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Article

Correlation between Destructive and Non-destructive Characteristics of Pumice and Scoria Lightweight Concretes

Hendro Suseno[a,*], **Ming Narto Wijaya**[b], **and Ananda Insan Firdausy**[c]

Department of Civil Engineering, Faculty of Engineering, Brawijaya University, Jl. MT Haryono 167 Malang 65145, Indonesia
E-mail: [a,*]hendros@ub.ac.id (Corresponding author), [b]mingnw@ub.ac.id, [c]nandafirdausy@ub.ac.id

Abstract. This study presents empirical correlations between destructive and non-destructive characteristics of structural lightweight concrete utilizing Medium-K basaltic andesitic pumice and scoria collected from Kelud Volcano, Indonesia. The non-destructive characteristics comprised the rebound number (N) obtained by Schmidt's Hammer test and the pulse velocity (V) obtained by the Ultrasonic Pulse Velocity test. The destructive characteristics were the compressive strength and modulus of elasticity from compressive test, while the tensile strength included splitting tensile strength as well as modulus of rupture from splitting tensile and bending tests. The correlations were determined using simple regression analysis which included linear, quadratic, power and exponential equations. Furthermore, the SonReb method, i.e. multiple regression analysis with linier and power forms of combination of rebound number and pulse velocity, was proposed for comparison. For pumice and scoria lightweight concrete, the simple regression results showed that all destructive characteristics were expressed by the power equation to the rebound number as well as the pulse velocity. This was indicated by coefficients of determination R^2 which were the largest compared to the other three equations. However, the results of SonReb method with power form, indicated that the coefficients of determination R^2 were greater than the individual regression results so that their formulas provided more reliable results.

Keywords: Destructive and non-destructive characteristics, correlation, lightweight concrete, pumice, scoria.

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1. Introduction

Structural lightweight concrete constitutes a lightweight concrete where the equilibrium density is practically about 1680 kg/m^3 to 1920 kg/m^3 and the compressive strength at 28 days is equal to and greater than 17 MPa [1]. The reduction of density is about 25% to 30% lower than normalweight concrete [2], therefore, structural dimensions decrease due to reduced dead loads and the overall cost also decreases significantly. One way to obtain it, is to use artificial lightweight aggregates such as expanded clay and fly ash or natural lightweight aggregates which include pumice and scoria [3]. These lightweight aggregates contain cellular pores in their structures so that they are relatively low. Aggregates in structural lightweight concrete can be a combination of normal fine aggregates such as river sand and both natural or artificial lightweight coarse aggregate [4]. The use of pumice and scoria as natural lightweight coarse aggregates is very beneficial, because of its abundance in volcanic areas. Similarly, these lightweight coarse aggregates produce structural lightweight concretes that may be cheaper, save more energy and greener than artificial coarse aggregates. The neccesity of high thermal energy in the sintering process of artificial lightweight coarse aggregate [2, 5] can be eliminated, and air pollution during manufacture can also be reduced. However, they have very varied characteristics [6] that their use in lightweight concrete requires strict considerations. Such as the selection of both volcanic rocks so that their characteristics fulfill the requirements and their qualities are optimal.

Kelud volcano, located in East Java, is one of the sources of high quality pumice and scoria in Indonesia. Each explosive eruption, it always ejects Medium-K basaltic andesitic pumice and scoria simultaneously [7, 8, 9]. Therefore, these vesicular rocks have unique characteristics compared to common similar rocks. They only differ in color, but the chemical composition, mineralogy and texture are not significantly different. The structures are dominated by relatively high pores and amorphous glass microstructure that they remain light but rather brittle. This may be due to the combination of andesitic and basaltic minerals, so that pumice with a pale white color becomes heavier, denser and harder while scoria with a black color becomes lighter, less dense and less hard. The specific gravities of both vesicular rocks are greater than one such that they immediately submerge in water, while the characteristics of scoria are slightly higher than that of pumice. In the form of coarse aggregates, they also meet the physical characteristics requirements of lightweight coarse aggregate [10, 11]. However, the mechanical characteristics expressed by abrasions with LA machine are quite high. This indicates that their compressive strengths are also not high caused by the high porosity as well as the amorphous glass microstructure which composes the solid masses.

The utilization of pumice and scoria for coarse aggregates of structural lightweight concrete has been carried out by several researchers. The absorption and absorption rate of these coarse aggregates are high [12] which are caused by their high porosities, so that they absorb water excessively during concrete mixing and the workability becomes low. Therefore, the lightweight coarse aggregates need to be presoaked before concrete mixing or added water reducing admixtures. Although the productions are rather complicated and take a long time, the results can overcome workability problems and the structural lightweight concrete criteria are fulfilled. The studies on the application of pumice as well as scoria on this lightweight concrete have been conducted previously. Such as pumice and scoria from Papua New Guinea [12, 13], pumice and scoria from Turkey [14, 15] and pumice and scoria from Yaman [16]. The lightweight concrete with scoria aggregate from Saudi Arabia added by water reducing and mineral agents was studied by [17]. The lightweight concrete with pumice aggregate from Iran as replacement of Leca artificial aggregate was studied by [18]. Meanwhile, the lightweight concretes with typical pumice and scoria aggregates from Indonesia were studied by [10, 11]. These studies produced structural lightweight concretes which produce 20% to 25% reduction of density.

Compressive strength is a mechanical characteristic of hardened concrete used as a general index of strength because the test is the easiest to perform [5, 19]. Furthermore, other mechanical characteristics, such as modulus of elasticity, tensile strength and modulus of rupture are considered to be directly related to it. The static modulus of elasticity is the slope of the stress-strain relationship and is the stiffness of the material, because this relationship is non-linear, the chord modulus of elasticity is recommended [5]. Tensile strength and modulus of rupture are used to control the deflection and crack width of reinforced concrete structures at service loads [20]. In general, these three destructive characteristics are proportional to the compressive strength, they increase simultaneously for increasing the compressive strength [5, 6]. The surface hardness of concrete is used to predict the compressive strength or dynamic modulus of elasticity of the specimen and its actual structure [21]. The dynamic modulus of elasticity is the modulus of elasticity due to longitudinal vibrations at natural frequencies [22] and can also be determined based on the ultrasonic pulse velocity [23]. The testing characteristics of hardened concrete are carried out in both destructive and non-destructive conditions [6, 24]. Destructive testing is a test conducted until destruction occurs [5] so it requires a certain specimen, it must be conducted in a laboratory and the results take a long time. Non-destructive testing is a test that is carried out without destruction [20, 24] so that it can be carried out on both the specimen and the actual structure, the results can be obtained immediately and used to predict the compressive strength and modulus of elasticity of normal concrete or lightweight concrete [25, 26].

The non-destructive testing commonly used in quality control, is the determination of compressive strength based on the rebound number of Schmidt's Hammer on its surface [27]. Or the determination of compressive strength and dynamic modulus of elasticity based on the ultrasonic pulse velocity through it [28]. For normal and lightweight concretes, the rebound number is proportional to the compressive strength and modulus of rupture [21] whereas for normal concrete, this rebound number is also proportional to the modulus of elasticity [6]. In addition, the pulse velocity is also proportional to the compressive strength of normal concrete [23]. However, the results of both non-destructive test are not reliable [19] and one way to overcome them, is to combine these testing results, namely SonReb Method which provides more accurate results [29]. For normal concrete, the compressive strength is proportional to the combination of rebound number and pulse velocity [6].

The destructive characteristics of hardened concrete as mentioned previously, are needed for the design of reinforced concrete structures [19, 30] and also for quality control purposes [6]. A good prediction for compressive strength, for example, provides a significant impact to the quality of structures and this prediction can be applied to new structures and restoration of buildings [31]. These characteristics can be obtained quickly by predicting them using non-destructive characteristics [24]. The modulus of elasticity of the coarse aggregate is influenced by its porosity, but to simplify the estimation, generally the density of concrete is only used [5, 6]. The regression model to predict it, is a power function of the density and the root of compressive strength [30, 32]. To predict the tensile strength as well as the modulus of rupture, the power or root function of the compressive strength is used [33, 34]. The empirical correlation of compressive strength with rebound number is commonly expressed in linear, exponential, logarithmic or exponential regressions [6, 24, 35]. Meanwhile, the empirical correlation between dynamic modulus of elasticity and pulse velocity is expressed by linear or power regressions [6, 19]. Two simple combinations proposed by SonReb Method, are a linear form and power form of rebound number and pulse velocity. However, the power form provided more reliable results for predicting the previous destructive characteristics of concrete. This power form is very simple and by transforming into logarithmic form, the solution can be obtained easily by the linear multiple regression analysis [36, 37]. For normal concrete, the combination of results of these non-destructive tests in the power form, provided a more accurate prediction of compressive strength than that of individual tests [38].

The empirical correlation between the destructive and non-destructive characteristics of lightweight concrete using natural porcelanite from Iraq as coarse aggregates, was investigated by [25]. The results showed that the compressive strength and static modulus of elasticity were expressed by the power fuction of pulse velocity. The empirical correlation between destructive and non-destructive characteristics of lightweight concrete using crushed thermo stone from Iraq as coarse aggregates, was investigated by [26]. The result showed that the compressive strength was expressed by the linear function of the rebound number and the exponential function of the pulse velocity. The empirical correlation of the destructive characteristics of lightweight concrete using Medium-K basaltic andesitic pumice and scoria were studied by [39]. The result showed that the modulus of elasticity was also expressed by the power function of density and the root of compressive strength, while the splitting tensile strength and the modulus of rupture were expressed by the power functions of compressive strength. The empirical correlation between the destructive and non-destructive characteristics of lightweight concrete using scoria from Cameron as coarse aggregates, was studied by [40]. The result of SonReb method showed that compressive strength was expressed by a linear combination of the rebound number and the pulse velocity, however this result was poor when compared to normal concrete as control.

Meanwhile, the empirical correlation between destructive and non-destructive characteristics for pumice and scoria lightweight concretes has not been widely carried out, even though application studies on structural elements have been carried out. For example, reinforced pumice lightweight concrete beams [41, 42], reinforced scoria lightweight concrete beams [43] and pumice and scoria lightweight concrete one-way slabs [44]. Taking into account these developments as well as the random physical properties of the pumice and scoria, it is very important to obtain precise and rapid mechanical properties so that the results are reliable. The purpose of this study is to estimate the probable destructive properties including compressive strength, chord modulus of elasticity, splitting tensile strength and modulus of rupture with non-destructive characteristics including the rebound number of Schmidt's Hammer and ultrasonic pulse velocity. The proportion of the lightweight concrete mixture is designed with a varied target of compressive strength so that the evaluation can be carried out accurately and thoroughly. From this research, it is obtained simple empirical formulas that may be used practically on reinforced pumice and scoria lightweight concrete designs as well as for quality control insitu.

2. Experimental Methods

2.1. Materials

The lightweight coarse aggregates constituted typical pumice and scoria mentioned previously and collected from Putih River which located in Kelud volcano southern slope, East Java, Indonesia. The maximum grain size was 19 mm and their gradations include four grain sizes which were designed to fulfill the requirements described by ASTM C330-04 [45]. The weight percentages consisted of 38% retained in the 12.5 mm sieve, 32% in the 9.5 mm sieve, 25% in the No. 4 sieve and 5% in the No. 8 sieve such that produced fineness modulus of 6.65. Meanwhile, the normal coarse aggregate of local crushed stone with similar gradation was used as a control. Photographs of pumice, scoria and four grain sizes of the design gradation are presented by Fig. 1. The physical characteristics of coarse aggregates were tested according to ASTM C 127-01 [46] and the results are presented in Table 1. The fine aggregate was river sand obtained from Kelud volcano eruptive deposit with maximum grain size of 4.75 mm. The result of sieving test showed that its gradation met the requirements as described by ASTM C330-04 [45] which produced fineness modulus of 2.64. The characteristics of fine aggregate were tested in accordance with ASTM C 128-01 [47] and the results are also presented in Table 1. Portland Cement Composite (PCC) commonly used for construction in the region at that time, was used as the substitute for Ordinary Portland Cement (OPC), while clean water was used to produce binders.

Fig. 1. Four grains sizes of design gradation: a. Pumice and b. Scoria.

Table 1. Characteristics of fine and coarse aggregates.

Physical characteristic	Typical aggregates			
	Sand	Pumice	Scoria	Crushed stone
Oven dry density (kg/m^3)	1463.47	787.96	850.12	1383.83
Bulk specific gravity	2.53	1.51	1.60	2.70
24 hours absorption (%)	1.77	18.05	16.08	1.51
Abrasion by LA machine (%)	-	58.85	56.44	17.53
Fineness modulus	2.64	6.65	6.65	6.65

Table 2. Result of concrete mix design.

Group	Label mixture	Specified compressive strength (MPa)	Mix proportion per 1 m^3 of volume (kg)			
			PCC	Water	Sand	Coarse Aggregates
A	PLCF1	18	324.00	186.42	796.82	558.23
	PLCF2	20	340.00	193.81	797.44	541.74
	PLCF3	24	382.00	185.77	765.48	559.49
	PLCF4	28	414.00	192.69	760.93	540.43
	PLCF5	30	430.00	190.07	739.80	555.70
B	SLCF1	18	324.00	179.55	826.68	584.81
	SLCF2	20	340.00	175.92	818.02	588.61
	SLCF3	24	382.00	192.82	795.48	572.15
	SLCF4	28	414.00	172.90	778.31	592.41
	SLCF5	30	430.00	161.78	769.66	596.20
C	NCF3	24	311.23	202.80	855.70	975.27

2.2. Mix Design of Structural Concretes

The mix proportion of pumice and scoria lightweight concretes were designed by Volumetric Method described by ACI 211.2-98 (R04) [48]. Pumice lightweight concrete (PLCF) and scoria lightweight concrete (SLCF) were grouped in Group A and Group B. Each group included five mix proportions according to the specified compressive strength F1 = 18 MPa, F2 = 20 MPa, F3 = 24 MPa, F4 = 28 MPa, F5 = 30 MPa with the mean compressive strength as described by SNI 2847:2013 [49]. Meanwhile, Group C was the normalweight concrete (NCF) as control with the specified compressive strength of F3 = 24 MPa and the mix proportion designed in accordance with ACI 211.1-91 (R02) [50]. The slump values for the concrete mixture were taken account in the range of 50 mm to 70 mm and the air content was estimated about 2% to 3%. In this mix design, the lightweight coarse aggregates (CA) were weighed after presoaking them during 16 hours and draining to dry the surfaces and water proportions were based on the water content as well as the absorption of aggregates. The results are presented in Table 2, where the proportions of material were expressed by weight per 1 m^3 of volume.

2.3. Fresh and Hardened Concrete Characteristics

Before mixing, both pumice and scoria lightweight coarse aggregates were presoaked as mentioned before, meanwhile the normal coarse aggregate was simply washed and then dried. The concrete mixings were conducted using a mixer of 150 kg capacity. To determine the workability, the slump tests were carried out according to ASTM C 143M-03 [51]. The results were the mean of three specimens and are showed in Table 3. Cylindrical specimens of 150×300 mm were utilized for measuring densities of 1 day and 45 days. All internal compaction of specimens were performed carefully by a vibrator with 12 mm diameter of steel rod. Demolding for all specimens was carried out 24 hours after their castings. Curings for the physical characteristic tests were carried out by covering the specimens with wet burlap during 7 days until the test was carried out at 45 days. The testings at 45 days were performed to wait for the specimens to dry from the remaining water in the coarse aggregates due to previous presoaking. The similar size of cylindrical specimens were also used for the equilibrium density test in accordance with ASTM C567-00 [52]. The results constituted the mean of three specimens which are also showed in Table 3.

Table 3. Testing results of fresh and hardened concrete characteristics.

Group	Label	Slump value (mm)	Typical density (kg/m^3)			
			1 Day	45 Days	Oven dry	Equilibrium
A	PLCF1	60	1896.79	1821.59	1704.79	1754.79
	PLCF2	59	1903.15	1827.01	1709.40	1759.40
	PLCF3	60	1908.79	1835.42	1713.46	1763.46
	PLCF4	56	1913.42	1841.16	1720.26	1770.26
	PLCF5	55	1919.36	1850.99	1725.39	1775.39
B	SLCF1	61	1932.97	1854.33	1732.35	1782.35
	SLCF2	60	1936.13	1859.83	1734.94	1784.94
	SLCF3	58	1941.88	1865.81	1741.70	1791.70
	SLCF4	57	1947.62	1871.41	1747.57	1797.57
	SLCF5	57	1952.08	1878.82	1752.77	1802.77
C	NCF3	62	2354.05	2328.60	-	-

Table 4. Destructive characteristics of hardened concretes.

Group	Label	Compressive strength (MPa)	Chord modulus of elasticity (MPa)	Splitting tensile strength (MPa)	Modulus of rupture (MPa)
A	PLCF1	19.46	9894.97	1.71	3.17
	PLCF2	21.25	10975.95	1.79	3.43
	PLCF3	24.75	12958.85	2.02	3.81
	PLCF4	29.18	15350.40	2.27	4.15
	PLCF5	30.21	16036.81	2.38	4.46
B	SLCF1	19.88	10271.74	1.74	3.31
	SLCF2	21.16	11071.83	1.81	3.47
	SLCF3	24.84	12978.90	2.03	3.82
	SLCF4	29.70	16035.26	2.30	4.34
	SLCF5	31.50	16695.12	2.41	4.54
C	NCF3	24.84	19833.19	2.17	4.14

2.4. Destructive Characteristics of Hardened Concrete

Two types of specimens were used for the destructive characteristics testing, namely 150×300 mm cylinder and 100×100×400 mm prism. The cylinders were used for compressive test to determine the compressive strength and chord modulus of elasticity as well as for splitting tensile test to determine the splitting tensile strength, while the prisms were used for bending test to determine the modulus of rupture. Casting, compacting, demolding and curing were carried out as before, and all destructive testing were conducted on a compressive machine with 3000 kN capacity. The testings of compressive strength were in accordance with ASTM C 39M-03 [53], the static or chord modulus of elasticity were in accordance with ASTM C 469-02 [54], whereas the splitting tensile strength and bending tests were according to ASTM C 496M-04 [55] and ASTM C78-02 [56]. All the results were the mean of three specimens and are showed in Table 4. The photographs of destructive testing are presented by Fig. 2.

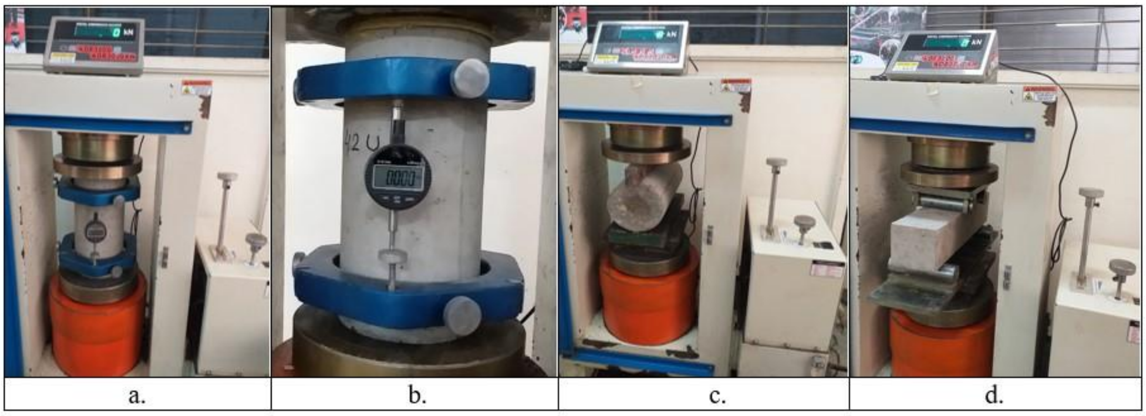

Fig. 2. Destructive testings: a. and b. Compressive test c. Splitting tensile test d. Bending test.

2.5. Non-destructive Characteristics of Hardened Concrete

The specimens for non-destructive characteristic testing, were the similar 150×300 mm cylinder used for destructive testing and were carried out before them. The rebound number was measured by the digital Schmidt Hammer tester in an upright down position and carried out according to ASTM C 805-02 [27]. The ultrasonic pulse velocity was a direct transmission which was measured by the Pundit's UPV set tester in a horizontal position and carried out according to ASTM C 597-02 [28]. The rebound number and pulse velocity were the mean of three specimens and their results are showed in Table 5. The photographs of non-destructive testing are presented by Fig. 3.

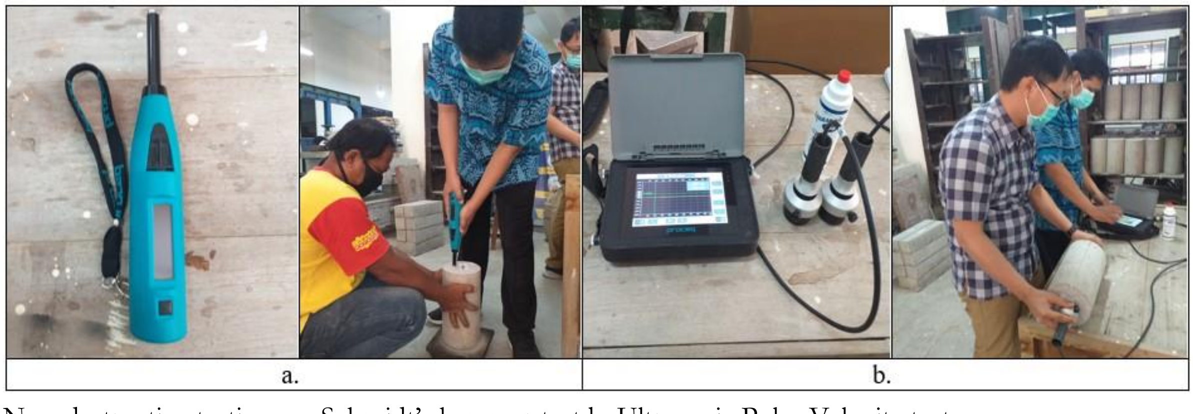

Fig. 3. Non-destructive testings: a. Schmidt's hammer test b. Ultrasonic Pulse Velocity test.

2.6. Correlations between Destructive and Non-Destructive Characteristics

In this study, the empirical correlations between destructive and non-destructive characteristics were evaluated for pumice and scoria lightweight concretes, respectively. The compressive strengths were expressed in functions of the rebound number and the pulse velocity. Both chord modulus of elasticity and two typical tensile strengths, i.e. splitting tensile strength as well as modulus of rupture, were also expressed in the similar way. The correlations were analyzed using simple regression which included four types of equation, namely linear, quadratic, power and exponential equations. Similarly, these correlations were also analyzed using multiple regression of the combination of rebound number and pulse velocity, i.e. SonReb method. However, in order to obtain simple formulas, especially for practical consideration, they were only analized for linear and power forms. Furthermore, for each type of equation and combination form analyzed, the coefficients of determination R^2 were evaluated and regression formulas that produce the largest coefficient of determination, were appropriately selected.

Table 5. Non-destructive Characteristics of Hardened Concrete.

Group	Label	Compressive strength (MPa)	Rebound number	Pulse velocity (m/s)
A	PLCF1	19.46	35.10	3516.67
	PLCF2	21.25	36.87	3583.33
	PLCF3	24.75	38.73	3701.33
	PLCF4	29.18	40.80	3807.33
	PLCF5	30.21	42.37	3876.33
B	SLCF1	19.88	36.13	3575.00
	SLCF2	21.16	36.63	3634.33
	SLCF3	24.84	39.30	3739.67
	SLCF4	29.70	42.40	3842.67
	SLCF5	31.50	43.07	3935.33
C	NCF3	24.84	40.17	3847.67

3. Results and Discussion

3.1. Lightweight Coarse Aggregate Characteristics

Table 1 indicates that the oven dry density for pumice and scoria lightweight coarse aggregate are lower than the control of crushed stone coarse aggregate. These coarse aggregates meet the requirements of lightweight coarse aggregate as stated by ASTM C-330-04 [45], which are less than 880 kg/m^3. Their specific gravities also meet the requirements as stated by SNI 03-2461-2002 [57], which are between 1.0 to 1.8 and are lower than the control. Their 24-hour absorptions are quite high, but they are still lower than that required by Indonesian stadard [57], i.e. 20%. However, their abrasions by LA Machine are relatively high and exceed the coarse aggregate requirement in accordance with ASTM C131-03 [58], i.e. 20% and are higher than the control. This may be due to the high porosity and amorphous glass microstructure contained in the solid masses of both lightweight coarse aggregate. It can also be seen that the physical characteristics of these typical lightweight coarse aggregates differ less significantly as stated by [10, 11].

3.2. Fresh and Hardened Concrete Characteristics

Table 3 indicates that the mean of the equilibrium density of pumice lightweight concrete is between 1754 kg/m^3 to 1776 kg/m^3 with standard deviation (SD) in the range of 18 kg/m^3 to 34 kg/m^3 and scoria lightweight concrete is between 1782 kg/m^3 to 1803 kg/m^3 with SD in the range of 29 kg/m^3 to 32 kg/m^3. These densities meet the requirement of structural lightweight concrete described by [1], i.e. about 1680 kg/m^3 to 1920 kg/m^3. The 45 days densities, for these lightweight concretes, are about 3.81% to 4.22% greater than the equilibrium densities. This shows that the drying of specimens has not been maximized and they need to be prolonged such that they approach the equilibrium densities. The density reduction to the normal concrete as control is 24.27% for pumice lightweight concrete whereas for scoria lightweight concrete is 23.06%. For these typical pumice and scoria lightweight concretes, it can be said that the equilibrium densities also differ less significantly as stated by [10, 11]. In addition, all slump values are in the range of 55 mm to 62 mm and meet the previously designed values so that the satisfactory workabilities were obtained.

3.3. Destructive Characteristics of Hardened Concrete

Table 4 shows that the mean of compressive strengths of pumice lightweight concrete meet the previous designed values with SD in the range of 0.34 MPa to 0.73 MPa. Similarly, for scoria lightweight concrete, they also meet the previous designed values with SD in the range of 0.36 MPa to 0.70 MPa. Meanwhile, the control also meet the previous designed values with SD is 0.54 MPa. The means of chord modulus of elasticity are between 9894 MPa to 16037 MPa with SD in the range of 158 MPa to 401 MPa for pumice lightweight concrete and 10271 MPa to 16696 MPa with SD in the range of 116 MPa to 420 MPa for scoria lightweight concrete. When compared to the control, the percentage of chord modulus of elasticity is 65.34% for pumice lightweight concrete whereas for scoria lightweight concrete is 65.44%. The means of splitting tensile strength are between 1.70 MPa to 2.39 MPa with SD in the range of 0.04 MPa to 0.10 MPa for pumice lightweight concrete and 1.73 MPa to 2.42 MPa with SD in the range of 0.02 MPa to 0.09 MPa for scoria lightweight concrete. When compared to the control, the percentage in splitting tensile strength is 93.10% for pumice lightweight concrete while for scoria lightweight concrete, it is 93.37%. The means of modulus of rupture are between 3.18 MPa to 4.47 MPa with SD in the range of 0.05 MPa to 0.10 MPa for pumice lightweight concrete and 3.30 MPa to 4.55 MPa with SD in the range of 0.07 MPa to 0.12 MPa for scoria lightweight concrete. When compared to the control, the percentage of the modulus of rupture for pumice lightweight concrete, is 92.07% and 92.15% for scoria lightweight concrete. These reductions may be also caused by the high porosity as well as the amorphous glass microsructure in the lightweight coarse aggregates. It can be seen that three mechanical characteristics of the typical pumice and scoria lightweight concretes are also proportional to the compressive strengths, they increase simultaneously for increasing the compressive strengths as stated previously by [5, 6, 39].

3.4. Non-destructive Characteristics of Hardened Concrete

Table 5 shows that the means of rebound number are between 35.00 to 42.40 with SD in the range of 0.64 to 0.90 for pumice lightweight concrete and 36.10 to 42.40 with SD in the range of 0.41 to 0.95 for scoria lightweight concrete. The means of pulse velocity are between 3516.60 m/s to 3876.34 m/s with SD in the range of 30.56 m/s to 58.09 m/s for pumice lightweight concrete and 3575.00 m/s to 3935.34 m/s with SD in the range of 34.33 m/s to 41.51 m/s for scoria lightweight concrete. It can be seen that the rebound number and pulse velocity of the typical pumice and scoria lightweight concretes are also proportional to the compressive strengths, they increase simultaneously for increasing the compressive strengths as stated by [6]. Thus, these non-destructive charaterisics are directly related to the modulus of elasticity, splitting tensile strength and modulus of rupture. From the pulse velocity obtained in both the lightweight concretes and the control, it can be said that their qualities are categorized as good because they are in the range of 3500 m/s to 4500 m/s [6, 19]. For pumice lightweight concrete, the rebound number is 96.43% compared to the control whereas for scoria lightweight concrete, it is 97.84%. Also, for pumice lightweight concrete, the pulse velocity is 96.20% compared to the control whereas for scoria lightweight concrete, it is 97.19%.

3.5. Correlations between Compressive Strength with Rebound Number and Pulse Velocity

Table 6 shows the result of the analysis of simple regression which comprises four types equation, i.e. linear, quadratic, power and exponential equations for pumice and scoria lightweight concretes. For pumice lightweight concrete, the empirical correlation between the compressive strength with the rebound number expressed by the power equation, provides the largest coefficient of determination. Similarly, this correlation with the pulse velocity expressed by the power equation, also provides the largest coefficient of determination. For scoria lightweight concrete, these correlations with the rebound number, as well as the pulse velocity which are also expressed by the power equation, provide the largest coefficients of determination. Thus, the empirical correlations between compressive strength and the rebound number, as well as the pulse velocity for pumice lightweight concrete are given by:

$$f_c^{'} = 0.0039 \ N^{2.3909} \tag{1}$$

$$f_c^{'} = 0.0752 \ V^{4.4313} \tag{2}$$

where the compressive strength $f_c^{'}$ is in MPa and the pulse velocity V is in km/s. Meanwhile, for scoria lightweight concrete, the empirical correlations are:

$$f_c^{'} = 0.0033 \ N^{2.4291} \tag{3}$$

$$f_c^{'} = 0.0394 \ V^{4.8892} \tag{4}$$

For pumice and scoria lightweight concretes, the correlations above are graphically presented by Fig. 4a for rebound number and Fig. 4b for pulse velocity.

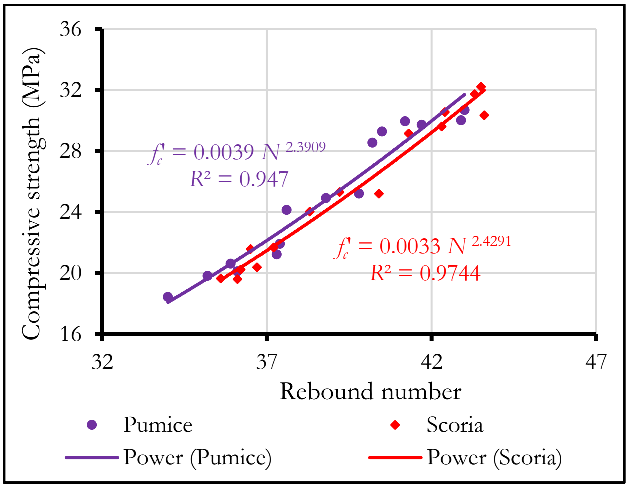

Fig. 4a. Correlation between compressive strength with rebound number.

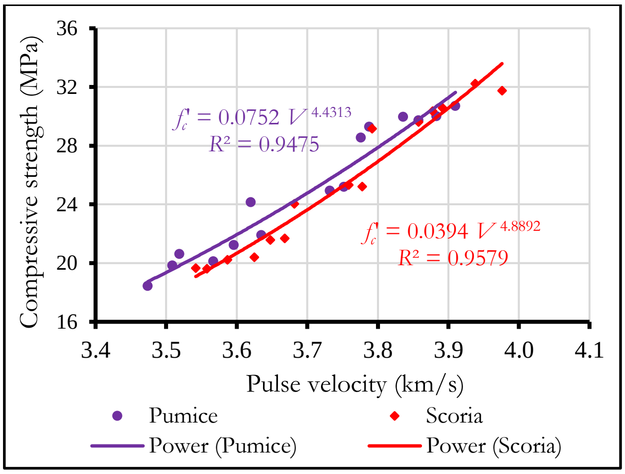

Fig. 4b. Correlation between compressive strength with pulse velocity.

Table 6. Results of the analysis of simple regression with four typical equations.

Group	ND Characteristic	Typical Equation	Formula	R^2
A	Rebound Number (N)	Linier	$f_c' = 1.5159\ N - 33.81$	0.9423
		Quadratic	$f_c' = -\ 0.0089\ N^2 + 2.2088\ N - 47.16$	0.9425
		Power	$f_c' = 0.0039\ N^{2.3909}$	0.9470
		Exponential	$f_c' = 2.2341\ e^{0.0619\ N}$	0.9442
	Pulse Velocity (V)	Linier	$f_c' = 29.437\ V - 83.862$	0.9458
		Quadratic	$f_c' = 4.0127\ V^2 - 29.437\ V - 83.862$	0.9460
		Power	$f_c' = 0.0752\ V^{4.4313}$	0.9475
		Exponential	$f_c' = 0.2904\ e^{1.2008\ V}$	0.9467
B	Rebound Number (N)	Linier	$f_c' = 1.5511\ N - 35.862$	0.9736
		Quadratic	$f_c' = -\ 0.0055\ N^2 + 1.9911\ N - 44.54$	0.9736
		Power	$f_c' = 0.0033\ N^{2.4291}$	0.9744
		Exponential	$f_c' = 2.215\ e^{0.0613\ N}$	0.9723
	Pulse Velocity (V)	Linier	$f_c' = 32.928\ V - 97.911$	0.9568
		Quadratic	$f_c' = 0.215\ V^2 + 31.314\ V - 94.888$	0.9568
		Power	$f_c' = 0.0394\ V^{4.8892}$	0.9579
		Exponential	$f_c' = 0.1898\ e^{1.3031\ V}$	0.9567

Table 7. Results of the multiple regression analysis.

Group	ND Characteristic	Typical Equation	Formula	R^2
A	Rebound Number (N) Pulse Velocity (V)	Linier	$f_c' = 0.5843\ N + 18.2015\ V - 64.9774$	0.9480
	Rebound Number (N) Pulse Velocity (V)	Power	$f_c' = 0.0175\ N^{1.1612}\ V^{2.2972}$	0.9511
B	Rebound Number (N) Pulse Velocity (V)	Linier	$f_c' = 1.0676\ N + 10.6028\ V - 54.4724$	0.9782
	Rebound Number (N) Pulse Velocity (V)	Power	$f_c' = 0.0067\ N^{1.6780}\ V^{1.5601}$	0.9787

Table 7 shows the results of SonReb method, i.e. the multiple regression analysis of compressive strength with the combination of rebound number and pulse velocity. The results provide the coefficients of determination that are greater than those of the individual regression analysis mentioned previously. And the power multiple regression analysis provides the coefficients of determination that are greater than those of the linear multiple regression analysis. Thus, for pumice lightweight concrete, the emperical correlation is given by:

$$f_c' = 0.0175\ \ N^{1.1612} V^{2.2972} \tag{5}$$

Meanwhile, for scoria lightweight concrete, it is given by:

$$f_c' = 0.0067\ \ N^{1.6780} V^{1.5601} \tag{6}$$

3.6. Correlations between Chord Modulus of Elasticity with Rebound Number and Pulse Velocity

From the results of similar analysis as before, for pumice lightweight concrete, it is found that the empirical correlation between the chord modulus of elasticity with the rebound number expressed by the power equation, provides the largest coefficient of determination. Similarly, this correlation with the pulse velocity expressed by the power equation, also provides the largest coefficient of determination. The results of similar analysis are also provided by scoria lightweight concrete. For pumice lightweight concrete, the emperical correlations are given by:

$$E_c = 0.0009\ \ N^{2.6149} \tag{7}$$

$$E_c = 0.0226\ \ V^{4.8504} \tag{8}$$

where the chord modulus of elasticity E_c is in GPa and the pulse velocity V is in km/s. Meanwhile, for scoria lightweight concrete, the correlations are given by:

$$E_c = 0.0009\ \ N^{2.5963} \tag{9}$$

$$E_c = 0.0139\ \ V^{5.1914} \tag{10}$$

For pumice and scoria lightweight concretes, the correlations above are graphically presented by Fig. 5a for rebound number and Fig. 5b for pulse velocity.

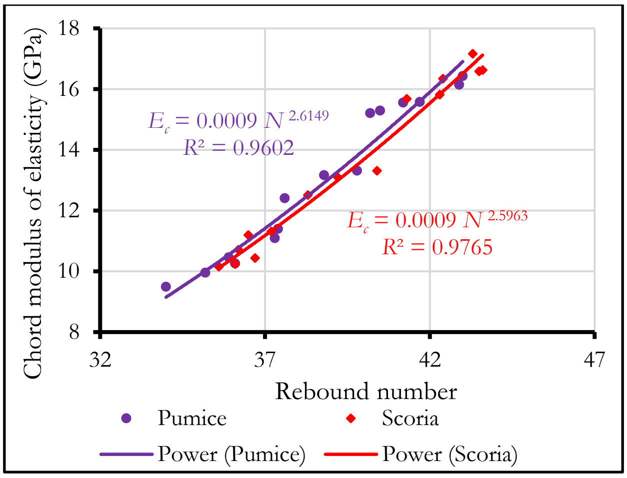

Fig. 5a. Correlation between chord modulus of elasticity with rebound number.

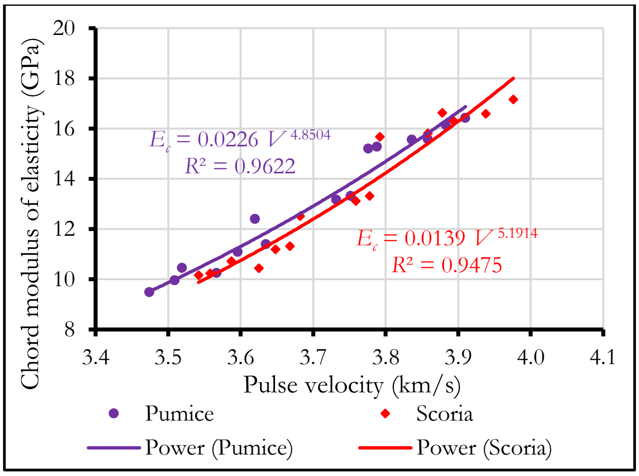

Fig. 5b. Correlation between chord modulus of elasticity with pulse velocity.

From the results of SonReb method, the power multiple regression analysis of chord modulus of elasticity provides the coefficients of determination that are greater than the previous coefficients. For pumice lightweight concrete, the emperical correlation is given by:

$$E_c = 0.0054\, N^{1.1416}\, V^{2.7523} \quad (11)$$

Meanwhile, for scoria lightweight concrete, it is given by:

$$E_c = 0.0014\, N^{2.1626}\, V^{0.9008} \quad (12)$$

3.7. Correlations between Splitting Tensile Strength with Rebound Number and Pulse Velocity

For pumice lightweight concrete, the empirical correlation between splitting tensile strength with rebound number expressed by the power equation, provides the largest coefficient of determination. Similarly, this correlation with pulse velocity expressed by the power equation, also provides the largest coefficient of determination. The results of similar analysis are also provided by scoria lightweight concrete. For pumice lightweight concrete, the emperical correlations are given by:

$$f_t = 0.0026\ N^{1.8171} \quad (13)$$

$$f_t = 0.0245\ V^{3.3744} \quad (14)$$

where the splitting tensile strength f_t is in MPa and the pulse velocity V is in km/s. Meanwhile, for scoria lightweight concrete, the correlations are given by:

$$f_t = 0.0032\ N^{1.7594} \quad (15)$$

$$f_t = 0.0193\ V^{3.5297} \quad (16)$$

For pumice and scoria lightweight concretes, the correlations above are graphically presented by Fig. 6a for rebound number and Fig. 6b for pulse velocity.

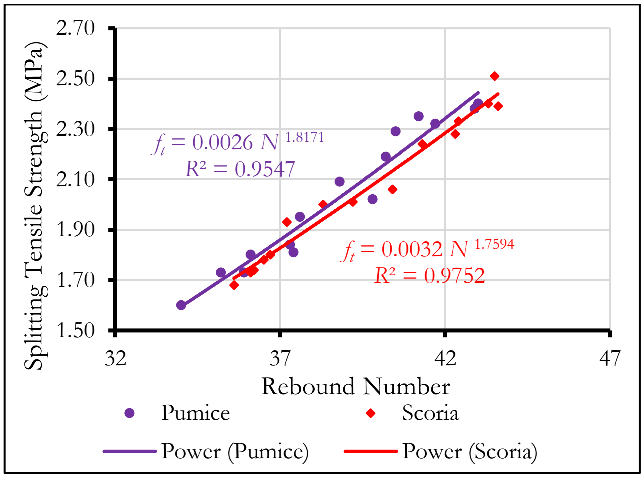

Fig. 6a. Correlation between splitting tensile strength with rebound number.

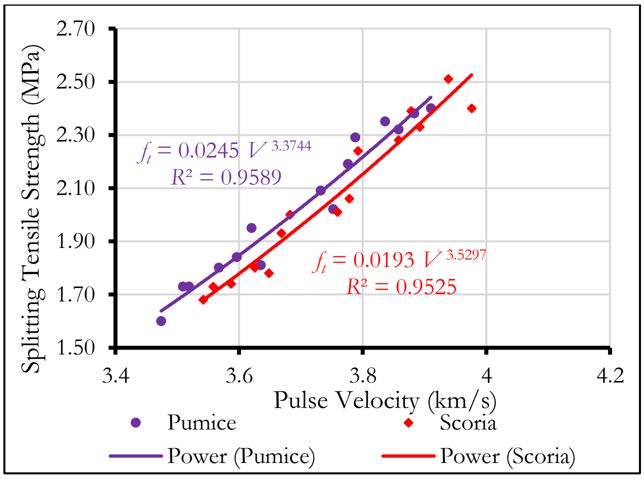

Fig. 6b. Correlation between splitting tensile strength with pulse velocity.

From the results of SonReb method, the power multiple regression analysis of splitting tensile strength provides the coefficients of determination that are greater than the previous coefficients. For pumice lightweight concrete, the emperical correlations are given by:

$$f_t = 0.0106\, N^{0.6687}\, V^{2.1453} \quad (17)$$

Meanwhile, for scoria lightweight concrete, it is given by:

$$f_t = 0.0047\ N^{1.3385}\ V^{0.8741} \quad (18)$$

3.8. Correlations between Modulus of Rupture with Rebound Number and Pulse Velocity

For pumice lightweight concrete, the empirical correlation between modulus of rupture with rebound number expressed by the power equation, provides the largest coefficient of determination. Similarly, this correlation with pulse velocity expressed by the power equation, also provides the largest coefficient of determination. The results of similar analysis are also provided by scoria lightweight concrete. For pumice lightweight concrete, the correlations are given by:

$$f_r = 0.0057\ N^{1.7785} \quad (19)$$

$$f_r = 0.0517\ V^{3.2853} \quad (20)$$

where the modulus of rupture f_r is in MPa and the pulse velocity V is in km/s. Meanwhile, for scoria lightweight concrete, the correlations are given by:

$$f_r = 0.0088\ N^{1.6551} \quad (21)$$

$$f_r = 0.0465\ V^{3.3483} \quad (22)$$

For pumice and scoria lightweight concretes, the correlations above are graphically presented by Fig. 7a for rebound number and Fig. 7b for pulse velocity.

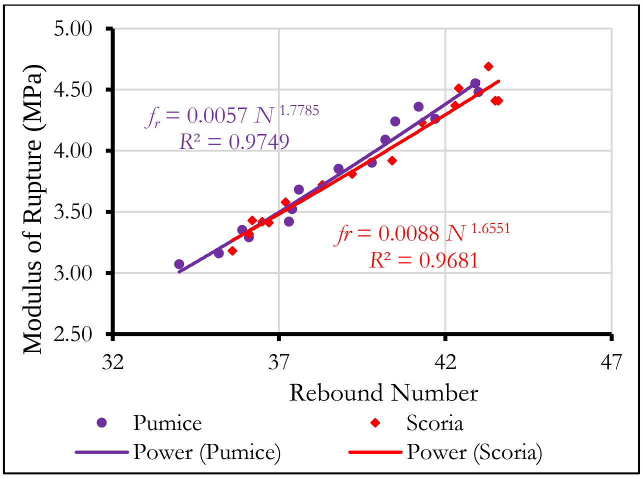

Fig. 7a. Correlation between modulus of rupture with rebound number.

From the results of SonReb method, the power multiple regression analysis for modulus of rupture with the combination of rebound number and pulse velocity, also provides the coefficients of determination that are greater than the previous coefficients. For pumice lightweight concrete, the empirical correlation is given by:

$$f_r = 0.0110\ N^{1.2344}\ V^{1.0165} \quad (23)$$

Meanwhile, for scoria lightweight concrete, it is given by:

$$f_r = 0.0169\ N^{0.9590}\ V^{1.4457} \quad (24)$$

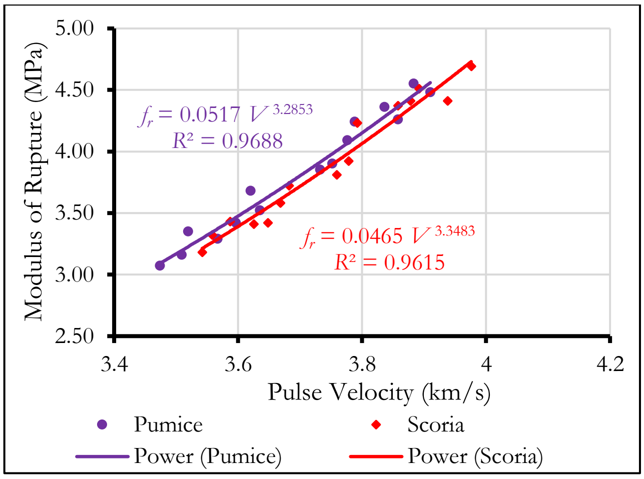

Fig. 7b. Correlation between modulus of rupture with pulse velocity.

The results of above analysis indicate that the empirical correlations between compressive strength as well as chord modulus of elasticity with the rebound number and ultrasonic pulse velocity for both lightweight concrete, are expressed by the power function. These results are similar to those studied by [25] for lightweight concrete with porcelanite coarse aggregate and normal concrete. The analysis of linear multiple regression with the combination of rebound number and pulse velocity, indicates the more accurate result than that presented by [40] for lightweight concrete with scoria coarse aggregate. However, for the compressive strength of both lightweight concrete, the power multiple regression analysis indicates the most accurate results as stated by [36, 38]. Similarly, the splitting tensile strength and modulus of rupture are also expressed by the power function in analysis of simple regression. However, the power form in analysis of multiple regression also provides more accurate results. The results of the analysis of regression also show that for pumice as well as scoria lightweight concretes, it can be said that the empirical correlations are not significantly different. This may be caused by the physical characteristics of both pumice and scoria which do not differ as mentioned previously. These formulas may be used to estimate the destructive characteristics with non-destructive characteristics such that they can be used to accelerate the process of structural design and quality control.

4. Conclusions

This study presented the empirical correlations between destructive and non-destructive characteristics for structural lightweight concretes from Medium-K basaltic andesitic pumice and scoria as coarse aggregates. Furthermore, the formulas obtained may be used to estimate these destructive characteristics, especially for structural design and quality control purposes. From the results of this investigation the conclusions can be drawn:

1. The correlations between destructive and non-destructive characteristics which include the

compressive strength and the chord modulus of elasticity, are expressed by the power equation of the rebound number of Schmidt's Hammer. Similarly, the splitting tensile strength and modulus of rupture are also expressed by similar type of equations.
2. The correlations between destructive and non-destructive characteristics as stated above are also expressed by the power equation of the ultrasonic pulse velocity.
3. The SonReb method with the combination of rebound number and pulse velocity in power form provides reliable destructive characteristics compared to the individual regression analysis with power function.
4. The correlation results for pumice lightweight concrete are not significantly different from scoria lightweight concrete, this may be due to their physical characteristics which are significantly not different. For this reason, it is possible to apply one of the formulas for predicting the destructive characteristics of the typical pumice or scoria lightweight concrete.

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Hendro Suseno was born in Blitar, East Java, Indonesia in 1958. he received the B. Eng. degree in Civil Engineering from the Brawijaya University, Malang, in 1984, the M. Sc degree in Solid Mechanic from ECL, Lyon, France in 1989 and the Doctor degree in Structural Engineering from Brawijaya University, Malang, in 2018. From 1993 to 2000, he was an Assistant Professor and from 2000 until now, he was a Lecturer and Associate Professor with the Civil Engineering Department, Brawijaya University. He is the author of two books, 25 articles in domestic and international journals and conferences, and 1 invention on pumice and scoria lightweight concretes. His research interests include analysis and design orthotropic plates, pumice and scoria lightweight concrete technologies, and reinforced pumice and scoria lightweight concretes precast slabs. Dr. Hendro Suseno was a member of the Indonesian Association of Precast and Prestressed Engineers and The Institution of Engineers Indonesia (PII).

Ming Narto Wijaya was born in Madiun, East Java, Indonesia in 1984. He received B. Eng. degree in Civil Engineering from the Brawijaya University, Malang, in 2008, the M. Sc degree in Civil Engineering from NCU, Taiwan in 2010 and the Doctor degree in Structural Engineering from Kumamoto University, Japan in 2014.. From 2011 to 2019, he was a Research Assistant. Since 2020, he has been an Head of Stuctural and Construction Material Laboratory of Civil Engineering Department of Brawijaya University. He is the author of one book, 15 articles in domestic and international journals and conferences. His research interests include analysis and design structure, high performance reinforced concrete and steel structures. Dr. Ming Narto Wijaya was a member of The Institution of Engineers Indonesia (PII) and Indonesian Society of Civil and Structural Engineers (HAKI).

Ananda Insan Firdausy was born in Jombang, East Java, Indonesia in 1990. He received the B. Eng degree in Civil Engineering from the University of Brawijaya, Malang, in 2011 and the M.Sc degree in structural engineering from National Central University, Taoyuan, Taiwan in 2014. He is author of one book, more than five articles in domestic and international journals and conference. His research interests include analysis and design structure, high performance fiber reinforced concrete structure, cold-formed steel structure, and steel-hybrid material. Ananda Insan Firdausy, M.Sc was a member of The Institution of Engineers Indonesia (PII) and Indonesian Society of Civil and Structural Engineers (HAKI).