# MECHANICAL PROPERTIES OF CONCRETE WITH VARIOUS WATER-CEMENT RATIO AFTER HIGH TEMPERATURE EXPOSURE

**M.I. Retno Susilorini[1], Budi Eko Afrianto[2], Ary Suryo Wibowo[2]**

## ABSTRACT

Concrete building safety of fire is better than other building materials such as wood, plastic, and steel, because it is incombustible and emitting no toxic fumes during high temperature exposure. However, the deterioration of concrete because of high temperature exposure will reduce the concrete strength. Mechanical properties such as compressive strength and modulus of elasticity are absolutely corrupted during and after the heating process. This paper aims to investigate mechanical properties of concrete (especially compressive strength and modulus of elasticity) with various water-cement ratio after concrete suffered by high temperature exposure of 500$^o$C.

This research conducted experimental method and analytical method. The experimental method produced concrete specimens with specifications: (1) specimen's dimension is 150 mm x 300 mm concrete cylinder; (2) compressive strength design, $f'_c$ = 22.5 MPa; (3) water-cement ratio variation = 0.4, 0.5, and 0.6. All specimens are cured in water for 28 days. Some specimens were heated for 1 hour with high temperature of 500$^o$C in huge furnace, and the others that become specimen-control were unheated. All specimens, heated and unheated, were evaluated by compressive test. Experimental data was analyzed to get compressive strength and modulus of elasticity values. The analytical method aims to calculate modulus of elasticity of concrete from some codes and to verify the experimental results. The modulus elasticity of concrete is calculated by 3 expressions: (1) SNI 03-2847-1992 (which is the same as ACI 318-99 section 8.5.1), (2) ACI 318-95 section 8.5.1, and (3) CEB-FIP Model Code 1990 Section 2.1.4.2.

The experimental and analytical results found that: (1) The unheated specimens with water-cement ratio of 0.4 have the greatest value of compressive strength, while the unheated specimens with water-cement ratio of 0.5 gets the greatest value of modulus of elasticity. The greatest value of compressive strength of heated specimens provided by specimens with water-cement ratio of 0.5, while the heated specimens with water-cement ratio of 0.4 gets the greatest value of modulus of elasticity, (2) All heated specimens lose their strength at high temperature of 500$^o$C, (3) The analytical result shows that modulus of elasticity calculated by expression III has greater values compares to expression I and II, but there is only little difference value among those expressions, and (4)The variation of water-cement ratio of 0.5 becomes the optimum value.

**Keywords :** Concrete, Compressive strength, Modulus of elasticity, Water-cement ratio, High temperature.

## ABSTRAK

Keamanan bangunan yang terbuat dari beton lebih baik dibandingkan bangunan yang terbuat dari material lain misalnya kayu, plastik, baja, karena beton merupakan bahan yang tidak mudah terbakar dan tidak mengandung racun selama terkena suhu tinggi. Meskipun demikian, kerusakan beton akibat mengalami suhu tinggi tersebut dapat mengurangi kekuatan beton. Sifat-sifat mekanis beton seperti kuat tekan dan modulus elastisitas dipastikan akan mengalami penurunan selama dan setelah proses pemanasan. Tulisan ini bertujuan untuk meneliti sifat-sifat mekanis beton setelah mengalami pemanasan suhu tinggi sebesar 500$^o$C.

Penelitian ini mengimplementasikan metode eksperimental dan analitis. Metode eksperimental menggunakan benda uji dengan spesifikasi: (1) benda uji adalah silinder beton berdimensi 150 mm x 300 mm; (2) kuat tekan rencana, $f'_c$ = 22.5 MPa; (3) variasi faktor air-semen = 0.4, 0.5, and 0.6.

Semua spesimen dirawat selama 28 hari. Sebagian spesimen dipanaskan selama 1 jam dengan suhu 500$^o$C dalam tungku pembakaran yang besar, sementara sebagin yang lain berlaku sebagai spesimen kontrol yang tidak dipanaskan. Seluruh spesimen, dengan maupun tanpa pemanasan, dievaluasi melalui uji tekan. Data eksperimental dianalisis guna mendapatkan nilai kuat tekan dan modulus elastisitas. Metode analitis bertujuan untuk menghitung besarnya modulus elastisitas menurut beberapa peraturan serta melakukan verifikasi dengan hasil uji eksperimental. Modulus elastisitas beton dihitung berdasarkan beberapa persamaan yaitu: (1) SNI 03-2847-1992 (sama dengan ACI 318-99 sub-bab 8.5.1), (2) ACI 318-95 sub-bab 8.5.1, dan (3) CEB-FIP Model Code 1990 sub-bab 2.1.4.2.

Hasil uji eksperimental dan perhitungan analitis menunjukkan bahwa: (1) Spesimen tanpa pemanasan dengan faktor air-semen 0.4 memiliki nilai kuat tekan terbesar, sedangkan spesimen tanpa pemanasan dengan faktor air-semen 0.5 memiliki nilai modulus elastisitas terbesar. Nilai kuat tekan spesimen dengan pemanasan ditunjukkan oleh spesimen dengan faktor air-semen 0.5, sedangkan spesimen dengan pemanasan dengan faktor air-semen 0.4 menunjukkan nilai modulus elastisitas terbesar, (2) Semua spesimen yang mengalami pemanasan dengan suhu 500$^o$C kehilangan kekuatannya, (3) Hasil perhitungan analitis menunjukkan bahwa nilai modulus elastisitas yang dihitung dengan persamaan III memiliki nilai yang lebih besar dibandingkan persamaan I dan II, namun hanya terdapat sedikit saja selisih antara nilai-nilai tersebut, serta (4) Variasi faktor air-semen 0.5 merupakan nilai optimal.

**Kata kunci :** Beton, Kuat tekan, Modulus elastisitas, Faktor air-semen, Suhu tinggi.

## 1. INTRODUCTION

Concrete is used widely as an engineering material around the world. The wide application of concrete basically supported by 3 reasons (Mehta and Monteiro, 1993): (1) concrete is water-resistant material, (2) concrete is easy to be shaped and formed, and (3) concrete is cheap and readily available material on the job. According to the advantage and widely used of concrete, it can be understood that safety and durability of concrete becomes a great consideration until nowadays. Concrete building safety of fire is better than other building materials such as wood, plastic, and steel, because it is incombustible and emitting no toxic fumes during high temperature exposure (Mehta and Monteiro, 1993; Neville, 1999). However, the deterioration of concrete because of high temperature exposure will reduce the concrete strength. Therefore, degradation of concrete's mechanical properties after high temperature exposure were reviewed by some researchers (Shetty, 1982; Neville, 1999).

The strength of concrete decreasing in high temperature exposure becomes an important consideration in designing concrete structures. Mechanical properties such as compressive strength and modulus of elasticity are absolutely corrupted during and after the heating process. It should be noted that concrete consists of multi phases: cement paste phase and aggregate phase, and also transition zone phase (Mehta and Monteiro, 1993). Those multi phases are very much influenced by heating process and getting fragile, even failure or collapse after high temperature exposure.

Mechanical properties of concrete performance should become a fundamental factor in concrete structures design. Therefore, this paper aims to investigate the mechanical properties of concrete (especially compressive strength and modulus of elasticity) with various water-cement ratio after concrete suffered by high temperature exposure of 500$^o$C.

## 2. METHODOLOGY OF RESEARCH

This research conducted by 2 methods of research which are experimental method and analytical methods. The experimental method were producing of concrete specimens with specifications: (1) specimen's dimension is 150 mm x 300 mm concrete cylinder; (2) compressive strength design, $f'_c$ = 22.5 MPa; (3) water-cement ratio variations were 0.4, 0.5, and 0.6. All specimens were cured in the water both for 28 days. Some specimens were heated for 1 hour with high temperature of 500$^o$C in huge furnace, and the others for specimen-control were unheated. All specimens, heated and unheated, were evaluated using compressive test. Experimental data was analyzed to obtain compressive strength and modulus of elasticity values.

The analytical method aims to calculate the modulus of elasticity of concrete from some codes and to verify the experimental results. There are some expressions for modulus of elasticity of concrete established by some codes, for examples SNI code, ACI code, and CEB-FIP code. In this paper, modulus elasticity of concrete is calculated by 3 expressions. The expressions are SNI 03-2847-1992 (which is the same as ACI 318-99 section 8.5.1) as defined by equation (1), ACI 318-95 section 8.5.1 as defined by equation (2), and CEB-FIP Model Code 1990 Section 2.1.4.2 as defined by equation (3).

According to SNI 03-2847-1992 (ACI 318-99 section 8.5.1), modulus elasticity of concrete is expressed by:

$$E_c = W_c^{1.5} 0.043 \sqrt{f_c^{'}} \quad (1)$$

According to ACI 318-95 section 8.5.1, modulus elasticity of concrete is expressed by:

$$E_c = 33 W_c^{1.5} \sqrt{f_c^{'}} \quad (2)$$

According to CEB-FIP Model Code 1990 Section 2.1.4.2, modulus elasticity of concrete is expressed by:

$$E_c = 2.15x10^4 \left( \frac{f_{cm}}{10} \right)^{1/3} \quad (3)$$

where: $f'_c$ = compressive strength of concrete (MPa)
P = maximum load (N)
A = specimen section area (mm$^2$)

$E_c$ = modulus of elasticity of concrete at 28 days (MPa)
$W_c$ = content weight (kg/m$^3$)
$f_{cm}$ = average compressive strength at 28 days (MPa)

## 3. LITERATURE'S REVIEW

### 3.1 Compressive Strength and Modulus Elasticity of Concrete

Compressive strength is the most important property of concrete that is widely used to determine whether qualitative or quantitative of other hardened concrete properties (Shetty, 1982; Neville, 1999). The failure of concrete under compressive load is complicated because of it suffers a mixture of crushing and shear failure (Shetty, 1982). Resisting the failure phenomenon, concrete generates cohesion and internal friction. Those cohesion and internal friction is engaged to one or more parameters such as water-cement ratio, air entrainment, cement type, mixing water, curing condition, and testing parameters (Mehta and Monteiro, 1993).

Among those parameters mentioned above, water-cement ratio may take an important role because it affects the porosity between concrete phases (Mehta and Monteiro, 1993). The weakening of matrix caused by increasing porosity and water-cement ratio will decrease the strength of concrete. It should be noticed that the strength of concrete depends upon the strength of cement paste. Shetty (1982) emphasized that the strength of paste increases with cement content and decreases with air and water content.

Another concrete property that it must be taken into account is modulus of elasticity. Modulus of elasticity is a measure of concrete stiffness (Carino, et. al, 1994). It is also noted by Tomosawa and Noguchi (2006) that modulus of elasticity of concrete is a fundamental factor in determining the deformation of building and its members, especially the design of member that is subjected to flexure. The modulus elasticity is static modulus elasticity that is generally used to distinct the dynamic modulus elasticity. Dynamic modulus of elasticity is characterized by a very small instantaneous strain given by initial tangent modulus (Mehta and Monteiro, 1993). Static modulus elasticity of concrete is defined by the slope of stress-strain curve for concrete under uniaxial loading. According to Mehta and Monteiro (1993), there are 3 methods for computing the modulus elasticity: (1) tangent modulus, (2) secant modulus, and (3) chord modulus. The tangent modulus is given by a line drawn tangent to stress-strain curve at any point on the curve, while the secant modulus is drawn from the origin to a point corresponding to a 40% stress of failure load, and the chord modulus is drawn between two points on the stress-strain curve. A standard test method for measurement of the modulus elasticity of concrete and Poisson's ratio is given by ASTM C 469.

### 3.2 Concrete Performance Due to High Temperature Exposure

The advantage of concrete application compares to steel as building material is its fire resistance (Kützing, 2006). Concrete is generally used for encasing steel as fire protection (Shetty, 1982). Obviously, the structural capacity of concrete will decrease under high temperature exposure but resists the collapse until 3 hours (Kützing, 2006).

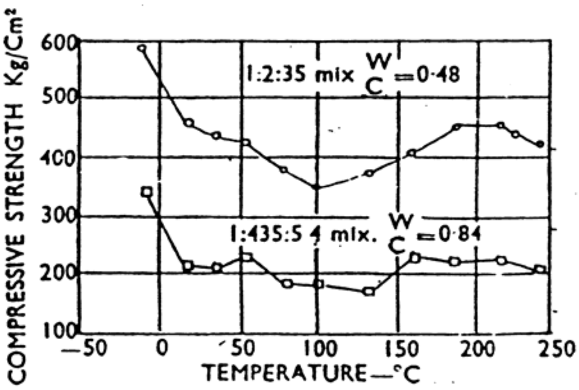
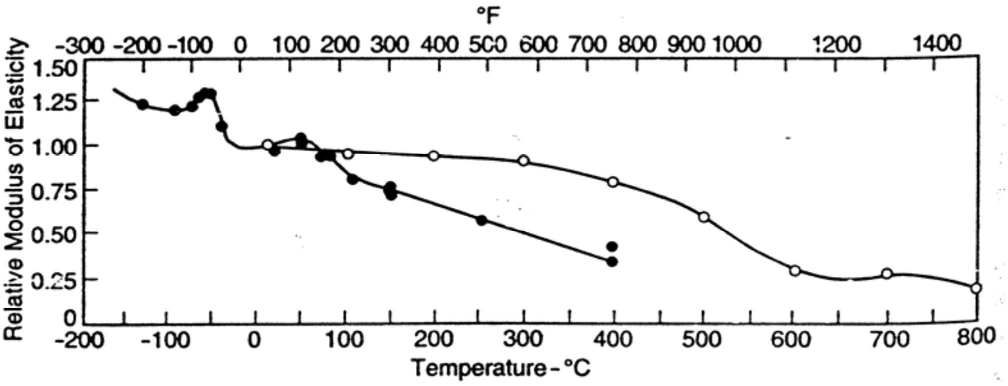



**Figure 1.** Compressive strength of concrete after various temperatures heating (Shetty, 1982)

Mechanical concrete properties are affected significantly by thermal exposure (Pan and Carino, 2006). Abrams (1971, cited in Neville, 1999) investigated that siliceous aggregate concrete will loose its strength at temperature above 430°C (810°F) greater than concrete with limestone or lightweight aggregate. This difference will be vanished when the temperature reaches about 800°C (1470°F). Figure 1 describes the effect of various temperatures on the compressive strength of concrete with 2 series of water-cement ratio variation (Shetty, 1982). It is shown by Figure 1 that the bigger value of water-cement ratio, the bigger decrease of compressive strength will be. Pan and Carino (2006) found that concrete lose its compressive strength 10-20% when heated by 300°C and 60-75% when heated by 600°C, and so does the modulus of elasticity.

High temperature exposure will also give strong influence to modulus of elasticity of concrete (Neville, 1999). While temperature ranged by 50°C - 800°C (120°F - 1470°F), water can be expelled from concrete, emerges a progressive decrease of modulus of elasticity of concrete. It is also emphasized by Jumppanen (1989) that temperature of 800°C is the starting point for modulus of elasticity of concrete decrease. The influence of temperature on modulus of elasticity of concrete is described by Figure 2 below. This Figure 2 is based on Marechal (1972, cited in Neville) and also Castillo and Durani (1990, cited in Neville, 1999).




**Note:**
○ = reference from Castillo-Durani (1990)
● = reference from Marechal (1972)

**Figure 2.** The influence of temperature on modulus of elasticity of concrete based on Marechal and Castillo-Durani (Neville, 1999)

Sumardi (2000) noted that chemical reaction will be introduced when concrete is under high temperature exposure. When temperature ranged by 100$^{o}$C - 500$^{o}$C, water evaporates from the concrete pores. Dehydration of Portlandite, $Ca(OH)_2$ change to CaO occurs when temperature reaches 400$^{o}$C - 600$^{o}$C. Decomposition of C-S-H (cement hydrat compound) to become its oxides emerges in temperature range of 600$^{o}$C - 900$^{o}$C. Finally, when the temperature exceeds 900$^{o}$C, decomposition of cement hydrate compound and minerals occurs and forms a new ceramic chain.

The color change of concrete made with siliceous or limestone aggregate after high temperature performance has been reviewed by Zoldners (1960, cited in Neville, 1999) few decades ago. While the temperature ranged by 300$^{o}$C - 600$^{o}$C, the concrete color is pink or red, then goes into grey up to 900$^{o}$C, and buff above 900$^{o}$C.

## 4. RESULT AND DISCUSSION

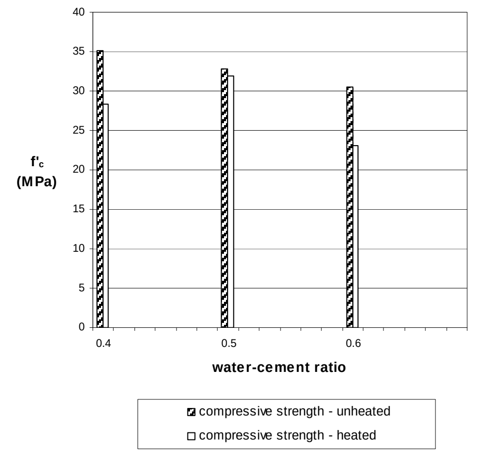
Experimental results described in Table 1 and Table 2, and also Figure 3.a and Figure 3.b. Table 1 and Figure 3.a show that unheated specimens with water-cement ratio of 0.4 have the greatest value of compressive strength compared to water-cement ratio of 0.5 and 0.6. The unheated specimens with water-cement ratio of 0.5 have the greatest value of modulus of elasticity as shown in Table 2 and Figure 3.b. The greatest value of compressive strength of heated specimens provided by specimens with water-cement ratio of 0.5 compared to water-cement ratio of 0.4 and 0.6 as shown by Table 1 and Figure 3.a. The heated specimens with water-cement ratio of 0.4 have the greatest value of modulus of elasticity as shown in Table 2 and Figure 3.b.

The compressive strength of heated specimens decrease from unheated specimens, 19.09% for specimens with water-cement ratio of 0.4, 3.02% for specimens with water-cement ratio of 0.5, and 24.15% for specimens with water-cement ratio of 0.6. The modulus of elasticity of heated specimens decrease from unheated specimens, 20.79% for specimens with water-cement ratio of 0.4, 45.18% for specimens with water-cement ratio of 0.5, and 11.79% for specimens with water-cement ratio of 0.6.

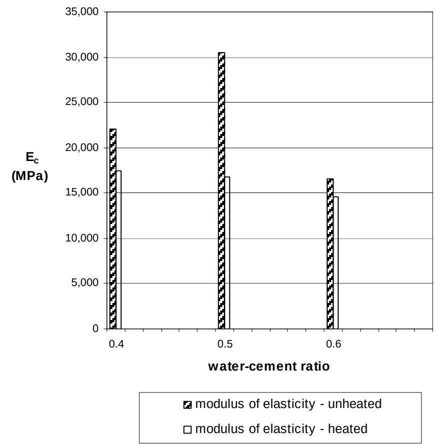
The analytical result of modulus of elasticity is shown in Table 3 which verifies the experimental result successfully. The experimental results of compressive strength and content weight become input data for the calculation. Modulus of elasticity calculated by expression III has greater values compares to expression I and II, but there is only little difference value among those expressions.

It is clearly shown by the experimental results that all heated specimens lose their strength at high temperature of 500$^{o}$C. There are micro cracks along the specimen's surface caused by water evaporating from the concrete pores (Sumardi, 2000). The concrete porosity will increase and dehydration of Portlandite, $Ca(OH)_2$ change to CaO was occurred.

The variation of water-cement ratio of 0.5 becomes the optimum value because of some reasons. It has the greatest value of compressive strength, before and after heated. It also has greater value of modulus of elasticity before high temperature exposure and reducing its value in small value after heated. Analytical result confirmed that variation of water-cement ratio of 0.5 has the closest value to experimental result.




(a). Compressive strength




(b). Modulus of elasticity

**Figure 3.** Experimental Results of unheated and heated specimen (Primary data of Afrianto and Wibowo, 2002)

**Table 1.** Experimental result of compressive strength of unheated and heated specimen (Primary data of Afrianto and Wibowo, 2002)

| WATER CEMENT RATIO | UNHEATED | | | HEATED | | |
|---|---|---|---|---|---|---|
| | SPECIMEN CODE | COMPRESSIVE STRENGTH f'$_c$ (MPa) | AVERAGE COMPRESSIVE STRENGTH f'$_c$ (MPa) | SPESIMEN CODE | COMPRESSIVE STRENGTH f'$_c$ (MPa) | AVERAGE COMPRESSIVE STRENGTH f'$_c$ (MPa) |
| 0.4 | A1-1 | 28.860 | 35.085 | A2-1 | 31.689 | 28.389 |
| | A1-2 | 38.480 | | A2-2 | 22.069 | |
| | A1-3 | 38.480 | | A2-3 | 29.426 | |
| | A1-4 | 33.387 | | A2-4 | 28.86 | |
| | A1-5 | 35.651 | | A2-5 | 28.294 | |
| | A1-6 | 35.651 | | A2-6 | 29.992 | |
| 0.5 | B1-1 | 31.690 | 32.869 | B2-1 | 32.821 | 31.878 |
| | B1-2 | 31.972 | | B2-2 | 31.255 | |
| | B1-3 | 34.519 | | B2-3 | 30.558 | |
| | B1-4 | 32.538 | | B2-4 | 28.294 | |
| | B1-5 | 35.368 | | B2-5 | 33.953 | |
| | B1-6 | 31.124 | | B2-6 | 33.387 | |
| 0.6 | C1-1 | 32.255 | 30.463 | C2-1 | 20.372 | 23.107 |
| | C1-2 | 32.255 | | C2-2 | 18.108 | |
| | C1-3 | 32.821 | | C2-3 | 22.635 | |
| | C1-4 | 31.125 | | C2-4 | 29.426 | |
| | C1-5 | 26.031 | | C2-5 | 23.201 | |
| | C1-6 | 28.294 | | C2-6 | 24.899 | |

**Table 2.** Experimental result of modulus of elasticity of unheated and heated specimen (Primary data of Afrianto and Wibowo, 2002)

| WATER CEMENT RATIO | UNHEATED | | | HEATED | | |
|---|---|---|---|---|---|---|
| | SPECIMEN CODE | MODULUS OF ELASTICITY $E_c$ (MPa) | AVERAGE MODULUS OF ELASTICITY $E_c$ (MPa) | SPESIMEN CODE | MODULUS OF ELASTICITY $E_c$ (MPa) | AVERAGE MODULUS OF ELASTICITY $E_c$ (MPa) |
| 0.4 | A1-1 | 25,625.131 | 22,085.722 | A2-1 | 16,074.426 | 17,494.928 |
| | A1-2 | 21,063.934 | | A2-2 | 24,599.088 | |
| | A1-3 | 17,030.209 | | A2-3 | 18,748.468 | |
| | A1-4 | 17,670.979 | | A2-4 | 11,363.514 | |
| | A1-5 | 22,336.743 | | A2-5 | 19,169.543 | |
| | A1-6 | 28,787.338 | | A2-6 | 15,014.531 | |
| 0.5 | B1-1 | 31,667.348 | 30,531.267 | B2-1 | 15,461.835 | 16,737.451 |
| | B1-2 | 27,368.830 | | B2-2 | 18,298.155 | |
| | B1-3 | 48,593.398 | | B2-3 | 9,158.661 | |
| | B1-4 | 21,010.309 | | B2-4 | 22,061.640 | |
| | B1-5 | 32,525.190 | | B2-5 | 14,214.827 | |
| | B1-6 | 22,022.524 | | B2-6 | 21,229.585 | |
| 0.6 | C1-1 | 24,950.558 | 16,602.333 | C2-1 | 13,992.421 | 14,644.652 |
| | C1-2 | 17,162.501 | | C2-2 | 14,192.233 | |
| | C1-3 | 16,571.895 | | C2-3 | 11,147.662 | |
| | C1-4 | 16,868.290 | | C2-4 | 18,732.003 | |
| | C1-5 | 7,841.218 | | C2-5 | 9,944.134 | |
| | C1-6 | 16,219.535 | | C2-6 | 19,859.461 | |

**Table 3.** Analytical result of modulus of elasticity calculation from 3 expressions (Primary data of Afrianto and Wibowo, 2002)

| SPECIMEN CODE | MODULUS OF ELASTICITY $E_c$ (MPa) | | | | |
|---|---|---|---|---|---|
| | UNHEATED EXPERIMENTAL RESULT | HEATED EXPERIMENTAL RESULT | EXPRESSION I | EXPRESSION II | EXPRESSION III |
| A1 | 22,085.722 | | 30,229.22 | 30,102.90 | 32,669.68 |
| B1 | 30,531.267 | | 29,036.31 | 28,914.98 | 31,966.75 |
| C1 | 16,602.333 | | 27,270.80 | 27,156.85 | 31,167.19 |
| A2 | | 17,494.928 | 25,630.24 | 25,523.15 | 30,442.89 |
| B2 | | 16,737.451 | 26,675.82 | 26,564.36 | 31,642.36 |
| C2 | | 14,644.652 | 22,543.46 | 22,449.26 | 28,424.00 |

**Note:**
Expression I = SNI 03-2847-1992 (= ACI 318-99 section 8.5.1)
Expression II = ACI 318-95 section 8.5.1
Expression III = CEB-FIP Model Code 1990 Section 2.1.4.2

## 5. CONCLUSIONS

The experimental and analytical results meet conclusions as follows:

1. The unheated specimens with water-cement ratio of 0.4 have the greatest value of compressive strength, while the unheated specimens with water-cement ratio of 0.5 gets the greatest value of modulus of elasticity. The greatest value of compressive strength of heated specimens provided by specimens with water-cement ratio of 0.5, while the heated specimens with water-cement ratio of 0.4 gets the greatest value of modulus of elasticity.
2. All heated specimens lose their strength at high temperature of 500$^o$C. The compressive strength of heated specimens decrease from unheated specimens, 19.09% for specimens with water-cement ratio of 0.4, 3.02% for specimens with water-cement ratio of 0.5, and 24.15% for specimens with water-cement ratio of 0.6. The modulus of elasticity of heated specimens decrease from unheated specimens, 20.79% for specimens with water-cement ratio of 0.4, 45.18% for specimens with water-cement ratio of 0.5, and 11.79% for specimens with water-cement ratio of 0.6.
3. The analytical result shows that modulus of elasticity calculated by expression III has greater values compared to expression I and II, but there is only small difference value among those expressions.
4. The variation of water-cement ratio of 0.5 becomes the optimum value because of some reasons. It has the greatest value of compressive strength, before and after heated. It also has greater value of modulus of elasticity before high temperature exposure and reducing

its value in small value after heated. Analytical result confirmed that variation of water-cement ratio of 0.5 has the closest value to experimental result.

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[1] **M.I. Retno Susilorini**, Lecturer, Study Program of Civil Engineering, Faculty of Engineering, Soegijapranata Catholic University, Jl. Pawiyatan Luhur IV/1, Bendan Dhuwur, Semarang 50234, susilorini@unika.ac.id

[2] **Budi Eko Afrianto**, **Ary Suryo Wibowo**, Alumnus, Study Program of Civil Engineering, Faculty of Engineering, Soegijapranata Catholic University, Jl. Pawiyatan Luhur IV/1, Bendan Dhuwur, Semarang 50234.