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STRENGTH DEVELOPMENT OF HIGH-PERFORMANCE CONCRETE USING NANOSILICA

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ABSTRACT

The mechanical properties and durability of high-performance concrete can be improved with the use of nanosilica. Still, the relationship between the content of nanosilica and the mechanical properties of concrete needs to be verified in order to develop of compressive strength that can be applied to any concrete mixture. The aim of this study was to develop mathematical equations that account for the relationship among concrete's compressive strength, the modulus of elasticity with its compressive strength, and the modulus of rupture with its compressive strength. The specimens of f'c80-NS10-SF5 and f'c100-NS10-SF5 were fabricated by mixing natural nanosilica and silica fume, and those of f'c80-NSHD5-SF5 and f'c100-NSHD5-SF5 were fabricated by mixing commercial nanosilica and silica fume as the main composition materials, with the addition of other materials. The compressive strength and indirect tensile strength of the concrete were tested at 1, 3, 7, and 28 days. New mathematical models of generalized compressive strength against concrete age were empirically developed and then validated in order to derive new insights into the substitution of natural nanosilica for commercial nanosilica in the civil-engineering industry.

Keywords: Compressive strength; High-performance concrete; Modulus of elasticity; Modulus of rupture; Nanosilica

1. INTRODUCTION

Commercial nanosilica (NSHD) has been widely used as a construction material by the civil engineering industry in many countries; however, the application of nanosilica originating from the local natural sand of Indonesia must be verified and validated. Many studies have reported that nanosilica can be used to improve the mechanical properties and durability of concrete in many areas (Sanchez & Sobolev, 2010; Schoepfer & Maji, 2009; Collepardi et al., 2004). Despite the abundance of silica sand in many areas of Indonesia, the use of this natural sand to make concrete mix has been widely used as a filler and widely incorporated into the concrete surface of reactive nanosilica. The use of natural nanosilica in the civil-engineering industry must be tested for its mechanical properties, such as compressive strength, modulus of elasticity, and modulus of rupture. Many studies have been reported that the use of either nanosilica or silica fume can affect the strength development of high-performance concrete (HPC). Magee and Olek (2000) collected and analysed approximately 260 HPC mixtures proposed in that more than 200 publications to show that the use of relatively low water content (150–175 kg/m^3) and high binder content (350–500 kg/m^3) is very common for HPC. The most

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commonly used fine and coarse aggregate ranges for HPC are 700–800 kg/m^3 and 1000–1100 kg/m^3, respectively, and they look like conventional concrete. The use of two different mixtures of local sand to make HPC can result in compressive strengths of 80 and 100 MPa (Jonbi et al., 2012).

Even though NSHD and NS have been widely used in the civil-engineering industry, the development of empirical models for the testing and validation of the use of these materials in HPC needs to be verified. The objectives of this study are: (1) to conduct experiments using NS and NSHD in order to collect the data on of compressive strength, the modulus of elasticity, and the modulus of rupture needed for of regression analysis; and (2) to develop empirical equations for compressive strength, modulus of elasticity, and the modulus of rupture that can be used to assess the strength development of HPC and to derive insights into the future use of NS in the civil-engineering industry.

2. METHODOLOGY

2.1. Specimen Preparation and Testing

The NSHD used in this study originally coming from the industrial waste of semiconductor factories, was obtained from a local distributor in Jakarta city, and had a particle size of 20–30 nm. The NS used in this study, which originated from the local natural sand, was processed using a polishing liquid milling technology and had a particle size of 36–80 nm. The concrete specimens were fabricated according to the optimal mix proportion and have been described by Jonbi et al. (2012). The specimens of f'_c100-NS10-SF5 and f'c100-NSHD5-SF5 were used to develop the empirical equations representing the compressive strength of NS and NSHD, respectively. The empirical equations representing both the modulus of elasticity and modulus of rupture for NS and NSHD were developed on the basis of the specimens of f'_c80-NSHD5-SF5 and f'_c80-NS10-SF5, respectively. The specimens of f'_c80-NSHD5-SF5 and f'_c80-NS10-SF5 were used to test the NS and NSHD samples because the equipment had a limited ability to read the strengths of both the modulus of elasticity and modulus of rupture. Three samples were used to test the compressive strength at 1, 3, 7, and 28 days. Four experiments were carried out in triplicate to test the modulus of elasticity and modulus of rupture at day 28. All the tests utilized the universal testing machine with data- logging system.

2.2. Specimen Composition

The composition materials used to fabricate the HPC samples are presented in Table 1. The specimens of f'_c80-NS10-SF5 and f'_c80-NSHD5-SF5 were fabricated using the same composition materials, but with the addition of the content of NS and NSHD. Likewise, the specimens of f'_c 100-NS10-SF5 and f'_c100-NSHD5-SF5 were fabricated using the same composition materials, but with the addition of the content of NS and NSHD. The compositions of cement type I, silica fume 5%, binder, fine aggregate, and superplasticizier 0.6% x binder used in the specimens of f'_c80-NS10-SF5 and f'_c80-NSHD5-SF5 were used lower than those used in the specimens of f'_c 100-NS10-SF5 and f'_c100-NSHD5-SF5. The air/binder composition was the same in all specimens. The coarse-aggregate composition used in the specimens of f'_c80-NS10-SF5 and f'_c80-NSHD5-SF5 was used higher than that used in the specimens of f'_c 100-NS10-SF5 and f'_c100-NSHD5-SF5.

2.3. Model Development

This study developed a model for predicting the compressive strength of HPC for the specimens of f'_c100-NS10-SF5 and f'_c100-NSHD5-SF5 by combining the empirical model constructed from the experimental data with the model proposed by the Comité Euro-International du Béton. This may yield new models for assessing the performance of HPC to be used in the future in the civil-engineering industry. An analysis of both the elastic modulus and modulus of rupture was carried out in order to compare the results of this study to those of previous studies.

Then, appropriate models can be developed, with either minor or no modifications of the existing models.

Table 1 Composition materials used to fabricate the specimens of f'_c80-NS10-SF5, f'_c80-NSHD5-SF5, f'_c 100-NS10-SF5, and f'_c100-NSHD5-SF5 (Jonbi et al., 2012)

Type of material	A	B	C	D
Cement type I (kg/m^3)	600	600	800	800
Silica fume 5% (kg/m^3)	30	30	40	40
Binder (kg/m^3)	630	630	840	840
Air/binder (kg/m^3)	0,23	0.23	0.23	0.23
Fine aggregate (kg/m^3)	603	603	637	637
Coarse aggregate (kg/m^3)	1119	1119	1091	1091
Superplasticizier 0.6% × binder (L)	3.78	3.78	5.04	5.04
NS 10% (kg/m^3)	63	-	84	-
NSHD 5% (kg/m^3)	-	31.5	-	42

Note: A = f'_c80-NS10-SF5, B = f'_c80-NSHD5-SF5, C = f'_c 100-NS10-SF5, and D = f'_c100-NSHD5-SF5.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength for the Specimen of *f*'c100-NS10-SF5

The plot (Figure 1) of compressive strength (y) versus age of the concrete (x) for the specimen of f'_c100-NS10-SF5 gives us an empirical model of $y = a\ (1\text{-}e^{bx})$, where a (= 125.4) is the regression coefficient (in MPa) and b (= 0.205) is constant (in d^{-1}).

The empirical equation obtained from Figure 1 can be used to determine the compressive strength for the HPC of using NS10% with a composition of 84 kg/m^3 (see Table 1) because an R^2 value of 0.905 has been verified by the regression analysis. Thus, it can be written as

$$y = 125.4\ (1 - e^{0.205x}) \tag{1}$$

where y is compressive strength of the concrete (in MPa) and x is age of the concrete (in d).

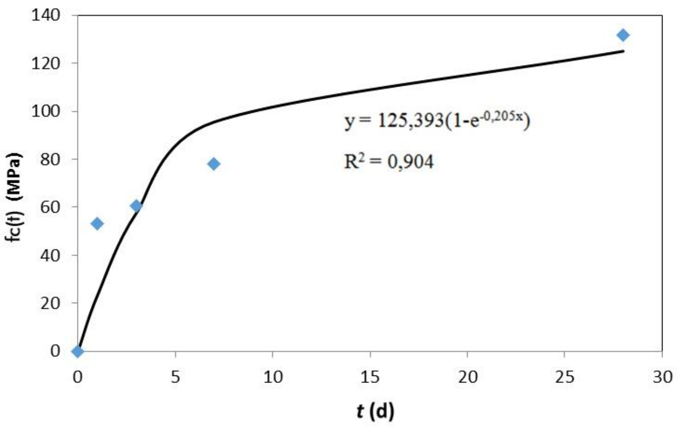

Figure 1 Relationship between compressive strength and age of the concrete for the specimen of f'_c100-NS10-SF5

By substituting the compressive strength of the concrete at 28 days with y replaced by $f_c(t)$ and x replaced by t, Equation 1 can be rewritten as

$$f_c(t) = (1 - e^{-0.205t})\ f_c(28) \tag{2}$$

where $f_c(t)$ is compressive strength of the concrete at t day (in MPa), t is age of the concrete (in d), and $f_c(28)$ is the constant representing the compressive strength of the concrete at 28 days of the experiment (in MPa).

The value of $f_c(t)$ at t day as described by the Comité Euro-International du Béton in the CEB-FIB model code (CEB-FIP, 1999) can be determined using the following equation:

$$f_c(t) = \beta_{cc}(t)\, f_c(28) \tag{3}$$

where $f_c(t)$ is compressive strength of the concrete at t day (in MPa). $\beta_{cc}(t)$ can then be used to replace $(1–e^{-0.205t})$ and is defined as:

$$\beta_{cc}(t) = e^{S[1-(\frac{28}{t})^{p}]} \tag{4}$$

Combining Equation 3 and Equation 4 yields the following equation:

$$f_c(t) = e^{S[1-(\frac{28}{t})^{p}]} f_c(28). \tag{5}$$

According to the Comité Euro-International du Béton (CEB-FIP, 1999): (1) when an S value is equal to 0.20, this represents a rapid-hardening high-strength cement; (2) when an S value is equal to 0.25, this represents a normal and rapid-hardening cement; and (3) when an S value is equal to 0.38, this represents a slow-hardening cement. The value of p as a constant is always equal to 0.5.

Using Equation 5 permits us to calculate the value of S at 1, 3, and 7 days, because the compressive strength of the concrete at 1, 3, 7, and 28 days has been verified by the experiments. Every S value can then be tested to validate the most appropriate formula, which has a value of R^2 close to one.

At day 1 of the experiment, the value of S was found to be 0.378, and this represents slow-hardening cement. A plot of $f_c(t)$ versus t yielding an R^2 value of 0.973 gives the following expression that:

$$f_c(t) = e^{0.378[1-(\frac{28}{t})^{0.5}]} f_c(28) \tag{6}$$

Using the experimental data permits us to validate whether Equation 6 can be used to determine the compressive strength of HPC. Because an R^2 value of 0.973 has been verified by a regression analysis of the experimental data, Equation 6 can be used as long as another formula gives an R^2 value below 0.973.

At day 3 of the experiment, an S value of 0.250 was found, and this represents normal and rapid-hardening cement. A plot of $f_c(t)$ versus t gives an R^2 value of 0.952 and yields the following expression:

$$f_c(t) = e^{0.250[1-(\frac{28}{t})^{0.5}]} f_c(28). \tag{7}$$

Because the R^2 value of 0.952 obtained from the plot of $f_c(t)$ versus t according to Equation 7 is lower than that of 0.973 obtained from plotting $f_c(t)$ versus t according to Equation 6, the use of Equation 7 to determine the compressive strength of HPC may be less accurate.

It was verified in this study that the S value is 0.359 at day 7 of the experiment, and this may represent slow-hardening cement. A plot of $f_c(t)$ versus t can give a R^2 value of 0.979 with its mathematical formula, as follows:

$$f_c(t) = e^{0.359[1-(\frac{28}{t})^{0.5}]} f_c(28) \tag{8}$$

Because the R^2 value obtained from plotting $f_c(t)$ versus t according to eqn (8) is much closer to 1 as compared with that obtained from both Equation 6 and Equation 7, Equation 8 may be the most appropriate equation for calculating the compressive strength of HPC for the specimen of f'_c100-NS10-SF5.

3.2. Compressive Strength for the Specimen of *f*'c100-NSHD5-SF5

The plot (Figure 2) of $f_c(t)$ versus t for the specimen of f'_c100-NSHD5-SF5, yielding an R^2 value of 0.894, gives the following expression:

$$f_c(\mathrm{t}) = 131.4\ (1\text{-}e^{0.338t}) \tag{9}$$

where a constant of 131.4 MPa represents $f_c(28)$ as the compressive strength of the HPC at day 28 of the experiment.

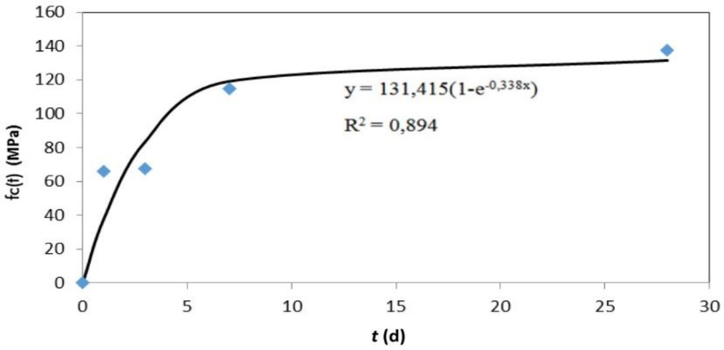

Figure 2 Plot of $f_c(t)$ versus t for the specimen of f'_c100-NSHD5-SF5

At day 1 of the experiment, the value of S was 0.39, and this represents slow-hardening cement. The plot of $f_c(t)$ versus t, yielding an R^2 value of 0.979, gives the following expression:

$$f_c(t) = e^{0.39\left[1-\left(\frac{28}{t}\right)^{0.5}\right]} f_c(28). \tag{10}$$

Using the experimental data for the specimen of f'_c100-NSHD5-SF5 permits us to validate whether Equation 10 can be used to determine the compressive strength of HPC. Because an R^2 value of 0.979 has been verified by a regression analysis of the experimental data, Equation 10 can be used as long as another formula gives an R^2 value below 0.979.

At day 3 of the experiment, an S value of 0.25 was verified to represent normal and rapid-hardening cement. The plot of $f_c(t)$ versus t gives an R^2 value of 0.968 and yields the following expression:

$$f_c(t) = e^{0.25\left[1-\left(\frac{28}{t}\right)^{0.5}\right]} f_c(28). \tag{11}$$

Because the R^2 value of 0.968 obtained from a plot of $f_c(t)$ versus t according to Equation 11 is lower than that of 0.979 obtained from plotting $f_c(t)$ versus t according to Equation 10, the use of Equation 11 to determine the compressive strength of HPC for the specimen of f'_c100-NSHD5-SF5 may be less accurate.

In this study, it was verified that the S value is 0.39 at day 7 of the experiment, and this may represent slow-hardening cement. The plot of $f_c(t)$ versus t gives an R^2 value of 0.976 with the same mathematical formula expressed by Equation 10. Because of the R^2 value 0.976 is very close to that of 0.979, both of which were obtained from Equation 10, and is higher than that of 0.968, obtained from Equation 11, Equation 10 may be the most appropriate equation for calculating the compressive strength of HPC for the specimen of f'_c100-NSHD5-SF5.

3.3. Elastic Modulus for the Specimens of *f*'c80-NSHD5-SF5 and *f*'c80-NS10-SF5

The equations derived from experimental investigations can be used to predict the modulus of elasticity (E_c). Only the specimens of f'_c80-NSHD5-SF5 and f'_c80-NS10-SF5 can be used to determine the value of E_c, because the elastic modulus of the equipment is continuously increased to reach a maximum compression strength below 80 MPa. In this study, the determination of the E_c value for every experiment was carried out using the appropriate formulas at the age of 28 days. Because many studies have reported E_c values such as ACI 318M-05, with its formula of $E_{c\,=}$ 4730 $\sqrt{f'c}$; ACI 363R-92, with its formula of $E_{c\,=}$ 3200 $\sqrt{f'c}$ 6900; Ahmad and Shah (1985), with their formula of E_c = 8000 $(f'c)^{0,325}$; Norges (1992), with the formula of E_c = 9500 $(f'c)^{0,3}$; Gardner (2001), with the formula of E_c = 3500 + 4300 $\sqrt{f'c}$; CEB-FIP, with its formula of E_c = 21500 $(\frac{f'c}{10})^{\frac{1}{3}}$); and Nassif et al. (2005) with their formula of E_c = 4000 $\sqrt{f'c}$ - the E_c values obtained in this study can be compared to those obtained in previous studies, as shown in Table 2.

Table 2 Comparison of E_c values obtained in this study to those obtained in previous studies

	CE	AC05	AC92	AS	N	G	CF	NE
f'_c	E_c (MPa)							
Experiments for the specimen of f'_c80-NSHD5-SF5								
70.76	32852	39787.3	34826.8	31934.8	34092.1	39670.3	41275.7	33646.8
66.63	32942	38609.7	34000.2	31317.2	33483.0	38599.7	40457.1	32650.9
68.65	32904	39190.6	34408.0	31622.6	33784.4	39127.8	40861.9	33142.1
68.72	32843	39210.5	34422.0	31633.1	33794.7	39145.9	40875.8	33159.0
68.69	32885	39201.7	34415.8	31628.5	33790.1	39137.9	40869.7	33151.6
Difference in E_c		19.21	4.65	-3.82	2.75	19.01	24.28	0.81
Experiments for the specimen of f'_c80-NS10-SF5								
66.28	31944	38508.1	33929.0	31263.6	33430.2	38507.4	40386.2	32565.0
55.47	27344	35227.1	31626.0	29505.3	31690.8	35524.7	38058.3	29790.4
64.70	30634	38046.4	33604.9	31019.4	33189.1	38087.6	40062.7	32174.5
57.07	28654	35732.6	31980.8	29779.9	31962.9	35984.2	38421.5	30217.9
60.88	29644	36905.9	32804.3	30411.8	32588.5	37050.8	39258.0	31210.0
Difference in E_c		24.50	10.66	2.59	9.93	24.99	32.43	5.28

Note: CE is the values of E_c obtained in this study, AC05 is the values of E_c reported by ACI 318M-05, AC92 is the values of E_c reported by ACI 363R-92, AS is the values of E_c reported by Ahmad and Shah (1985), *N* is the values of E_c reported by Norges (1992), *G* is the values of E_c reported by Gardner (2001), *CF* is the values of E_c reported by CEB-FIP, and *NE* is the values of E_c reported by Nassif et al. (2005).

Because the differences in E_c values are very small when comparing the results of this study with those reported in the studies by Ahmad and Shah (1985) and Nassif et al. (2005), new formulas can be proposed for predicting E_c values, and they can expressed by the following two equations:

$$E_c = 3900 \sqrt{f'c} \tag{12}$$

Equation 12 could reasonably be used for the prediction of the E_c value for the specimen of f'_c 80-NSHD5-SF5.

$$E_c = 3800 \sqrt{f'c} \tag{13}$$

Equation 13 could be used to predict the value of E_c for the specimens of f'_c80-NS10 -SF5.

A curve plotting E_c versus *t*, as shown in Figure 3, could be used to compare the E_c value pursuant to *t* for the specimens of f'_c80-NSHD5-SF5 and f'_c80 NS10-SF5. Empirical evidence shows that they are quite similar. This means that NS can replace NSHD in the fabrication of HPC in the civil-engineering industry.

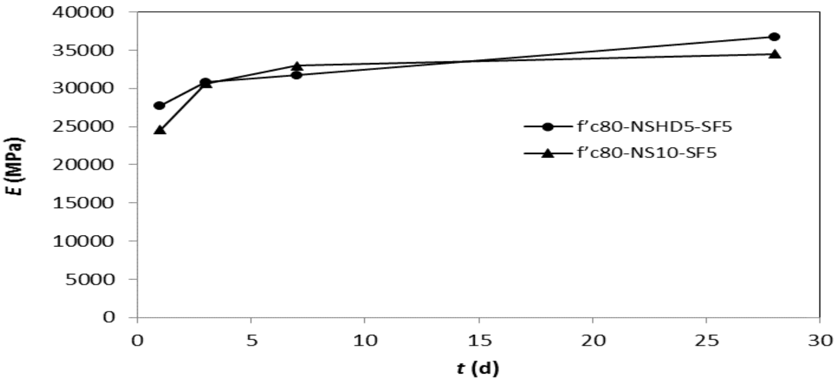

Figure 3 Plot of E_c versus *t* for the specimen of f'_c80-NSHD5-SF5 and for that of f'_c80 NS10-SF5

3.4. Modulus of Rupture for the Specimens of *f*'c80-NSHD5-SF5 and *f*'c80-NS10-SF5

The development of a formula for calculating the modulus of rupture (f_r) for the specimens of *f*'c80-NSHD5-SF5 and *f*'c80-NS10-SF5 should take into account the formulas that have been proposed by ACI 318M-05 ($f_r = 0.62\sqrt{f'c}$) Khalil (2002) and Issa (2008) ($f_r = 0.75\sqrt{f'c}$), and Carrasquillo et al. (1981) ($f_r = 0.97\sqrt{f'c}$). In all these formulas, the modulus of rupture ranges from 0.62 $\sqrt{f'c}$ to 0.97 $\sqrt{f'c}$. Every researcher has a unique perspective on and reasoned argument for the development of a formula for determining the modulus rupture for HPC. Zia et al. (1993) and Russell et al. (2006) suggested that the use of the formula proposed by ACI 318M-05 would be useful for predicting the modulus of rupture pursuant to the compressive strength, which is still applicable before reaching a maximum value of 103 MPa. Carrasquillo et al. (1981) suggested that the modulus of rupture can be predicted even when the compressive strength is higher than 83 MPa. The values of f_r obtained in the present study can be compared to those obtained in previous studies, as shown in Table 3.

Table 3 Comparison of f_r values obtained in this study to those obtained in previous studies

	CE	ACI05	KI	C
f'_c		f_r (MPa)		
The experiments for the specimen of f'_c80-NSHD5-SF5				
70.76	5.04	5.22	6.31	8.16
66.63	5.38	5.06	6.12	7.92
68.65	5.40	5.14	6.21	8.04
68.72	5.37	5.14	6.22	8.04
68.69	5.30	5.14	6.22	8.04
The difference in % of f_r		-3.0	17.40	51.70
The experiments for the specimen of f'_c80-NS10-SF5				
66.28	5.01	5.05	6.11	7.90
55.47	4.95	4.62	5.95	7.22
64.70	5.21	4.99	6.03	7.80
57.07	5.10	4.68	5.67	7.33
60.88	5.07	4.84	5.94	7.56
The difference in % of f_r		-4.5	17.16	49.00

Note: CE is the values of f_r obtained in this study, AC05 is the values of f_r reported by ACI 318M-05, KI is the values of f_r reported by Khalil (2002) and Issa (2008), and C is the values of f_r reported by Carrasquillo et al. (1981).

The values of f_r obtained in this study are very close to those reported by ACI (2005), Zia et al. (1993), and Russell et al. (2006). Therefore, the following equation, proposed by ACI (2005), could be a reliable predictor of the values of f_r for the specimens of f'c80-NSHD5-SF5 and f'c80-NS10-SF5:

$$f_r = 0.62\sqrt{f'c} \tag{14}$$

Equation 14 permits us to calculate the modulus of rupture for HPC to be used in the future in the civil-engineering industry in Indonesia.

4. CONCLUSION

This study performed a testable prediction of the outcome of scientific processes based on the analysis of the experimental data obtained from four different types of HPC. In conclusion, the formula $f_c(t) = e^{0.359[1-(\frac{28}{t})^{0.5}]} f_c(28)$ can be used to predict compressive strength for the specimen of f'_c100-NS10-SF5, and the formula $f_c(t) = e^{0.39[1-(\frac{28}{t})^{0.5}]} f_c(28)$ can be used to predict compressive strength for the specimen of f'_c100-NSHD5-SF5. The formulas $E_c = 3900\sqrt{f'c}$ and $E_c = 3800\sqrt{f'c}$ can be used to predict the modulus of elasticity for the specimens of f'_c80-NSHD5-SF5 and f'_c80-NS10-SF5, respectively. The formula $f_r = 0.62\sqrt{f'c}$ can be used to predict the modulus of elasticity for the specimens of f'c80-NSHD5-SF5 and f'c80-NS10-SF5. All the models have been validated by experimental data and represent contributions to the civil- engineering industry in Indonesia.

5. REFERENCES

ACI Committee 318., 2005. *Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05):An ACI Standard.* American Concrete Institue, Farmington Hills, Michigan, USA

ACI Committee 363., 1984. State of the Art Report on High-Strength Concrete. *Journal Proceedings*, Volume 81(4), pp. 364–411

Ahmad, S.H., Shah, S.P., 1985. Behavior of Hoop Confined Concrete under High Strain Rates. *Journal Proceedings*, Volume 84(5), pp. 634–647

Carrasquillo, R.L., Nilson, A.H., Slate, F., 1981. Properties of High Strength Concrete Subject to Short Term Loads. *ACI Structural Journal*, Volume 78(3), pp. 171–178

Collepardi, M., Collepardi, S., Troli, R., Skarp, U., 2004. Combination of Silica Fume, Fly Ash and Amorphous Nanosilica in Superplatisized High-performance Concretes. *In*: Proceedings of First International Conference on Innovative Materials and Technologies for Constructions and Rehabilitation, Lecce, Italy, pp. 459–468

Comite Euro-International du Beton (CEB-FIP)., 1999. *Structural Concrete Textbook*. Volume 3, 1st edn., CEB-FIP Model Code 1999, Swiss Federal Institute of Technology Lausanne, Lausanne, Switzerland

Gardner, N.J., Lockman, M., 2001. Design Provision for Drying Shrinkage and Creep of Normal Strength Concrete. *ACI Material Journal*, Volume 98(2), pp. 159–167

Issa, M.A., Khalil, A.A., Islam, S., Krauss, P.D, 2008. Mechanical Properties and Durability of High Performance Concrete for Bridge Decks. *Precast/Prestress Concrete Institute Journal*, Volume 53(4), pp. 108–130

Jonbi, J., Hariandja, B., Imran, I., Pane, I., 2012. Development of Mix Proportion for High-performance Concrete using Locally Available Ingredients based on Compressive Strength and Durability. *Applied Mechanics and Materials*, Volume 175–177, pp. 1067–1071

Khalil, A.M., 2002. *Strength and Durability Assessment of High Performance Concrete*. PhD Thesis, University of Illinois, Chicago IL, USA

Magee, B.J., Olek, J., 2000. High-performance Concrete for Highway Structures: A Generic Review of Definition, Mixture Proportion and Performance Levels. *In*: Proceedings of CI/FHWA/FIB International Symposium on High Performance Concrete, Chicago IL, USA

Nassif, H.H., Najm, H., Suksawang, N., 2005. Effect of Pozzolanic Materials and Curing Methods on the Elastic Modulus of HPC. *Cement and Concrete Composites*, Volume 27(6), pp. 661–670

Russel, H.G., Miller, R.A., Ozylidirim, H.C., Tadros, M.K., 2006. *Compilation and Evaluation of Results from High-performance Concrete Bridge Projects*, Volume 1: Final Report, Henry G. Russel, Inc. Glenview, IL, USA

Sanchez, F., Sobolev, K., 2010. Nanotechnology in Concrete: A Review. *Construction and Building Materials*, Volume 24(11), pp. 2060–2071

Schoepter, J., Maji, A., 2009, An Investigation into the Effect of Silicon Dioxide Particle Size on the Strength of Concrete. *ACI Special Publication*, Volume 267, pp. 45–58

Zia, P., Ahmad, S.H., Leming, M.L., Schemmel, J.J., Elliot, R.P., 1993. *Mechanical Behavior of High Performance Concrete*, Volume 5: Very High Strength Concrete. Strategic Highway Research Program, National Research Council, Washington, D.C., USA