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# A Proposal of an Elastic Modulus Equation for High-Strength and Ultra High-Strength Concrete

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**Abstract:** This paper presents an elastic modulus equation more appropriate for predicting the elastic modulus of structural materials designed for and made of high- and ultra high-strength concrete under current domestic situation in Korea. In order to validate and assess the proposed elastic modulus equation, more than 400 laboratory test data available in the domestic literature on compressive strength of concrete in the range between 400 to 1,000 kgf/cm$^2$ were used and analyzed statistically. Comparison analyses of the proposed elastic modulus equation with previously suggested equations of ACI363R, CEB-FIP, NS3473 and New-RC are also presented to demonstrate its applicability in domestic practice.

**Keywords:** compressive strength, high-strength concrete, modulus of elasticity, unit weight, elastic modulus equation.

## 1. Introduction

Making concrete of high-strength has not only an economic advantage of cost saving in materials due to the reduction in the cross-sectional material requirement but also verified structural advantages such as free-casting of the concrete material, long spanning and high-raising compared to regular-strength concrete. Thus, its application to construction of concrete structures is in an explosively increasing trend domestically and abroad. In Japan and North America, it has passed the initial stage of using high-strength concrete to reach the stage of regular application to civil structures, special structures and high building structures. Korea began to have a great interest in this application of high-strength concrete, and, simultaneously, many research related to its practical application in domestic situation have been actively carried out.

Advanced countries such as the USA and Japan have their own proposed experimental and theoretical equations for the material composition characteristics appropriate for their countries with respect to high-strength and ultra high-strength concrete. Nevertheless, there has been a definite lack of development of models for high-strength and ultra high-strength concrete material and its analytical theory appropriate for the material characteristics in Korea. It is current situation that domestic design standards, which can be relied on from the design stage, have not been established yet. In addition, the current domestic practice is to apply standard equations designed for regular-strength concrete or standard equations of abroad as of yet when the design and structural analysis of high-strength concrete is needed.

Thus, there is a definite need for elucidating such mechanical characteristics as elastic modulus, stress-strain property, Poisson's ratio, and tensile strength property for domestic high- and ultra high-strength concrete in order to develop high-strength concrete technology appropriate for Korea and its wide application in Korea. Moreover, it is necessary to reestablish existing standard equations and analytic methods systematically based on the preliminary study mentioned above. Especially, since the most important variable for concrete material in design and analysis of concrete structures or even only for the control of deflection of structures is elastic modulus, establishment of a theory on the elastic modulus of high- and ultra high-strength concrete and the variables influencing the elastic property must be set as the top priority.

According to domestic experimental results, as the strength of concrete gets stronger, its elastic modulus exhibits lower values compared to the reported values abroad.[1,2] In fact, it has been pointed out by many domestic researches[1,6-10] that the elastic modulus equation of ACI 318-89[3] and ACI 363[4] of the USA and the standard equations of AIJ,[5] which have been applied to the design and analysis of domestic steel bar-reinforced concrete structures, have overestimated the compressive strength values for high-strength concrete (over 400 kgf/cm$^2$) measured in domestic field.

Therefore, this study carries out a comparative analysis of the elastic modulus values measured by domestic experiments against existing elastic modulus equations of abroad standard and recently proposed equations for elastic modulus of domestic high- and ultra high-strength concrete. Its purpose is to propose an elastic modulus equation appropriate for domestic concrete materials. The proposed equation will serve as a fundamental basis for establishing a design standard for domestic high- and ultra high-strength concrete.

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## 2. Review of existing elastic modulus equations

In this section, the characteristics of prediction equations for concrete elastic modulus, which are widely used recently, is examined. In addition, they will be compared to the experimental values measured in domestic field in order to evaluate its applicability to domestic situation.

### 2.1 Existing elastic modulus equations

The modulus of elasticity, which is a very important material characteristics for designing and analyzing concrete structures, usually adopts the specifications of ASTM C469.[11] The specification uses secant modulus for 40% of the maximum compression strength ($f'_{ck}$) obtained from the stress-strain relationship based on compression testing of a test specimen. The domestic practice is to follow this specification unless otherwise indicated. The characteristics of prediction equations for aforementioned secant modulus method and elastic modulus of a cylindrical test specimen is examined as follows.

#### 2.1.1 ACI 318-89 equation

This is an experimental equation showing the factors influencing the elastic modulus of concrete as a function of unit mass (weight) and compressive strength based on experimental data. Up until recently, it has been used widely for design and analysis of domestic steel-reinforced concrete structures. However, the revised specification for concrete structures, KCI 96,[12] limits the application of ACI 318-89 equation (Eq. (1)) to the case of compressive strength below 300 kgf/cm$^2$. In fact, results of many recent researches[6-8] point out that this equation overestimates the elastic modulus of concrete with compressive strength over 420 kgf/cm$^2$.

$$E_c=\gamma_c^{1.5}\cdot 4{,}270\cdot\sqrt{f'_{ck}}\ (\text{kgf/cm}^2) \tag{1}$$

$$(1.442\text{t/m}^3 \le \gamma_c \le 2.483\ \text{t/m}^3)$$

#### 2.1.2 ACI 363 equation 1984

ACI 363 equation took account of the overestimating shortcoming of ACI 318 equation and suggested a revised prediction equation of Carrasquillo et al.[13] (Eq. (2)) for elastic modulus of concrete with normal unit weight of 2.346 tf/m$^3$ and compressive strength above 420 kgf/cm$^2$. This equation has been assessed to exhibit a reasonable predictive power with many reported experimental values of elastic modulus.[7,8] Nevertheless, there have been reported cases of this equation still overestimating the experimental values of elastic modulus of domestic high-strength concrete by about 5%.[1,14]

Meanwhile, the domestic revised specification for concrete, KCI 96,[12] suggests a simplified version of Eq. (2) as shown in Eq. (3) for prediction of the elastic modulus of concrete with compressive strength above 300 kgf/cm$^2$.

$$E_c=10.500\cdot\sqrt{f'_c}+70{,}000)\cdot\left(\frac{\gamma_c}{2.346}\right)^{1.5}\ (\text{kgf/cm}^2) \tag{2}$$

$$\begin{cases} 2.32\ \text{tf/m}^3 \le \gamma_c \le 2.42\ \text{tf/m}^3 \\ 326\text{kg/cm}^2 \le f_c' \le 786\text{kgf/cm}^2(\Phi 15.2\times 30.5\text{cm}) \end{cases}$$

$$E_c=10.500\cdot\sqrt{\sigma_{ck}}+70,000(\text{kgf/cm}^2) \tag{3}$$

Where, $f_{ck}'$, $\sigma_{ck}$= cylindrical compressive strength of concrete at 28 days $\ge$ 300kgf/cm$^2$

#### 2.1.3 CEB-FIP model code 90 equation 1990

The prediction equations of CEB-FIP MC 90 for elastic modulus of normal weight concrete are shown in Eqs. (4) and (5).

This prediction equation estimates the elastic modulus about 12~15% higher than ACI 363 prediction equation. Additionally, according to recent research on the mechanical characteristics of high-strength and ultra high-strength concrete, this prediction equation overestimated the elastic modulus of concrete of compressive strength over 410~460 kgf/cm$^2$ compared to the actual measured values.[16] Meanwhile, Noguchi[9] reported that this prediction equations had the tendency to reduce the prediction error against the actual measured values as the specific gravity of coarse aggregate was larger in his comparative analysis of predictions equations for elastic modulus of concrete (150~1,700 kgf/cm$^2$) using various aggregate.

$$Ec=\alpha\cdot 47{,}000\cdot\sqrt[3]{f_{ck}+8}\ (\text{kgf/cm}^2) \tag{4}$$

$$Ec=\alpha\cdot 47{,}000\cdot\sqrt[3]{f_{cm}} \tag{5}$$

where, $f_{ck}$ : compressive strength of concrete
$f_{cm}$: compressive strength of concrete at 28 days ($\Phi$15.2 × 30.5cm) } $\le$ 816 kgf/cm$^2$

$\alpha$ = 1.2 : basalt, hard limestone
1.0 : quartzite
0.9 : limestone
0.7 : sandstone

#### 2.1.4 Norwegian code NS 3473 equation 1992

NS 3473 suggests a prediction equation for elastic modulus of concrete with unit weight over 2.2 tf/m$^3$ and compressive strength below 85 MPa (867 kgf/cm$^2$) as shown in Eq. (6). In addition, it specifies that the elastic modulus of concrete of normal and light weight with compressive strength over 85 MPa (867 kgf/cm$^2$) should be set by an experiment. It has been reported that the predicted values of this equation is about 12~15% lower than CEB-FIP MC 90 equation.

$$E_c=48{,}300\cdot f_{cc}^{0.3}\cdot\left(\frac{\gamma_c}{2.4}\right)^{1.5}\ (\text{kgf/cm}^2) \tag{6}$$

$$\begin{cases} 204\text{kgf/cm}^2 \le f_{cc} \le 755\text{kgf/cm}^2(\Phi 15.2\times 30.5\text{cm}) \\ 204\text{kgf/cm}^2 \le f_{cc} \le 867\text{kgf/cm}^2(10.0\times 10.0\times 10.0\text{cm}) \end{cases}$$

RC Standard equation for Structural Computation and New RC Prediction equation[18] for Elastic Modulus of Concrete by Architectural Institute of Japan (AIJ)[5].

The RC Standard equation for Structural Computation of Architectural Institute of Japan (AIJ) (Eq. (7)) is currently used as the standard equation by the Architectural Institute of Korea and is applied to regular-strength concrete of design strength below 36 MPa (367 kgf/cm$^2$). It has been reported that its prediction error against the actual measured values increases as the strength of concrete increases.[9,10] Thus, in consideration of the development task for light and high-rise steel-reinforced concrete structures (abbreviated: New RC), which started in 1988, many researches have been conducted to experiment with various materials to collect about 3,000 data to formulate and suggest an elastic modulus prediction Eq of Eq. (8) below for concrete strength over 36 MPa to account for the varying characteristics of elastic modulus of high-strength concrete depending on the additives and characteristics of aggregate and their mixing ratio.

$$Ec = 21{,}000 \cdot \left(\frac{\gamma_c}{2.3}\right)^{1.5} \cdot \sqrt{\frac{f_{ck}}{200}} \ (\text{kgf/cm}^2) \qquad (7)$$

$$Ec = k_1 \cdot k_2 \cdot 40{,}250 \cdot \left(\frac{\gamma_c}{2.4}\right)^2 \cdot \sqrt[3]{f'_{ck}} \qquad (8)$$

Where $f_{ck}$ = cylindrical compressive strength of concrete at 28 days ≤ 367 kgf/cm$^2$

$$\begin{cases} 1.5\ \text{tf/m}^3 \le \gamma_c \le 2.5\ \text{tf/m}^3 \\ 204\ \text{kgf/cm}^2 \le f'_{ck} \le 1,632\ \text{kgf/cm}^2 \end{cases}$$

$K_1$ = 1.2 for limestone macadam, bauxite macadam
= 0.95 for quartzite schist macadam, basalt macadam, andecite macadam, jade macadam, clay slate macadam
= 1.0 for other thick (coarse) aggregate

$K_2$ = 1.1 for fly ash
= 0.95 for silica fume, blast furnace slag powder, fly ash
= 1.0 for other additives or no additive

### 2.2 Comparison of elastic modulus values measured by domestic experiments against predicted values of each prediction equation

This study defines concrete with compressive strength over 400 kgf/cm$^2$ as high-strength concrete. In order to suggest a prediction equation for elastic modulus of high-strength (400~700 kgf/cm$^2$) and ultra high-strength concrete (700~1,400 kgf/cm$^2$), which takes the characteristics of domestic concrete materials into account, 440 experimental data were collected from the *proceedings* of the Korea Concrete Institute, Korea Society of Civil Engineers, Architectural Institute of Korea and Journals of Korea Concrete Institute and Architectural Institute of Korea, etc. published between 1979~1996.[19] The scope of data collection was limited to test specimen of water-cured average weight concrete with 10 × 20 cm in dimension, 28 days of age, and the compressive strength over 350 kgf/cm$^2$. The mixing ratio, compressive strength, secant elastic modulus, and unit weight of the concrete were the variables of collected data.

The existing elastic modulus equations were evaluated in terms of the ratio of collected experimental values and the predicted values of each prediction equation, and the result is shown in Figs. 1~4. The horizontal axis represents the compressive strength of concrete and the vertical axis represents the ratio of the predicted elastic modulus value to the experimental value. Additionally, the computed values were analyzed by a regression analysis, and a straight-line fit for the regressed values is depicted.

In Fig. 1, it is shown that ACI-363 prediction equation overestimates the domestic experimental values by 4~12% generally. In addition, this equation showed the tendency for greater error in prediction as the compressive strength and unit weight increased.

In Fig. 2, CEB-FIP equation exhibited overestimation over domestic experimental values by 10% overall and showed the tendency to have the prediction error reduced as the unit weight and compressive strength increased.

Fig. 3 shows that the new elastic modulus equation as suggested by New-RC Project of Japan has the tendency to get closer to the domestic experimental values as the compressive strength of the concrete increased. In other words, its predictive power was fairly good for ultra high-strength concrete of over 700 kgf/cm$^2$ in compressive strength. However, for lower compressive strength, it overestimated the elastic modulus by 6~12% on the average. Meanwhile, it was deemed that the predictive power of this equation in response to the change in unit weight was evaluated to be in the acceptable range.

Fig. 4 shows that the NS equation overestimates the elastic modulus as compared to domestic experimental values for concrete of compressive strength below 850 kgf/cm$^2$ and underestimates for concrete of compressive strength above it.

Thus, it has been shown that the existing prediction equations for elastic modulus of concrete generally overestimate the elastic modulus as compared to domestic experimental values. Moreover, the values discussed so far pertain to the range of the ratio of the predicted value to experimental value around 1. Outside this range, the prediction error is more conspicuous as shown by the regression

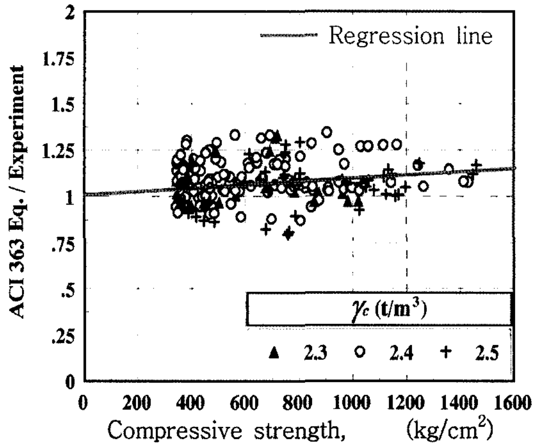


**Fig. 1** Relationship of compressive strength and elastic modulus prediction error (the ratio of the value predicted by ACI-363 equation to domestic experimental value).

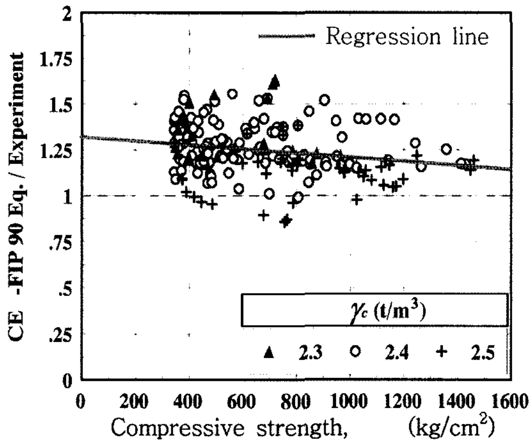


**Fig. 2** Relationship of compressive strength and elastic modulus prediction error (the ratio of the value predicted by CEB-FIP MC 90 equation to domestic experimental value).

line and the ratio of the predicted value to experimental value. This tendency to overestimate prediction error can result in overestimation of the strength of the concrete in the design stage of building structures. This in return can result in a safety hazard, and, thus, it is deemed that the application of these prediction equations to design of domestic high- and ultra high-strength concrete structures is not appropriate, if not dangerous. Using domestic experimental data on high- and ultra high-strength concrete collected for this study, the comparison analysis of domestic experimental values and those values predicted by existing equations confirmed previous domestic research findings,[1,2] which reported smaller elastic modulus values than the reported values abroad as the strength of concrete increased. Thus, it is deemed necessary to establish a new standard equation for elastic modulus of domestic high- and ultra high-strength concrete.

## 3. A proposal of an elastic modulus equation for high- and ultra high-strength concrete

### 3.1 Evaluation of unit weight

The unit weight of concrete is mainly determined by the aggregate, which composes 60~80% of total volume of the concrete. Especially, as the unit quantity of concrete is reduced, the unit weight of high-strength concrete has the tendency to increase relative to regular concrete even if it uses the same type of material. Thus, there is a special need for examining the unit weight of high-strength concrete in the structural design stage. The unit weight (density) of concrete being currently applied to the design of existing concrete structure is typically 2.3~2.4 tf/m$^3$. Nevertheless, using the domestic experimental data and Fig. 5 depicting the relationship between compressive strength and unit weight, there appears some dispersion of the unit weights, but most unit weights of high- and ultra high-strength concrete are distributed within the range of 2.25 tf/m$^3$ and 2.55 tf/m$^3$. From Fig. 5, the relationship between the unit weight and compressive strength of concrete was subject to a regression analysis (coefficient of correlation = 0.6) to derive Eq. (9). The trend of the unit weight increasing smoothly as the compressive strength increases can be seen. Thus, it is determined that the unit weight to be used in designing concrete structure within the range of compressive strength between 400~1,000 kgf/cm$^2$ should be about 2.37~2.45 tf/m$^3$. In fact, according to previous researches,[1,19] the unit weight of high-strength concrete was reported to be 2.40~ 2.45 tf/m$^3$ for standard water-curing and 2.39~2.41 tf/m$^3$ for air-curing regardless of the ratio of water to cement and the amount of water-reducing agent added.

In addition, data from normal weight concrete cured under water and at 28 days of age were collected in order to evaluate the unit weight of hardened concrete and the unit weight computed at the time of concrete mix (fresh concrete). From the collected data, the following linear relationship (coefficient of correlation = 0.78) between unit weight at the time of mixing (fresh concrete) and unit weight of hardened concrete was derived and is shown in Fig. 6 and Eq. (10). Fig. 6 shows that the unit weight of hardened concrete increased in comparison to unit weight computed at the time of concrete mixing. There were some variations due to different curing methods and age of the concrete. However, there was an increasing trend of the unit weight of hardened concrete compared to the unit weight of fresh concrete at the time of mixing under the conditions of water-curing and sealed curing while it showed a decreasing trend as the age increased for the case of air-curing.[9]

$$\gamma_c = 1,933.1 f'_{ck} \quad (9)$$

where, $\gamma_c$ : unit weight of hardened concrete (kgf/m$^3$)

$f'_{ck}$ : compression strength of concrete (kgf/cm$^2$)

$$\gamma_h = 600 + (0.76 \times \gamma_f) \quad (10)$$

where $\gamma_h$: unit weight of hardened concrete (at the time of measuring compression strength) (kgf/m$^3$)

$\gamma_f$: unit weight of fresh concrete at the time of mixing (kgf/m$^3$)

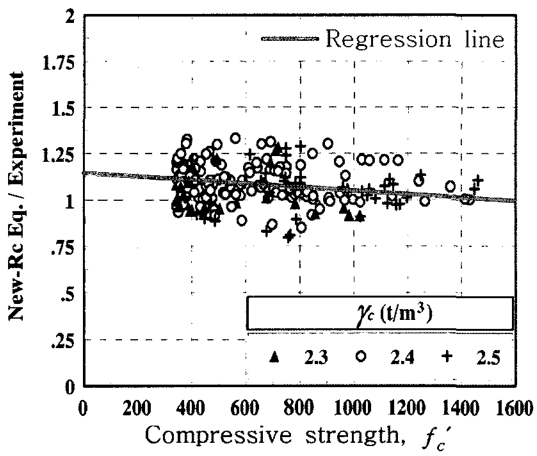


**Fig. 3** Relationship of compression strength and elastic modulus prediction error (the ratio of the value predicted by New RC equation to domestic experimental value)

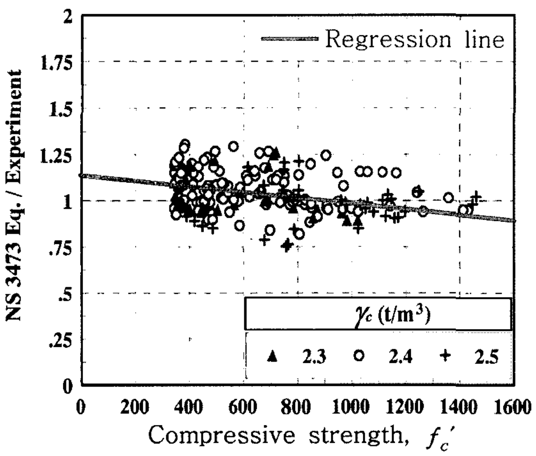


**Fig. 4** Relationship of compression strength and elastic modulus prediction error (the ratio of the value predicted by NS 3473 equation to domestic experimental value)

### 3.2 A Proposal of an elastic modulus equation using domestic experimental data

Noticing that each of CEB-FIP 90 equation and New-RC equation uses α and $k_t$ variable to account for regional differences in concrete mixing materials so as to provide a standard equation of uniquely their own, the establishment of elastic modulus prediction equation to be used in domestic practice should be derived from domestic experimental data. The suggested prediction equation for elastic modulus of concrete should be based on each experiment using the test specimens of the same mixing in order to establish the reliability of the suggested equation.

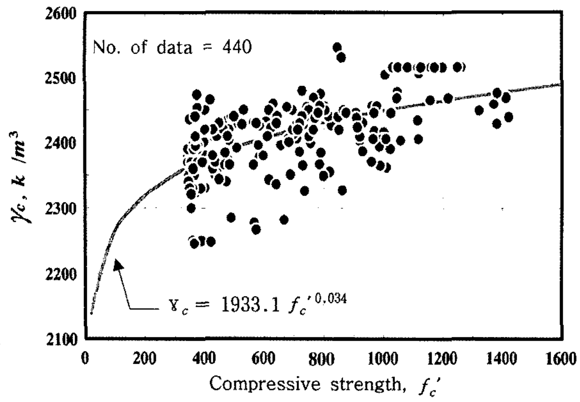


**Fig. 5** Relationship between the unit weight of hardened concrete and compressive strength.

However, the elastic modulus of concrete is influenced by many variables such as the elastic property and volume ratio of each mixing materials, the adhesion strength between thick (coarse) aggregate and cement paste, the usage amount of mixing agents, curing method and humidity condition, loading speed, individual characteristics of the experimenter, experimental devices, experimental method, the method for treating the compressed area of test specimen. Thus, it is very difficult to quantify the elastic characteristics of concrete clearly in one equation through the experiments considering all these variables.[9,18] It is construed that it is for this reason that New-RC Project of Japan recently collected about 3,000 domestic experimental data in order to suggest a New-RC elastic modulus equation for high-strength concrete based on such copious data.

Nevertheless, the elastic modulus equation can be simply defined, in general, as a function of such easily measured variables as unit weight and compressive strength as shown in Eq. (11) for practical purposes.[3,4]

$$E_c = \alpha((f'_{ck} + b)^c + d) \cdot \gamma_c^e \tag{11}$$

Where, $E_c$ : predicted value for elastic modulus of concrete

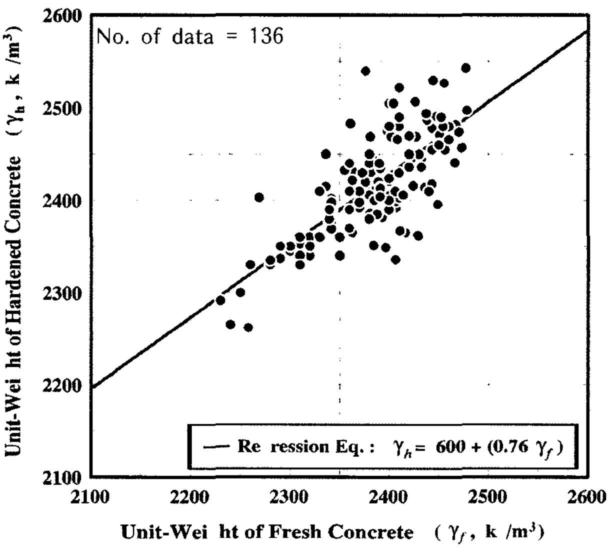


**Fig. 6** Relationship between unit weight of fresh concrete at the time of mixing and unit weight of hardened concrete.

$f'_{ck}$, $\gamma_c$ : predicted values for compression strength and unit weight of concrete, respectively

$a, b, c, d, e$ : regression constants

Th us, this study carried out a multiple regression analysis on the compressive strength data of high- and ultra high-strength concrete, secant elastic modulus, and the unit weight of the concrete as shown in Eq. (11).

Here, the unit weight of the concrete is expressed as a dimensionless ratio to the average value of collected data, 2.4 tf/m³. Fig. 7 depicts the relationship between elastic modulus and compressive strength by the unit weight of the concrete. From the result of a regression analysis on this data, a prediction equation for elastic modulus of concrete is derived and is shown in Eq. (12) (coefficient of correlation = 0.806).

Additionally, as it was mentioned above, the Fig. 1~4 shows regression analysis curves for the average unit weights of 2.3 tf/m³, 2.4 tf/m³, and 2.5 tf/m³. It can be seen that the elastic modulus has the tendency to increase as the unit weight increases.

$$E_c = (10{,}000\sqrt{f'_{ck}} + b)^c + d) \cdot \gamma_c^e \tag{12}$$

Where, $E_c$ : predicted value for elastic modulus of high- and ultra high-strength concrete (kgf/cm²).

$f'_{ck}$ : compression strength of concrete at 28 days of age (400~1,000 kgf/cm², 10 × 20 cm)

$\gamma_c$: unit weight of concrete (2.25~2.55 tf/m³)

Fig. 8 shows the relationship between the equations proposed by this study (Eq. (12)) and existing prediction equations of ACI 363 (Eq. (2)), CEB-FIP (Eq. (4)), and New-RC (Eq. (8)). It can be seen that the elastic modulus values predicted by the proposed equation, which was derived from domestic experimental data, are consistently lower than those predicted by aforementioned existing equations.

## 4. Conclusion

This study compared, analyzed, and reviewed the predictive power of existing elastic modulus equations with domestic experimental values for elastic modulus of high- and ultra high-strength concrete. The following conclusions are derived.

1) The result of comparison between the values reported by domestic experiments on elastic modulus of high- and ultra high-strength concrete and existing prediction equations for elastic modulus showed the existing prediction equations overestimated the elastic modulus of domestic concrete. This can result in over-estimation of the strength of the concrete in the design stage of building structures, and, in return, can result in a safety hazard. Thus, it is deemed that the application of these exiting prediction equations to the design of domestic high- and ultra high-strength concrete structures is not appropriate. Using domestic experimental data on high- and ultra high-strength concrete collected for this study, the comparison analysis of domestic experimental values and those values predicted by existing equations confirmed previous domestic research findings,[1,2] which reported smaller elastic modulus values than the reported values abroad as the strength of concrete increased. Thus, it is deemed necessary to establish a new prediction equation

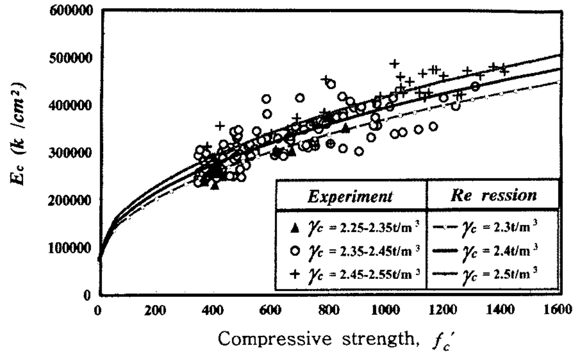


**Fig. 7** Relationship between compressive strength and elastic modulus of concrete by the unit weight of the concrete.

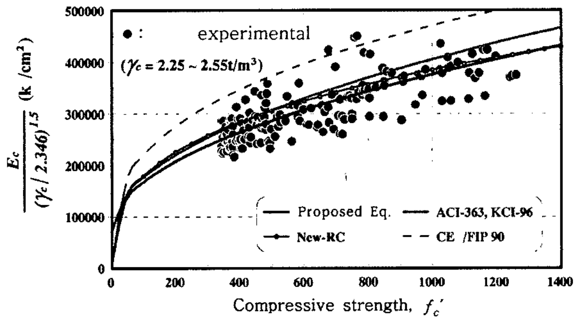


**Fig. 8** Comparison of the proposed prediction equation for elastic modulus of concrete to existing prediction equations.

for elastic modulus of domestic high- and ultra high-strength concrete.

2) Relational equations between dry unit weight of concrete and compressive strength (Eq. (9)) and between dry unit weight of hardened concrete and the unit weight of (fresh) concrete at the time of mixing (Eq. (10)) are proposed. The analysis indicated that the unit weight tended to increase smoothly as the compressive strength increased. Moreover, it is determined from the analysis that the unit weight to be used for designing concrete structure in the range of compressive strength between 400~1,000 kgf/cm$^2$ should be about 2.37~2.45 tf/m$^3$.

3) A new elastic modulus equation (Eq. (12)) appropriate for domestic high- and ultra high-strength concrete is proposed. It uses the unit weight and compressive strength as the main variables and predicts lower elastic modulus values compared to existing prediction equations. It is based on values derived from many domestic experiments. Thus, its use is deemed appropriate for domestic situation.

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