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# POINT LOAD TEST APPLICATION FOR ESTIMATING COMPRESSIVE STRENGTH OF CONCRETE STRUCTURES FROM SMALL CORE

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**ABSTRACT**

To estimate a compressive strength from existing concrete structures by core drilling are usually gathered with a diameter specimen of 100mm or three times of maximum coarse aggregate size and examined by uniaxial compressive strength (UCS) test as stated in JIS A1170. To get an alternative solution with smaller specimen, point load test (PLT) has been selected which is a simple test and widely accepted in rock materials research, but relatively new in concrete. The reliability of PLT is examined by extracting a lot of core drilled specimen from ready mixed concrete blocks with maximum coarse aggregate size, $G_{max}$ of 20mm in representative of architectural structures and 40mm in representative of civil structures on the range of concrete grade from 16 to 50. The reference of strength is resulted from concrete core diameter of 100 and 125mm with *h*/*d* ratio of 2.0, and examined by UCS test with compressive strength of concrete core of $f'_{cc}$ in results. The core specimen diameters are 35 and 50mm with *h*/*d* ratio of 1.5 and 2.0, and examined by PLT with point load index of $I_S$ in results. The estimation of compressive strength is conducted by making a linear approximation for $I_S$ to $f'_{cc}$ for each group of $G_{max}$ and *h*/*d*. This study also evaluates the reliability of test results for each core specimen and proposes a new geometric correction factor.

**Keywords**: concrete structures, compressive strength, small core specimen, point load index, strength.

## INTRODUCTION

Coring is usually the method ultimately chosen to determine in-situ compressive strength of concrete. In concrete structures with a lot of reinforcement bars, it may be impossible to obtain a core specimen from which compressive strength may be taken since reinforcing steel may be so prevalent in the concrete. The size of the core taken in diameter should be minimum three times of maximum size aggregate than used in the structure. In structures using larger aggregate, it may be practical to take cores larger in diameter, but costs increase rapidly and the large core usually cannot be taken deeper. Coring may prove expensive and the holes have to be backfilled, but the resulting data are usually accepted as the best evidence of the condition of the concrete in place.

It is established in JIS A1107 (1993) that a core drilled specimen diameter of 100mm or three times of maximum coarse aggregate size from a concrete structure member should be taken for performing strength evaluation. Small cores are often used as substitutes for large cores to test concrete strength. They have the advantages of being easily drilled and cut, minimum damage to structures, and a lower capacity machine is needed (Ruijie, 1996).

The PLT is intended as an index test for the strength classification of rock materials, but it may also be widely used to predict other material strength parameters with which is correlated. It is an attractive alternative method, because it can provide similar data at a lower cost its ease of testing, simplicity of sample preparation, and possible field application. Many research works had been conducted to acknowledge with regard to PLT and has resulted in widely used point load index and other parameters. However, more experimental works helps to substantiate the existing correlation. In order to estimate UCS indirectly, index-to-strength conversion factors are constructed (ISRM, 1985).

Richardson (1989) conducted a point load tests of cast specimens with various diameters as 50.8, 76.2 and 101.6mm. The advantages of using the point load test relate to a smaller cost per unit test when compared to compressive strength testing of concrete cores and to the speed with which the test can be performed. Testing large numbers of replicate specimens is feasible because of the test's speed and simplicity. The results showed a good relationship between the point load index of cast cylindrical specimens, $I_S$ and compressive strength of standard cylinders, $f'_{cs}$.

Zacoeb *et al*. (2007) showed a strong correlation between point load index of core drilled specimen ($I_S$) and compressive strength of concrete core ($f'_{cc}$) from small diameter of 35 and 50mm with maximum coarse aggregate size, $G_{max}$ of 20mm. It shows a linear approximation to estimate the compressive strength in the range of concrete grade from 16 to 50MPa.

Compressive strength is considered as one of the key properties in characterization of concretes in engineering practice. As the standard laboratory test to determine it require standard specimens, so indirect test are often used to predict the strength. The maximum aggregate size is played as considerable role for affecting the properties of concrete (Ibragimov, 1989).

### Theoretical considerations

The PLT method is based upon breaking off a cylindrical specimen. Broch, *et al.* (1972) started with a simple formula taking an idealized failure plane of diametric core sample as shown in Figure-1 into account as conceptual model for derivation on point load index Equation as:

$$I_S = \frac{P}{d^2} \tag{1}$$

Where:

$I_S$ : point load index (MPa)
$P$ : load (N)
$d$ : diameter of specimen (mm)

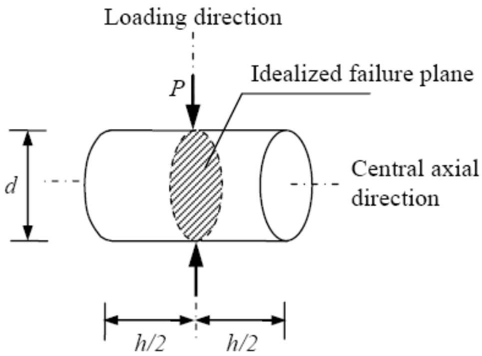


**Figure-1**. Cylindrical specimen diametric of PLT.

An argument can be made by taking the circular area of the core into account, so that Equation (1) should be written as:

$$I_S = \frac{4P}{\pi d^2} \tag{2}$$

Users of this test soon noticed, that the results of a diametric test were about 30% higher than those for an axial test using the same specimen dimensions. It seems a suggested acknowledge this difference by applying a size correction and introducing the equivalent core diameter (Broch *et al*, 1972; ISRM, 1985).

$$I_S = \frac{P}{D_e^2} = \frac{4P}{\pi d^2} \tag{3}$$

Where:

$I_S$ : point load index (MPa)
$P$ : load (N)
$D_e$ : equivalent core diameter (mm)
$d$ : diameter of specimen (mm)

Broch *et al*. (1972) considered a variations of $I_S$ with specimen size and shape lead to introduce a reference index $I_{S\,(50)}$ which corresponds to the $I_S$ of a diametrically loaded rock core of 50mm diameter. Accordingly, initial $I_S$ values are reduced to $I_{S(50)}$ by size correction factors that determined from empirical curves as a function of $d$. It is indicated that the considerably larger shape effect should be avoided by testing specimens with specified geometries. ISRM (1985) proposed a new correction function which accounts for both size and shape effects by utilizing the concept of equivalent core diameter ($D_e$). This function, known as geometric correction factor $F$ is given by:

$$I_{S(50)} = FI_S \tag{4}$$

Where:

$F$ : the geometric correction factor

$$= \left(\frac{D_e}{50}\right)^{0.45} \tag{5}$$

The size correction must be applied to obtain a unique point load index for the specimen as point load index of $I_S$ varies with core specimen diameter of $D_e$. The size-corrected point load index of $I_{S\,(50)}$ for each specimen is defined as the value of $I_S$ that would have been measured on a standard specimen diameter of $D_e$ = 50mm. In the case of testing specimen diameter of $D_e$ other than 50mm, size correction must be calculated by using of Equation (5).

## EXPERIMENTAL OUTLINE

### Concrete block specimen

Commonly in Japan, for architectural structures such as building construction is using the maximum coarse aggregate size, $G_{max}$ of 20mm. While for civil structures such as pier, abutment, bridge deck and check dam is using the maximum coarse aggregate size, $G_{max}$ of 40mm. The concrete block specimens were sized of 300mm x 300mm x 600mm made from ready-mixed concrete with typical slump range value from 8 to 12cm for most application as workability control and divided into two groups as shown in Table-1. For curing, all concrete block specimens were covered with plastic sheets and the humidity was set for about a week.

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**Table-1.** Group of concrete block specimens.

| Group | $G_{max}$ (mm) | Grade | Cement type | Concrete type |
|---|---|---|---|---|
| I | 20 | 16 | OPC (Ordinary Portland Cement) | Normal |
| | | 21 | | |
| | | 24 | | |
| | | 36 | | |
| | | 50 | | |
| II | 40 | 16 | PBSC (Portland Blast-Furnace Slag Cement) | |
| | | 21 | | |
| | | 24 | | |
| | | 30 | | |

**Core specimen**

Four types of core specimen diameter of 125, 100, 50 and 35mm were extracted from the above mentioned concrete block with the electric core pulling out machine. The wet type that used by flowing some water during the core drilled process is applied, and the extraction speed was assumed to be about 4cm/min. The direction of extraction is considered as the direction of concrete placing as vertical direction in assumption of practical work in construction. The situation of core specimen extraction is shown in Figure-2.


**Figure-2**. Extraction of core specimen.

Ishibashi *et al*. (2008) investigated the influence of *h*/*d* ratio of 0.5, 1.0, 1.5 and 2.0 on specific concrete grade and $G_{max}$, based on statistic analysis of test results, the core specimen with *h*/*d* ratio less than 1.0 is not suitable to be examined by PLT for the reason that specimens had different frequency distribution and failure in imperfect mode as it should be as shown in Figure-3.

a. Perfect mode b. Imperfect mode

**Figure-3**. Failure mode of PLT specimen.

The finite element analysis software "ANSYS" had been used for analyzing internal stress of core specimen that arising during the PLT. Poisson's ratio, $v$ of 0.18 and elastic modulus of concrete, $E_c$ of 24MPa are assumed as parameters for analysis. The analysis is conducted for two types of height-to-diameter ratio, *h/d* of 1.5 and 2.0. The results are shown in Figure-4. These figures shown that reduction in height-to-diameter ratio of *h/d* had contributed to tensile stress progress in central axis direction and prefer to produce a failure of PLT specimen in imperfect mode (splitting) than perfect mode (breaking).

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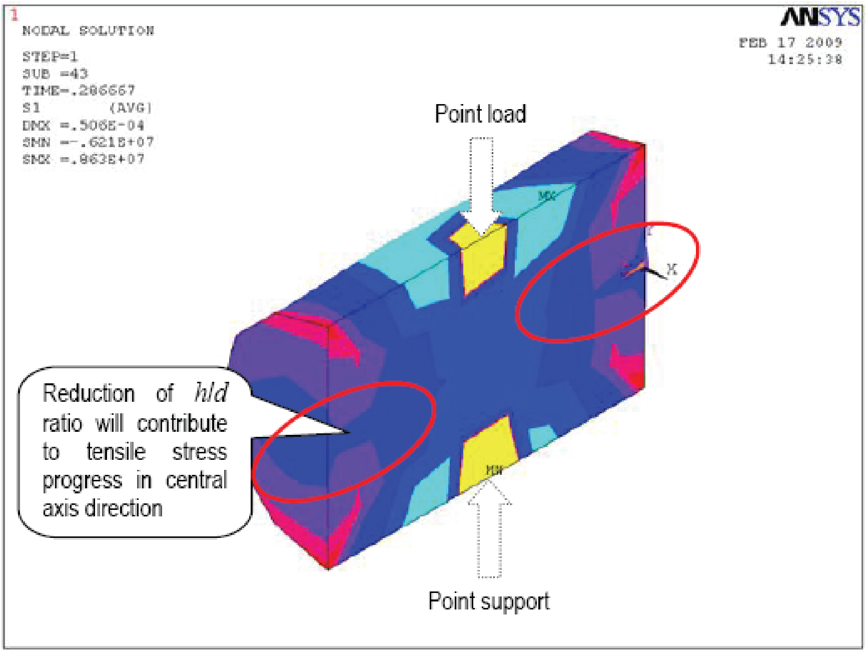
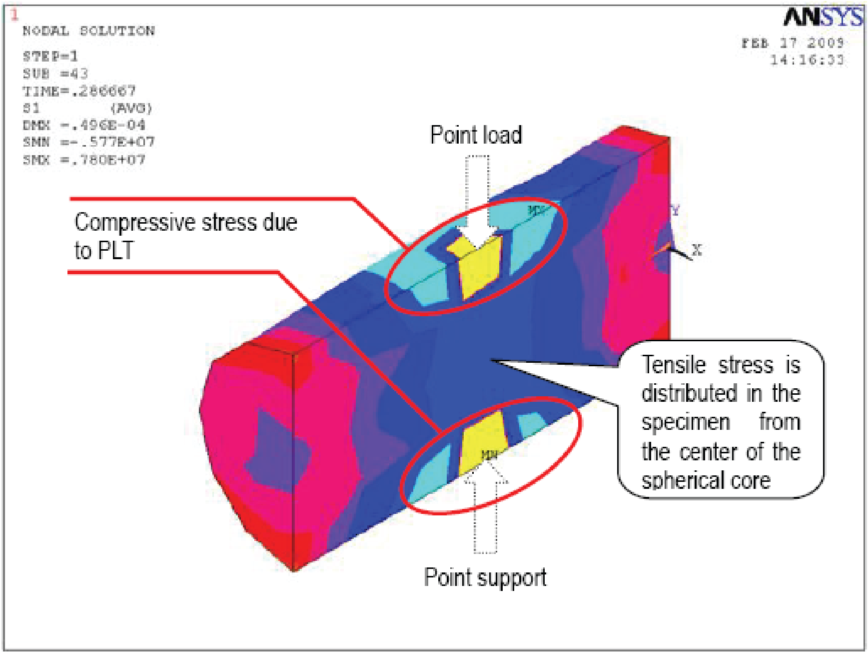



a. *h*/*d* of 1.5




b. *h*/*d* of 2.0

**Figure-4**. Distribution of stress on core specimen by PLT.

**Table-2**. Total number of concrete core specimens.

| Group I | | | | | Group II | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Grade** | ***d*** (mm) | ***d/G_max*** | ***h/d*** | **Total** | **Grade** | ***d*** (mm) | ***d/G_max*** | ***h/d*** | **Total** |
| 16 | 35 | 1.750 | 1.5 | 135 | 16 | 35 | 0.875 | 1.5 | 126 |
| | | | 2.0 | 135 | | | | 2.0 | 126 |
| | 50 | 2.500 | 1.5 | 105 | | 50 | 1.250 | 1.5 | 85 |
| | | | 2.0 | 99 | | | | 2.0 | 87 |
| 21 | 35 | 1.750 | 1.5 | 90 | 21 | 35 | 0.875 | 1.5 | 154 |
| | | | 2.0 | 90 | | | | 2.0 | 138 |
| | 50 | 2.500 | 1.5 | 60 | | 50 | 1.250 | 1.5 | 82 |
| | | | 2.0 | 60 | | | | 2.0 | 79 |
| 24 | 35 | 1.750 | 1.5 | 66 | 24 | 35 | 0.875 | 1.5 | 113 |
| | | | 2.0 | 66 | | | | 2.0 | 113 |
| | 50 | 2.500 | 1.5 | 59 | | 50 | 1.250 | 1.5 | 87 |
| | | | 2.0 | 58 | | | | 2.0 | 86 |
| 36 | 35 | 1.750 | 1.5 | 123 | 30 | 35 | 0.875 | 1.5 | 157 |
| | | | 2.0 | 126 | | | | 2.0 | 172 |
| | 50 | 2.500 | 1.5 | 111 | | 50 | 1.250 | 1.5 | 113 |
| | | | 2.0 | 108 | | | | 2.0 | 108 |
| 50 | 35 | 1.750 | 1.5 | 67 | | | | | |
| | | | 2.0 | 66 | | | | | |
| | 50 | 2.500 | 1.5 | 73 | | | | | |
| | | | 2.0 | 72 | | | | | |

**Testing method**

In the PLT, a piece of specimen is taken and loaded between two hardened steel cones. The system consists of a small hydraulic pump, a hydraulic jack, a pressure gauge and interchangeable testing frame of very high transverse stiffness. Spherically truncated, conical platens of the standard geometry shown in Figure-5 are to be used with the cylinder area of 14.52cm$^2$. The platens should be of hard material such as tungsten carbide or hardened steel so that they remain undamaged during testing (ISRM, 1985).

In this study, the core specimen is gradually loaded by activating the hand pump until failure and determined this load as $P$. The point load index of $I_S$ was calculated by using Equation (3) and for core specimen diameter of 35mm was corrected to the standard core diameter as point load index of $I_{S(50)}$ for core specimen diameter of 50mm by using Equation (4). The examination is conducted by using PLT machine with oil pressure cylinder type and maximum load capacity of 98kN. The setting up of PLT is shown in Figure-6.

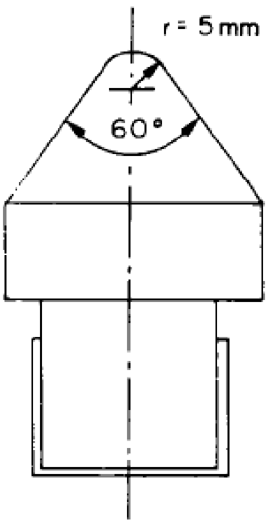



**Figure-5**. Point load cone platen.

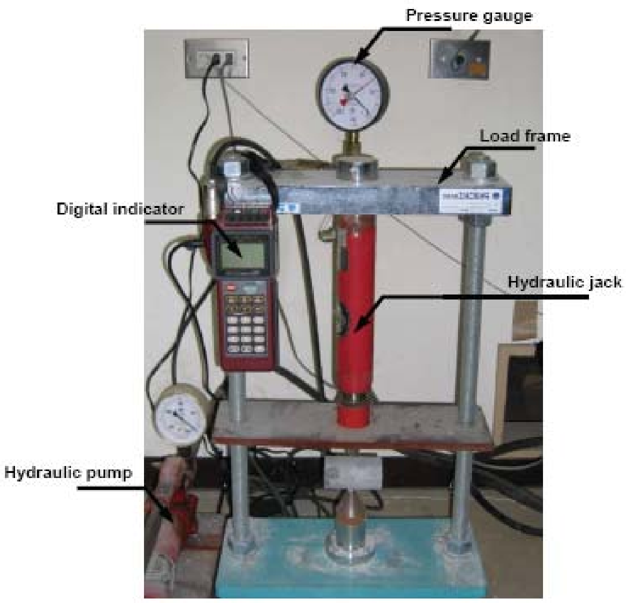



**Figure-6**. Setting up of PLT.

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## RESULTS AND DISCUSSIONS

### Compressive strength of concrete core

Based on JIS A1107 (1993), from a concrete block specimen is extracted a core specimen with diameter of 100 mm as minimum requirement and 125mm as three times of maximum coarse aggregate size, cut both ends of the core with a concrete cutting machine, end face polished, processed it to become specific *h*/*d* of 2.0 and examined by UCS test. The mean value of compressive strength of concrete core, $f'_{cc}$ is shown in Table-3, and assumed these values as reference on this study.

**Table-3**. Compressive strength of concrete core.

| Group I | | | Group II | | |
|---|---|---|---|---|---|
| **Grade** | **Age** (Days) | **$f'_{cc}$** (MPa) | **Grade** | **Age** (Days) | **$f'_{cc}$** (MPa) |
| 16 | 161 | 15.6 | 16 | 188 | 21.6 |
| 21 | 337 | 35.4 | 21 | 173 | 22.4 |
| 24 | 73 | 31.5 | 24 | 532 | 34.4 |
| 36 | 177 | 42.9 | 30 | 118 | 32.2 |
| 50 | 78 | 51.5 | | | |

### Point load index

The mean values of PLT were computed for both diameter sizes as shown in Table-4. Scattering characteristics were also investigated by mentioning of *CV* (coefficient of variation). The *CV* is the degree to which a set of data points varies. When assessing precision, the lower of *CV* percentage, the better of precision between replicates. For Group I, the level of *CV* is almost same or less than that on actuality of ready-mixed concrete product (Saga, 2008) from 10 to 15%. It can be stated that the test results are satisfy enough. For group II, the *CV* is bigger than the requirements (except for concrete grade of 30), so additional statistic analysis will be conducted to study the failure pattern effect.

**Table-4**. Point load index.

| Group I | | | | | Group II | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Grade** | ***d*** (mm) | ***h*/*d*** | **$I_S$** (MPa) | ***CV*** (%) | **Grade** | ***d*** (mm) | ***h*/*d*** | **$I_S$** (MPa) | ***CV*** (%) |
| 16 | 35 | 1.5 | 2.27 | 11.4 | 16 | 35 | 1.5 | 2.20 | 26.1 |
| | | 2.0 | 2.32 | 13.3 | | | 2.0 | 2.30 | 31.9 |
| | 50 | 1.5 | 1.87 | 10.7 | | 50 | 1.5 | 1.85 | 18.7 |
| | | 2.0 | 1.93 | 10.8 | | | 2.0 | 1.95 | 18.1 |
| 21 | 35 | 1.5 | 3.24 | 11.4 | 21 | 35 | 1.5 | 2.52 | 23.0 |
| | | 2.0 | 3.31 | 12.4 | | | 2.0 | 2.55 | 24.3 |
| | 50 | 1.5 | 2.57 | 9.7 | | 50 | 1.5 | 2.12 | 21.0 |
| | | 2.0 | 2.61 | 11.1 | | | 2.0 | 2.00 | 18.0 |
| 24 | 35 | 1.5 | 3.21 | 12.4 | 24 | 35 | 1.5 | 2.90 | 26.3 |
| | | 2.0 | 3.28 | 13.1 | | | 2.0 | 2.92 | 27.0 |
| | 50 | 1.5 | 2.71 | 8.1 | | 50 | 1.5 | 2.31 | 18.2 |
| | | 2.0 | 2.77 | 9.3 | | | 2.0 | 2.43 | 18.2 |
| 36 | 35 | 1.5 | 3.61 | 11.9 | 30 | 35 | 1.5 | 2.80 | 24.7 |
| | | 2.0 | 3.69 | 13.5 | | | 2.0 | 2.85 | 19.7 |
| | 50 | 1.5 | 3.06 | 10.4 | | 50 | 1.5 | 2.43 | 8.5 |
| | | 2.0 | 3.02 | 10.9 | | | 2.0 | 2.47 | 7.6 |
| 50 | 35 | 1.5 | 3.95 | 8.1 | | | | | |
| | | 2.0 | 4.05 | 9.6 | | | | | |
| | 50 | 1.5 | 3.27 | 8.2 | | | | | |
| | | 2.0 | 3.34 | 8.9 | | | | | |

For Group I, the level of *CV* for *h*/*d* of 1.5 is smaller than *h*/*d* of 2.0. It can be stated that *h*/*d* ratio of 1.5 is better than *h*/*d* of 2.0 for making a PLT specimens from core drilled extraction. While for core specimen diameter, *d* is better using 50mm than 35mm, because the level of *CV* is also smaller. Beside this reason, it is also fulfilled with the standard core diameter requirements of 50mm. For all groups, it is possible and acceptable for using a core diameter of 50mm and *h*/*d* ratio of 2.0 as PLT specimen with results in the range of *CV* from 8 to 18%. Application of PLT for small diameter of core specimen is not suggested for $d/G_{max}$ ratio below 1.25, considering the *CV* results for $G_{max}$ of 40mm and *d* of 35mm are larger than 20%.

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**Failure pattern effect on the point load index**

For group II, by considering that the PLT on concrete materials will lead the core specimen may be failure in splitting pattern as inapplicable as typical failure modes, therefore, more likely will contribute to the variation in strength measurement and impossible to determine the exact strength compare with in breaking pattern. To examine the difference between two mean values by neglecting splitting pattern, the significance test is conducted. Soong (2004), the 5% of confidence level and rejection in terms of the mean difference test is given by the following Equation:

$$\left|\bar{x}_1 - \bar{x}_2\right| > 1.96\sqrt{\frac{s_1^{\ 2}}{n_1} + \frac{s_2^{\ 2}}{n_2}} \qquad (6)$$

Where:

$\bar{x}_1, \bar{x}_2$ : mean value of sample
$n_1, n_2$ : number of sample
$s_1, s_2$ : deviation standard of sample

Table-5 shows the recalculation of point load index for each concrete grade by neglecting the results of splitting failure pattern. A significant difference due to the failure patterns were observed for two sizes of core diameter, *d* of 35 and 50mm as shown in Table-6. It shows that there is no significant difference and the two population means are equal. Thus, the failure pattern is not affecting the point load index for $G_{max}$ of 40mm. By considering that core specimen diameter of 35mm has a larger of the *CV* (more than 20%); the improvement of reliability is difficult, for the reason that PLT is assessing the strength of coarse aggregate, not the concrete.

**Table-5**. Recalculation of point load index for group II.

| Grade | *d* (mm) | *h*/*d* | Number of data | | Mean value | |
|---|---|---|---|---|---|---|
| | | | Before | After | Before | After |
| 16 | 35 | 1.5 | 126 | 104 | 2.20 | 2.17 |
| | | 2.0 | 126 | 116 | 2.30 | 2.28 |
| | 50 | 1.5 | 85 | 77 | 1.85 | 1.84 |
| | | 2.0 | 87 | 86 | 1.95 | 1.95 |
| 21 | 35 | 1.5 | 154 | 130 | 2.52 | 2.47 |
| | | 2.0 | 138 | 113 | 2.55 | 2.59 |
| | 50 | 1.5 | 82 | 69 | 2.12 | 2.11 |
| | | 2.0 | 79 | 74 | 2.00 | 2.01 |
| 24 | 35 | 1.5 | 113 | 83 | 2.90 | 2.76 |
| | | 2.0 | 113 | 95 | 2.92 | 2.92 |
| | 50 | 1.5 | 87 | 69 | 2.31 | 2.27 |
| | | 2.0 | 86 | 61 | 2.43 | 2.38 |
| 30 | 35 | 1.5 | 157 | 112 | 2.80 | 2.76 |
| | | 2.0 | 172 | 137 | 2.85 | 2.85 |
| | 50 | 1.5 | 113 | 85 | 2.43 | 2.43 |
| | | 2.0 | 108 | 79 | 2.47 | 2.46 |

**Table-6**. The significance test for failure pattern effect on group II.

| Grade | *h*/*d* | Diameter of 35mm | | | Diameter of 50mm | | |
|---|---|---|---|---|---|---|---|
| | | Mean difference | Region of rejection | Significant difference | Mean difference | Region of rejection | Significant difference |
| 16 | 1.5 | 0.027 | 0.146 | No | 0.008 | 0.108 | No |
| | 2.0 | 0.024 | 0.188 | No | 0.003 | 0.105 | No |
| 21 | 1.5 | 0.048 | 0.130 | No | 0.005 | 0.143 | No |
| | 2.0 | 0.040 | 0.148 | No | 0.003 | 0.116 | No |
| 24 | 1.5 | 0.143 | 0.213 | No | 0.037 | 0.132 | No |
| | 2.0 | 0.006 | 0.214 | No | 0.043 | 0.143 | No |
| 30 | 1.5 | 0.038 | 0.159 | No | 0.006 | 0.056 | No |
| | 2.0 | 0.004 | 0.126 | No | 0.007 | 0.055 | No |

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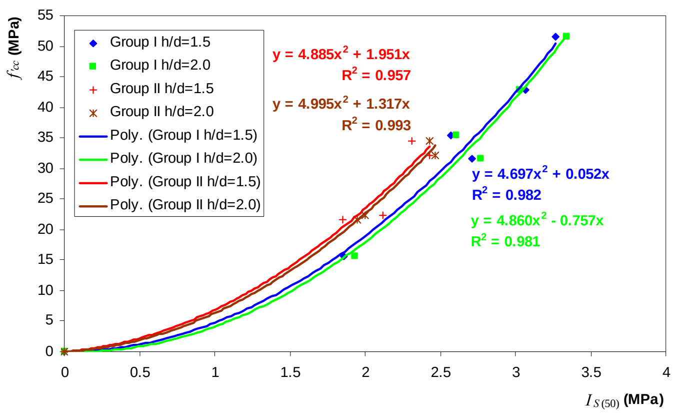
**Correlation between point load index and compressive strength**

Point load index of core specimen diameter of 50mm, $I_{S\,(50)}$ is determined as standard value. Hence, the value of different core specimen diameter, $I_{S\,(35)}$ should be corrected in order to show a relationship with $I_{S\,(50)}$ by using Equation (4) and (5). By correcting the point load index of $I_{S(35)}$ and assuming as standard core specimen diameter of 50mm, will add the number of data for analysis of point load index $I_{S(50)}$. The new result for this combination is shown in Table-7 corresponding with the compressive strength of concrete core ($f'_{cc}$) for each grade.

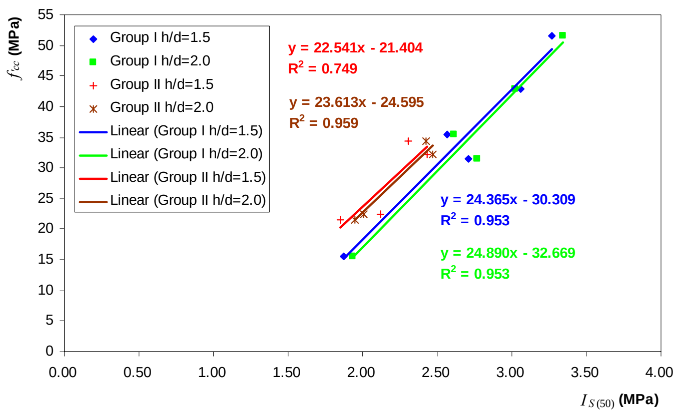
**Table-7**. Point load index and compressive strength of concrete core.

| Group I | | | | Group II | | | |
|---|---|---|---|---|---|---|---|
| **Grade** | $f'_{cc}$ (MPa) | ***h/d* = 1.5** | ***h/d* = 2.0** | **Grade** | $f'_{cc}$ (MPa) | ***h/d* = 1.5** | ***h/d* = 2.0** |
| 16 | 15.6 | 1.86 | 1.93 | 16 | 21.6 | 1.85 | 1.95 |
| 21 | 35.4 | 2.57 | 2.61 | 21 | 22.4 | 2.12 | 2.00 |
| 24 | 31.5 | 2.71 | 2.77 | 24 | 34.4 | 2.31 | 2.43 |
| 36 | 42.9 | 3.07 | 3.03 | 30 | 32.2 | 2.43 | 2.47 |
| 50 | 51.5 | 3.27 | 3.34 | | | | |

The correlation between point load index, $I_{S\,(50)}$ and compressive strength of concrete core, $f'_{cc}$ for both of groups is shown graphically in Figure-7. It is clearly evident to show the correlation by proposing a second order of polynomial and linear regression. It is proven by showing the square value of correlation coefficient which judges the effectiveness of a second order of polynomial approximation curve for $h/d$ = 1.5 is thought to be similar for $h/d$ = 2.0. Linier regression also showed the same trend of effectiveness except for group II.




a. Second order of polynomial regression




b. Linear regression

**Figure-7**. Correlation between $I_{S\,(50)}$ and $f'_{cc}$.

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JIS A5308 (2003) gives the compressive strength range of ready-mixed concrete in field application from 18 to 45MPa. Hence, the application of PLT for estimating in-situ strength of concrete structure should be confirmed in this range. So, the correlation was limited to this range for core specimen diameter of 35 and 50mm as shown in Figure-8. When using the linear regression as shown in Figure-7, the approximation line does not intercept in the origin point. However, Figure-8 shown that the fitted curve will pass through the origin which aims to establish the relation of the whole area would be overestimated. It is preferable to using linear approximation than other modes in order to minimize the standard for the assessment of risk.

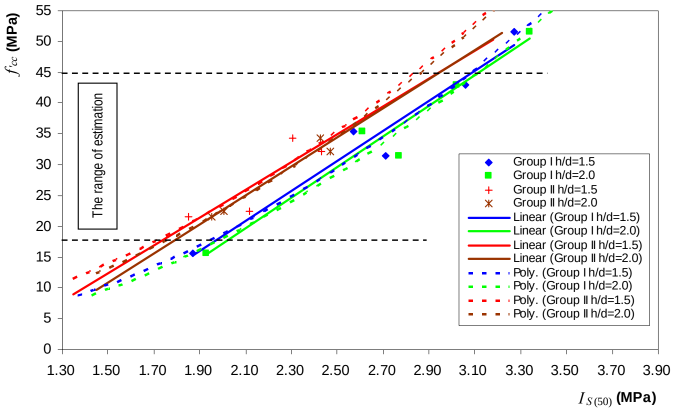


**Figure-8**. Linear approximation for $I_{S\,(50)}$ to $f'_{cc}$.

**The new geometric correction factor**

By considering the Equation (4) and (5) were proposed for rock specimen, so it is not suitable for concrete regarding the issue of homogeneity. The previous section already mentioned that maximum coarse aggregate size in concrete will affect the results of point load index. A new correction factor of $F$ is proposed by following the format of previous Equation as:

$$I_{S(50)} = \left(\frac{d}{50}\right)^{X} I_S \qquad (7)$$

The value of $X$ can be generated by using data from group I for core specimen diameter of 35mm. The selection of this data was considered more reliable by showing a lower $CV$. The solution is simple, because the nature of linear approximation as the origin. The exponent value of $X$ is calculated as 0.53 with coefficient of correlation is 0.982. Finally, the expression geometric correction factor for concrete core specimen is given by:

$$F = \left(\frac{D_e}{50}\right)^{0.53} \qquad (8)$$

Table-8 shows the absolute relative error between experimental and estimation values for point load index of $I_{S\,(35)}$ to become standard point load index of $I_{S\,(50)}$ by using Equation (8). The results are satisfied enough by showing a value of absolute relative error less than 5% in the case of $d$ of 35mm and $G_{max}$ of 20mm.

**Table-8**. Experimental and estimation values of $I_{S\,(50)}$.

| Group | $f'_{cc}$ (MPa) | h/d | Point load index (MPa) | | | Absolute relative error (%) |
|---|---|---|---|---|---|---|
| | | | $I_{S(35)}$ | $I_{S(50)}$ [a] | $I_{S(50)}$ [b] | |
| I | 15.6 | 1.5 | 2.27 | 1.88 | 1.87 | 0.53 |
| | | 2.0 | 2.32 | 1.92 | 1.93 | 0.52 |
| | 31.5 | 1.5 | 3.24 | 2.68 | 2.57 | 4.28 |
| | | 2.0 | 3.31 | 2.74 | 2.61 | 4.98 |
| | 35.4 | 1.5 | 3.21 | 2.66 | 2.71 | 1.85 |
| | | 2.0 | 3.28 | 2.72 | 2.77 | 1.81 |
| | 42.9 | 1.5 | 3.61 | 2.99 | 3.06 | 2.29 |
| | | 2.0 | 3.69 | 3.06 | 3.02 | 1.32 |
| | 51.5 | 1.5 | 3.95 | 3.27 | 3.27 | 0.00 |
| | | 2.0 | 4.05 | 3.35 | 3.34 | 0.30 |

*) a = estimation
b = experimental

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Recalculation procedure is conducted by using a new Equation (8) for correcting point load index of core specimen diameter of 35mm and performing linear regression analysis to propose a formula of compressive strength estimation for equivalent core diameter of 50mm as shown in Table-9. The coefficient of correlation, $R^2$ also shows an improvement in strong relationship between $I_{S(50)}$ and $f'_{cc}$.

**Table-9**. Formula of compressive strength estimation.

| Group | *h/d* | Formula of Estimation | $R^2$ |
|---|---|---|---|
| I | 1.5 | $f'_{cc} = 24.4I_S - 30.3$ | 0.953 |
| | 2.0 | $f'_{cc} = 24.9I_S - 32.7$ | 0.953 |
| II | 1.5 | $f'_{cc} = 20.8I_S - 16.7$ | 0.928 |
| | 2.0 | $f'_{cc} = 22.3I_S - 22.0$ | 0.979 |

**Minimum of sample size**

The required of sample size generally depends on the maximum allowable difference (or error) that one is willing to accept between the sample average and the true average, the variability of results and the risk one is willing to accept that the allowable difference is exceeded. Since the variability of test results is usually unknown in advance, estimation should be made and adjusted as the test results become reliable. Financial system should also be considered in the selection of sample size. In some cases increasing the sample size may not only result in a minimal decrease in the risk that the error is exceeded. The cost of additional sampling and testing would not be justified in these situations (ACI 437R-91, 1998).

The minimum number of sample for compressive strength, tensile strength and flexural strength test of hardened concrete should be taken 3 specimens. According to this knowledge, a sample survey is conducted to determine the equivalent number of specimen ($n$) for statistically test based on the same terms. In a sampling survey, the method of defining $n$ is in consideration of the mean value of population ($\mu$) for a sample mean of test result ($\bar{x}$) that had been taken as an estimation of the population size ($N$). If population distribution is assumed as normal distribution, $N(\mu,\sigma^2)$ based on sample size of $n$, the sample mean of test result ($\bar{x}$) will follow a normal distribution under the Equation:

$$N\left(\mu,\frac{\sigma^2}{n}\right) \tag{9}$$

Where:

$\sigma$ : deviation standard of population

Sample size estimation accuracy is represented by the following Equation:

$$P\left\{\left|\bar{x}-\mu\right| \le t\frac{\sigma}{\sqrt{n}}\right\} = P_0 \tag{10}$$

Where:

$P_0$ : probability set on specific confidence level of α

$\left|\bar{x}-\mu\right|$ : Error of estimation

$t$ : specific normal distribution value of $P_0$

Hence, the specific limit of error, $e$ is taken into account by assuming that $N$ >>1, the sample size of $n$ will be given by the following Equation:

$$n \ge \frac{t^2\sigma^2}{e^2} \tag{11}$$

Where:

$e$ : specific limit of error

The $CV$ in Table-4 can be modified as shown in Table-10 by calculating the mean of $CV$ to determine the minimum of sample size, $n$, required to assure that percentage error in the average measured is below a specified limit of error, $e$, at a certain level of confidence by using Equation (11). To use this Equation, the value of $\sigma/e$ from previous research is commonly applied to take into account for estimating the value of existing materials or similar results. Soong (2004), if the sample size of $n$ is determined as 3, probability set on confidence level of α = 5%, $P_0$ = 0.95 ($t$ = 1.96), $\sigma/e$ = 0.884 will be obtained if backward calculation is conducted. Therefore, $e/\sigma$ of 1.131 is established as the deviation standard of specified error limit. This value is not depending on compressive strength of concrete core, $f'_{cc}$.

**Table-10**. Mean of CV.

| Group | *d* (mm) | $d/G_{max}$ | *h/d* | *CV* (%) |
|---|---|---|---|---|
| I | 35 | 1.750 | 1.5 | 11.0 |
| | | | 2.0 | 12.4 |
| | 50 | 2.500 | 1.5 | 9.4 |
| | | | 2.0 | 10.2 |
| II | 35[a] | 0.875 | 1.5 | 25.0 |
| | | | 2.0 | 25.7 |
| | 50 | 1.250 | 1.5 | 16.6 |
| | | | 2.0 | 15.5 |

*) a = not recommended to use in the estimation

From Table-10, $CV$ for $G_{max}$ of 20mm is considered to be about 10% and tried to be calculated in the same condition of previous research for determining a sample size. From the research for porous concrete manufacture that conducted by the JCI, group of eco-concrete study had been proposed that sample size of 5 specimens is carrying out under the same condition setting and the value of $\sigma/e$ that obtained is 0.876 (Okamoto *et al*, 1998). This value is equivalent to the deviation standard of specified error limit that had been established as 0.884. Since the test specimen is porous concrete that compacted by vibration molding before hardened, the variation in test results became larger than ordinary concrete as liquid.

According to the record of laboratory work, the range of *CV* is adopted from 10 to 18%. Based on this argument and the *CV* for $G_{max}$ of 20mm is 10%, the value of $e/\sigma$ is considered as 1.131, so the minimum sample size, $n$ = 4.916. Therefore, sample size of 5 specimens for estimating in-situ compressive strength of concrete structure by PLT from core drilled specimen, $d$ of 35 and 50mm are reliable enough.

For $G_{max}$ of 40mm, the range of *CV* is 15 - 26%; especially for core specimen diameter of 35mm is out of the range. Hence, this specimen is not acceptable for estimating in-situ compressive strength of concrete by PLT because the significant influence of $d/G_{max}$ ratio. For core specimen diameter of 50mm, the fluctuation of *CV* still in the range as 15 - 17%, but strict limit is adopted for the deviation standard of specified error limit, $\sigma/e$ as 0.75. Therefore, the value of $e/\sigma$ is considered as 1.333, so the minimum sample size, $n$ = 6.829 or 7 specimens should be taken into account of estimation.

## CONCLUSIONS

The results obtained by this study can be concluded as follows:

- Considering the maximum coarse aggregate size in concrete, new criterion is proposed by determining the minimum value of $d/G_{max}$ ratio should not less than 1.25
- Core drilled diameter of 50mm and $h/d$ ratio of 2.0 is recommended to select as specimen for in-situ concrete strength estimation by using PLT.
- Considering the issue of homogeneity that concrete is composite material, a new correction factor is proposed for core specimen diameters differ from 50mm as $F = \left(\frac{d}{50}\right)^{0.53}$.
- Approximation line is preferred to produce a general formula for in-situ estimation of concrete compressive strength as $f'_c = k.I_S - C$ with $k$ is index-to-strength conversion factor and $C$ is constant.
- Correlation between point load index of $I_S$ and concrete compressive strength of $f'_c$ is strong by indicating a high value of correlation coefficient, $R^2 \approx$ 1.0.
- Minimum of sample size should be taken at least 5 specimens for architectural concrete structures ($G_{max}$ of 20mm) and 7 specimens for civil concrete structures ($G_{max}$ of 40mm) in order to fulfill the requirements of the specified limit of error test results as ready-mixed concrete products on confidence level of 95%.
- Application of PLT for in-situ concrete compressive strength estimation should be confirmed in the range of compressive strength of ready-mixed concrete product from18 to 45MPa.

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