m_t}{\Delta \sqrt{t}} \tag{6}$$

where

- $w_t$: absorption coefficient at $t$ (kg/m$^2$/h$^{0.5}$),
- $m_t$: mass of absorbed water per sectional area of specimen at $t$ (kg/m$^2$), and
- $t$: elapsed time since specimen soaking (h).

2.2. Test Results

The RDM of the concrete specimens subjected to freeze–thaw was estimated using the IE and FR methods, and the test results are shown in Figure 5. The RDM estimated using the IE method decreased as the number of freeze–thaw cycles increased because the durability of the concrete specimens was degraded according to the freeze–thaw cycle. In particular, the RDM substantially decreased to below 40% when the number of freeze–thaw cycles reached 300. Similarly, the RDM estimated using the FR method gradually decreased to approximately 40% when the number of freeze–thaw cycles reached 300.

![Figure 5](image.png)

**Figure 5.** Material Properties of Concrete Specimens According to Number of Freeze–Thaw Repetitions: (a) RDM by IE, (b) RDM by FR, (c) Absorption Coefficient, (d) Compressive Strength.

The compressive strength measured at 100 freeze–thaw cycles was larger than that measured at 0 cycles. Thereafter, the compressive strength gradually decreased as the number of freeze–thaw cycles increased. The test results were attributed to the faster development of compressive strength rather than the reduction in durability by freeze–thaw at a very early age of the concrete specimens. The compressive strength began to decrease when the freeze–thaw effect became larger than that of strength development, which gradually slowed down.
The absorption coefficient increased with the amount of absorbed water, which was caused by the degraded durability of the concrete specimens due to an increase in the number of freeze–thaw cycles. The absorption coefficient of the concrete specimens approximately doubled when the number of freeze–thaw cycles reached 300.

Figure 6 shows the correlations among the RDM, compressive strength, and absorption coefficient measured through laboratory tests. The coefficient of determination for the correlation between the RDMs estimated by the IE and FR methods was high (0.9079), as shown in Figure 6a, because the methods had the same characteristics, except for the manner in which vibration was applied and noise was removed.

Figure 6. Correlations between Material Properties of Concrete Specimens: (a) RDM by IE and RDM by FR, (b) RDM by IE and Compressive Strength, (c) RDM by FR and Compressive Strength, (d) RDM by IE and Absorption Coefficient, (e) RDM by FR and Absorption Coefficient, (f) Compressive Strength and Absorption Coefficient.
The compressive strength was affected more by its rapid development than by the repetitive freeze–thaw cycle at a very early concrete specimen age, whereas the RDM gradually decreased from the very early age according to the number of freeze–thaw cycles. Because of the opposite trend at a very early age of the concrete specimens, the coefficient of determination between the RDM estimated by the IE method and the compressive strength was slightly low (0.568), as shown in Figure 6b. The coefficient of determination between the RDM estimated by the FR method and the compressive strength was 0.3576 lower, as shown in Figure 6c.

The coefficient of determination between the RDM estimated by the IE method and the absorption coefficient was relatively high at 0.7145, as shown in Figure 6d. In addition, the coefficient of determination between the RDM estimated by the FR method and the absorption coefficient was also high (0.8722), as shown in Figure 6e. The coefficient of determination between the compressive strength, which was significantly affected by its rapid development at a very early age of the concrete specimens, and the absorption coefficient was significantly lower (0.1707), as shown in Figure 6f.

As a result, the IE method was selected, for which the impaction was applied, and the resulting vibration was measured at the same location of the concrete specimen considering the test condition of the concrete pavement slab. This was done instead of the FR method, for which the forced vibration generated on the side of the concrete specimen could be measured on the opposite side. In addition, the STFT technique instead of the FFT technique was selected because the noise generated by the field conditions could be minimized, and as a result, a relatively more accurate dynamic modulus could be estimated.

### 3. Field Test for Determination of Damaged Range

The field test was performed on a 20-year-old test road of the Korea Expressway Corporation (KEC). The test-road, located 1 km far away from Yeoju junction in the central part of Korea, was a two-lane road with 7.7 km length consisting of both 25 concrete and 33 asphalt pavement sections where over 1900 gauges and sensors were instrumented [26]. The dynamic modulus of the concrete pavement slabs where spalling occurred was estimated and analyzed using the IE method to determine the damage range in the slab according to the spalling severity.

#### 3.1. Test Method

A field test was performed to determine the damage range in the concrete pavement slab according to spalling severity. The severity was categorized into high, medium, and low according to spalling width, as shown in Table 3 [2]. The spalling width was the farthest distance from the joint of the slab to the end of spalling in the direction perpendicular to the spalled joint, as shown in Table 3. A sound slab and three slabs for each spalling severity were selected on the KEC test road. For the slabs with spalling distress, the dynamic modulus was estimated nine times at the slab center and at seven locations from the end of spalling to 300 mm away with 50 mm spacing in the direction perpendicular to the spalled joint using the IE method, as shown in Figure 7a. The dynamic modulus of the sound slab was also estimated nine times at the slab center and at seven locations from the sound edge of the slab. Unlike in the laboratory test, the RDM was defined as the dynamic modulus according to the distance from the end of spalling to that of the slab center, considered to be the soundest location in the slab, as expressed by Equation (7).

\[ E_{RF} = \frac{E_d}{E_c} \times 100 \]  

where

- \( E_{RF} \): RDM obtained by field test (%),
- \( E_c \): dynamic modulus at slab center (MPa), and
- \( E_d \): dynamic modulus at \( d \) mm from the end of spalling or slab edge (MPa).
Table 3. Definition and Figure of Spalling Severity.

| Severity | Definition [2] | Figure |
|----------|----------------|--------|
| Low      | <75 mm width   | ![Low Spalling](image) |
| Medium   | 75 to 150 mm width | ![Medium Spalling](image) |
| High     | >150 mm width  | ![High Spalling](image) |

3.2. Test Results

As shown in Figure 8, the RDMs of the spalled slabs and sound slab were estimated according to the distance from the end of spalling and the edge of the slab, respectively. The bars and lines in Figure 8 represent the average and deviation of the RDMs, respectively. The average was 2.3%, and the minimum and maximum deviations were 1.1% and 3.2%, respectively. Therefore, it was judged that the data were reliable because the deviations between the estimated RDMs were low.
3.2. Test Results

As shown in Figure 8, the RDMs of the spalled slabs and sound slab were estimated according to the distance from the end of spalling and the edge of the slab, respectively. The bars and lines in Figure 8 represent the average and deviation of the RDMs, respectively. The average was 2.3%, and the minimum and maximum deviations were 1.1% and 3.2%, respectively. Therefore, it was judged that the data were reliable because the deviations between the estimated RDMs were low.

Figure 8a shows the test results for high spalling severity. The RDM estimated at the end of spalling, 0 mm, was significantly low (less than 40%). The RDM was less than 80% up to 100 mm from the end of spalling and exceeded 80% from 150 mm. Figure 8b shows the test results for medium spalling severity. The RDM was low at approximately 50% at the end of spalling and less than 80% at 50 mm from the end of spalling. The RDM exceeded 80% at 100 mm. Figure 8c shows the test results for low spalling severity. The RDM at the
end of spalling was relatively high (>80%), whereas that at >90% was maintained at all measurement locations from 50 mm. The damage caused by joint cutting could explain the lower RDM at the end of spalling than at other locations, even for the low severity of spalling. Figure 8d shows the test results for the sound slab. The RDM estimated at the slab edge was relatively high (>80%) and higher than that estimated at the end of the spalling of low severity. RDMs higher than 90% were maintained at all locations over a distance of 50 mm from the slab edge.

![Figure 8a](image1.png)

![Figure 8b](image2.png)

Figure 8. Cont.
Figure 8. Field Test Results Obtained by IE Method: (a) High Severity, (b) Medium Severity, (c) Low Severity, (d) Sound Slab.

The criteria for the RDM of concrete pavements were investigated, as shown in Table 4, to determine the boundary between the damaged and undamaged parts of the slab [9,10]. Most criteria indicated that the concrete slab was damaged when the RDM dropped below 80%. Therefore, 80% RDM was defined as the boundary between the damaged and undamaged parts of the concrete slab caused by spalling.
Table 4. Criteria on Soundness of Concrete Pavement Using Relative Dynamic Modulus.

| Agency       | FHWA [9]                        | MoLIT [10]                     |
|--------------|---------------------------------|--------------------------------|
| Regulation   | Relative dynamic modulus (RDM) using resonance frequency method | RDM when crushed fine aggregate is included in concrete pavement | RDM when chemical admixture is included in concrete pavement |
| Criteria     | 60% or 80%                      | 80%                            | 80% |

In the case of high spalling severity, the boundary between the damaged and undamaged parts of the slab was considered to be located between 100 and 150 mm from the end of spalling, based on the 80% criterion determined in this study. In addition, for medium spalling severity, the boundary was located between 50 and 100 mm from the end of spalling. Therefore, the damaged range in the slab was conservatively determined to be 150 and 100 mm from the end of spalling for the high and medium severities, respectively. The existing criteria for the PDR distance from end of spalling is 75 mm, as shown in Table 1 [2–6]. However, this criterion was determined empirically from the sound produced by hammering or dragging a steel chain onto the slab [2,27,28]. Compared with this, as a result of quantitatively estimating the properties of the concrete slab, in the case of medium and high spalling severity, the slab was damaged in a much longer distance from end of spalling.

In the case of low spalling severity, the distribution of RDMs was similar to that of the sound slab, and the RDM at the end of spalling was higher than 80%, even though it was slightly lower than that at the edge of the sound slab. Therefore, the concrete slab around the spalling of low severity was deemed undamaged.

4. Laboratory Tests for Suggestion of PDR Size

The dynamic modulus of the specimens cored from the concrete slabs where the field test was performed was estimated in the laboratory using the IE and FR methods. In addition, compressive strength and absorption tests were conducted on the core specimens. The PDR size was determined according to the severity of spalling based on the damaged range in the slab determined in the field test and the results of the laboratory test conducted for the core specimens.

4.1. Test Method

The specimens were cored from three slabs with a high severity of spalling and three slabs with medium spalling severity, as shown in Figure 7b. Eighteen core specimens over 200 mm in length were obtained from the six slabs at three locations in each slab: inside and outside the damaged range in the slab and slab center. In the field test, the damaged range in the slab was determined to be 150 and 100 mm from the end of spalling for high and medium severities, respectively. However, in the case of medium severity, core specimens with a 100 mm diameter could not be obtained within the 100 mm range of damage because clearance was required for the coring works. Therefore, the specimens were cored under the assumption that the boundary between the damaged and undamaged parts of the slab was 150 mm from the end of spalling for both high and medium severities.

Laboratory tests were conducted on the core specimens, as listed in Table 5. First, the core specimens were dried in a room at a constant temperature and humidity of 20 °C and 50%, respectively, for two weeks. Thereafter, the absorption test was conducted after coating the sides of the specimens with paraffin to repel water. The core specimens used in the absorption test had the same roughness of the top surface and lengths of over 200 mm when cored from the concrete slabs.

The top of the core specimens was ground, and the bottom below 200 mm was cut and removed after completion of the absorption test. Concrete slabs on site can have various moisture conditions. The dry core specimens and saturated core specimens were prepared to confirm that the dynamic modulus using the IE and FR methods did not change.
depending on the moisture condition. Specimens with a length of 200 mm were dried in a room at a constant temperature and humidity of 20 °C and 50%, respectively, and saturated in water at 20 °C for two weeks, immediately prior to the test.

Table 5. Laboratory Test Methods for Core Specimens.

| Length of Specimen       | Moistness of Specimen | Test Method                        |
|--------------------------|-----------------------|------------------------------------|
| Full Length (Initial length over 200 mm) | Dried                 | Absorption                         |
| 200 mm (Grind top and eliminate below 200 mm) | Dried and Saturated | Dynamic Modulus by Impact Echo (IE) Dynamic Modulus by Forced Resonance (FR) |
| 100 mm (Divide into two pieces) | Dried and Saturated | Dynamic Modulus by IE Dynamic Modulus by FR Compressive Strength |

Core specimens with a length of 200 mm were cut into upper and lower parts with a length of 100 mm each. The dynamic modulus test was conducted for the dried and saturated upper and lower parts of the specimens using the IE and FR methods. In addition, a compressive strength test was conducted on the dried upper and lower parts of the specimens.

4.2. Test Results

The absorption coefficient of the specimens, which maintained the same roughness of the top surface and lengths over 200 mm from the concrete slabs, were measured as shown in Figure 9. The dynamic modulus of the dried and saturated specimens, which were ground and cut into 200 mm lengths, was also estimated using the IE and FR methods, as shown in the same figure.

Figure 9. Laboratory Test Results for Core Specimens: (a) High Severity, (b) Medium Severity.
Figure 9a shows the test results for the specimens cored from the slab with high-severity spalling. The absorption coefficient of the specimens cored at the damaged part of the slab, 75 mm from the end of spalling, was approximately 1.7 times higher than that at the slab center. However, the absorption coefficient of the specimens cored at the undamaged part of the slab, 225 mm from the end of spalling, was similar to that observed at the slab center. The RDM of the dried and saturated specimens cored at the damaged part of the slab, 75 mm from the end of spalling, was between 60% and 80% in all cases, which was lower than the criterion for soundness, as estimated using the IE and FR methods. However, the RDM of the specimens cored at the undamaged part of the slab, 225 mm from the end of spalling, was relatively high (over 80%), satisfying the criterion regardless of the test method.

Figure 9b shows the test results for the specimens cored from the slab where spalling with medium severity occurred. The absorption coefficient of the specimens cored at the damaged part of the slab, 75 mm from the end of spalling, was 1.2 times higher than that at the slab center. However, similar to the high severity, the absorption coefficient of the specimens cored at the undamaged part of the slab, 225 mm from the end of spalling, was similar to that observed at the slab center. The RDM of the dried and saturated specimens cored at the damaged part of the slab, 75 mm from the end of spalling, was lower than the 80% criterion for soundness in all cases, as estimated using the IE and FR methods. However, similar to the high-severity case, the RDM of specimens cored at the undamaged part of the slab, 225 mm from the end of spalling, was relatively high (over 80%), satisfying the criterion.

The test method and moisture condition of the core specimen did not significantly affect the test results as compared to Figure 9a,b. In both the IE and FR methods, the RDM of the dried and saturated core specimens was similar for both the IE and FR methods. However, the severity of spalling affects the test results. The RDM of the core specimens with high severity was lower than that with medium severity, regardless of the test method and moisture condition of the specimen. Therefore, it was confirmed that the moisture condition did not affect the test results.

Core specimens with a length of 200 mm were cut into upper and lower parts of 100 mm each. The RDM of the dried and saturated upper and lower parts was estimated using the IE and FR methods, whereas the compressive strength was measured for the dried upper and lower parts, as shown in Figure 10.

![Graph](image-url)
Figure 10. Laboratory Test Results for Upper and Lower Parts of Core Specimens: (a) Upper Part, High Severity, (b) Upper Part, Medium Severity, (c) Lower Part, High Severity, (d) Lower Part, Medium Severity.
Figure 10a shows the test results for the upper part of the specimens cored from the slab where spalling with high severity occurred. The RDM of both the dried and saturated upper parts of the specimens cored at the damaged part of the slab estimated by both the IE and FR methods was lower than the criterion for soundness, which was approximately 60%. In addition, their compressive strength was also low, approximately 75% of that of the upper part of the specimens cored at the slab center. In contrast, the RDM of the upper part of the specimens cored at the undamaged part of the slab was over 80%, satisfying the criterion. Furthermore, their compressive strength was also high, approximately 90% of that of the upper part of the specimens cored at the slab center.

Figure 10b shows the test results for the upper part of the specimens cored from the slab where spalling with medium severity occurred. The RDM of both the dried and saturated upper parts of the specimens cored at the damaged part of the slab estimated by both the IE and FR methods was lower than the criterion, with values below 80%. In contrast, the RDM of the upper part of the specimens cored at the undamaged part of the slab was over 80%, satisfying the criterion. The compressive strength of the specimens cored at the damaged part of the slab was slightly lower than that of the slab center, whereas that of the undamaged part of the slab was similar to that of the slab center.

Figure 10c,d show the test results for the lower part of the specimens cored from the slab where spalling with high and medium severities occurred, respectively. The RDM of both the dried and saturated lower parts of the specimens cored at both the damaged and undamaged parts of the slab, estimated by both the IE and FR methods, were over 80%, satisfying the criterion. The compressive strength of the specimens cored at the damaged part of the slab was similar to that of the undamaged part of the slab. In addition, the compressive strength at both the damaged and undamaged parts of the slab was relatively high (over 90% of that of the slab center).

Comparing Figure 10a–d, the test method and moisture condition of the core specimen did not significantly affect the test results. For the upper part of the core specimens, the RDM for high severity was higher than that for medium severity, regardless of the test method and moisture condition of the core specimen. In contrast, the RDM of the lower part of the core specimens was similar in all cases regardless of the severity of spalling, test method, and moisture condition of the specimen. Therefore, it was confirmed that the moisture condition did not affect the test results.

As a result of laboratory tests conducted on the core specimens, the range of the damaged part of the slab according to the severity of spalling determined by field tests performed on the KEC test road was verified to be appropriate. Therefore, the PDR size based on the severity of spalling was suggested based on the damaged range in the slab, as shown in Figure 11. In the cases of high severity, a PDR of up to 150 mm from the end of spalling in both the parallel and perpendicular directions was suggested. In the case of medium spalling severity, a PDR up to 100 mm from the end of spalling in both the parallel and perpendicular directions was suggested. While the suggested PDR size can be increased at the engineer’s discretion, using the suggested PDR size as the minimum size is recommended. The suggested PDR size was much larger than the existing criteria [2–6]. It was judged that additional distress propagation was frequent because the existing criteria underestimated the size of damage near the spalling.

The soundness of the concrete slab directly below spalling could not be investigated in this study. The existing minimum depth criteria for PDR is 50 mm as shown in Table 1 [2–6]. However, due to the limitations of the test method, the soundness at a depth of 50 mm could not be investigated. Instead of, it was found that the slab below a depth of 100 mm was undamaged even within the damaged range in the slab with a high severity of spalling. Therefore, the minimum depth of the PDR was conservatively suggested to be 100 mm for both high and medium spalling severity. In addition, it was suggested that the depth of the PDR can be determined by engineers considering factors such as the depth of spalling, slab thickness, depth of dowel bars, and tie bars.
was determined according to the severity of spalling by field tests using the IE method, 
(4) Additional laboratory tests were conducted on the upper and lower parts of the core 
(3) A laboratory test was conducted on specimens cored from the concrete pavement 
(2) An RDM of 80% was determined as the criterion for dividing the damaged and 
(1) The IE method, which allows vibrations of impaction to be estimated at the same 
The soundness of the concrete slab directly below spalling could not be investigated in 
Comparing Fig 10c, 10d show the test results for the lower part of the specimens cored from the 
The compressive strength of the lower part of the specimens cored 

Figure 11. Determined PDR Size by Severity of Spalling.

5. Conclusions

In this study, in order to make the pavement structure sustainable by minimizing 
the distress propagating from the boundary of the PDR, the damaged range in the slab 
was determined according to the severity of spalling by field tests using the IE method, 
the applicability of which was verified by laboratory tests. In addition, the PDR size was 
determined by conducting laboratory tests on the specimens cored from the slabs where 
the field test was performed. The main conclusions are as follows:

1) The IE method, which allows vibrations of impaction to be estimated at the same 
   specimen location, was used in this study given the test condition of the concrete 
pavement, rather than the FR method, which requires the forced vibrations to be 
estimated on the opposite side. In addition, the noise that occurs under field conditions 
can be minimized, and as a result, a relatively more accurate dynamic modulus was 
estimated using the STFT technique instead of the FFT technique.

2) An RDM of 80% was determined as the criterion for dividing the damaged and 
   undamaged parts of the slab based on the existing criteria. Measuring the RDM of 
   the concrete pavement where spalling occurred using the IE method indicated that 
   the locations between 100 and 150 mm from the end of spalling were the boundary 
   between the damaged and undamaged parts of the slab in the case of high severity. 
   Similarly, the locations between 50 and 100 mm from the end of spalling were the 
   boundary between the damaged and undamaged parts of the slab in the case of medium severity. 
   In the case of low severity, it was judged that the entire slab, including the end of spalling, was not damaged when compared to the sound slab, 
   thus a boundary was not required.

3) A laboratory test was conducted on specimens cored from the concrete pavement 
   where spalling with high and medium severity occurred. Consequently, in both cases 
of high and medium severities, the RDM of the specimens cored from the damaged 
part of the slab, 75 mm from the end of spalling, did not satisfy the 80% criterion for 
soundness, whereas that from the undamaged part of the slab, 225 mm from the end 
of spalling, satisfied the criterion.

4) Additional laboratory tests were conducted on the upper and lower parts of the core 
specimens. The RDM of the upper part of the specimens cored from the damaged 
part of the slab satisfied the criterion for soundness, whereas that of the damaged part 
of the slab did not satisfy the criterion regardless of the spalling severity. On the other 
hand, the RDM of the lower part of the specimens satisfied the criterion regardless of 
the location of the coring and severity of spalling.

5) According to the field and laboratory test results, a PDR of up to 150 mm from the 
end of spalling in both the parallel and perpendicular directions was suggested for
high severity. In the case of medium severity, a PDR up to 100 mm from the end of spalling in both the parallel and perpendicular directions was suggested. The minimum depth of the PDR was conservatively suggested to be 100 mm for both high and medium spalling severity. In addition, it was suggested that the depth of the PDR can be determined by engineers, considering factors such as the depth of spalling, slab thickness, depth of dowel bars, and tie bars.

(6) The soundness of the concrete slab directly below spalling could not be investigated in this study. In addition, the soundness at a 50 mm depth of the slab, which is the minimum PDR depth designated in most criteria, could not be investigated. Therefore, a more accurate and reasonable depth of the PDR needs to be suggested by performing additional studies.

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