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RELATIONSHIP BETWEEN MECHANICAL PROPERTIES OF LIGHTWEIGHT CONCRETES MADE WITH MEDIUM-K BASALTIC ANDESITIC PUMICE AND SCORIA

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Abstract

This study investigates relationships between the modulus of elasticity with compressive strength, splitting tensile strength with compressive strength and modulus of rupture with a compressive strength of the pumice and scoria lightweight concrete. The modulus of elasticity is expressed in term of the square root of the compressive strength and combined power function of density with the square root of the compressive strength. While the splitting tensile strength and modulus of rupture are expressed in term of square root and in power function of the compressive strength. The results showed that the modulus of elasticity is precisely expressed in term of combined power functions of equilibrium density and the square root of compressive strength. While the splitting tensile strength and modulus of rupture are precisely expressed in term of the power function of compressive strength. All empirical formulas are expressed by the empirical coefficients that are not significantly different between both lightweight and validated by codes then it may be applicable to them together.

Keywords: Lightweight concrete, Mechanical properties, Pumice, Relationships Scoria.

1. Introduction

Kelud volcano is an active stratovolcano with an explosive type of eruption located in the southern part of East Java, Indonesia. This volcano occupies a subduction zone where the Indo-Australian Plate enters under the Eurasian Plate and one of the volcanoes that are part of the Pacific Ring of Fire [1]. Any periodic eruption is between 9 to 75 years and it always ejects pumice and scoria simultaneously that are classified as a combination of basalt and andesite. According to Bourdier et al. [2], the eruption of 1990, one of the eruption products was medium-K basaltic andesitic pumice and scoria with volume ranged approximately 120 million m^3. Both were just different in colour but the chemical compositions, mineralogies and textures were similar, while their specific gravities were larger than one so they were directly immersed in water. Pumice was light grey, while scoria was dark-coloured, their vesicles were separated by thin cavity walls and their groundmasses were dominated by amorphous glass. The content of silica, alumina and iron oxide were almost similar and significantly different from pumice and scoria from Papua New Guinea [3, 4] or from Yemen [5].

Suseno et al. [6] carried out studies of the suitability of this pumice and scoria on structural lightweight concretes. As coarse aggregates, the physical properties of this typical pumice and scoria, i.e., oven dry densities, bulk specific gravities and maximum absorptions, satisfied with the lightweight aggregate requirements. This may be due to their porosities, which were the main factor determining other properties [7], while their existences on vesicular rocks, such as pumice and scoria were determined by its characteristic of lava as the source of volcanic rock. Kelud’s lava may be a combination of the andesitic and basaltic type that tend to be less viscous, rather easy to flow and its capacity to release gases in lava is rather easy so that the ability to trap the gases becomes low [8]. Thus, the porosity of both vesicular rocks was not so high that the three physical characteristics above can fulfill the requirements. However, the mechanical properties, i.e., compressive strengths and abrasions by LA Machine were relatively low. This may be due to their relative high porosity compared to the normal aggregate and their microstructures dominated by amorphous glass. Applications on lightweight concrete using PPC and both coarse aggregates in wet condition after 18 hours of presoaking, indicated that the pumice and scoria lightweight concretes could be categorized as structural lightweight concrete [9]. The mix proportion were designed according to ACI 211.2-98 (R2004) [10] with the content of PPC on all concrete mixtures was smaller than 450 kg per m^3. Maximum compressive strengths can reached 31 MPa and 32 MPa with a reduction of density compared to normal weight concrete as control were about 19% and 20%, respectively. All modulus of elasticity were still proportional, their magnitutes were approximately 75% and 76% compared to control, however, their splitting tensile strength and modulus of rupture were relatively low.

Other studies on the use of those vesicular rocks as coarse and fine aggregates on lightweight concrete were also performed previously, such as pumice and scoria from Papua New Guinea [3, 4], pumice and scoria from Turkey [11, 12], scoria from Saudi Arabia [13], the pumice breccia from Central Java Indonesia [14], and pumice and scoria from Yemen [5]. The results showed that the lightweight concrete obtained could be categorized as structural lightweight concrete with certain treatments. These studies resulted in mix proportions and characteristics of lightweight concrete that varied according to the origin of the lightweight aggregates used. This may be due to their characteristics or qualities of the pumice and scoria, which also varied according to local geological conditions. In addition, other treatments such as admixture types and types of prewetting coarse aggregate before concrete mixing also affected their properties.

The uniaxial compressive strength is usually used as a general index of concrete strength because its test is the easiest to be conducted in the laboratory [15]. Then other characteristics, such as modulus of elasticity, tensile strength, modulus of rupture strength and shear strength, are considered to be directly related to the compressive strength and their magnitudes are deduced from the compressive strength data. The compressive strength is significantly affected by capillary porosity of hydrated cement paste where its magnitude is dependent on water/cement ratio [7]. As the water/cement ratio increase, the capillary porosity also increases and the compressive strength decreased significantly. More precisely, the compressive strength is related to a gel/space ratio, which is defined as the ratio of the volume of hydrated cement paste and the sum of the volume of hydrated cement paste and capillary porosity [16]. It can be stated that as the gel/space ratio increase, the compressive strength also increases significantly. Concrete is a particulate composite material, in which, the modulus of elasticity is a mixture of aggregate and cement paste. The modulus of elasticity of the aggregate is significantly influenced by its porosity, however, to facilitate its estimation in concrete, it is only used the concrete density [15].

The concrete static modulus of elasticity is defined as the slope of the stress-strain relationship of the cylinder compressive test at 28 days. This modulus is also a coefficient expressing the stiffness of the material. Based on studies by Mehta and Monteiro [15], since the curve is non-linear, several types of the modulus of elasticity can be described, but only chord modulus of elasticity recommended by the codes. This modulus of elasticity is usually used for deflection calculations in the design of reinforced concrete structures [17-19]. Concrete tensile strength can be obtained from the direct tensile test with a typical specimen. This strength is relatively low compared to compressive strength and often neglected in the design of reinforced concrete sections [18, 19]. However, this tensile strength is required in the calculation of deflections and crack width of the reinforced concrete structures at service load [17, 20]. The test of direct tensile strength is relatively difficult to carry out, the uniformity of stress on the cross section is difficult to obtain, while the testing result is always varied and less recommended by the code [15, 21]. Therefore, the usual practical way to measure the tensile strength is by splitting tensile test of the cylindrical specimens or four-point bending test of prism specimens [17, 21]. However, the result of both tests is overestimated when compared to their direct tensile strength [15] so reduction factors are necessary to correct them.

In the design of reinforced concrete structures, either normal weight or structural lightweight concretes, the static modulus of elasticity is expressed empirically in terms either square root of compressive strength or combination of the power’s function of density and the square root of compressive strength [17, 18, 22]. While the splitting tensile strength and the modulus of rupture are expressed in terms either square root of compressive strength or power function of compressive strength [18, 21, 23]. Hossain et al [24] performed a study on lightweight concrete with pumice from Papua New Guinea as coarse aggregates. The modulus of elasticity was also expressed in terms of either square root of compressive strength or combination of the power function of density and the square root of compressive strength while the direct tensile strength is expressed in linear function of compressive strength. All empirical constants were determined by plotting the equation of regression from data of density, compressive strength, modulus of elasticity and tensile strength measured in the laboratory. The results showed that the modulus of elasticity was still valid compared to empirical formulas presented by ACI 318M-08 [16].

The experimental results showed a tendency that was not significantly different between pumice and scoria lightweight concretes but significantly different from previous studies. Thus, these relationships may result in different empirical formulas that are also different from previous studies and then it may be used together. The objective of this study is to find the relationship between modulus of elasticity with compressive strength, the relationship between splitting tensile and modulus of rupture with the compressive strength of the structural lightweight concretes using medium-K basaltic andesitic pumice and scoria as coarse aggregates. Furthermore, the results of this study may be used easily to predict them in the structural design of pumice and scoria lightweight reinforced concretes.

2. Analysis of Methods

2.1. Experimental Programs

Medium-K basaltic andesitic pumice and scoria were collected from the Check dam of Badak and Putih rivers on the southern slopes of the volcano. Specimens in cobbles size were crushed into four different particle sizes of coarse aggregates with 19 mm maximum particle size. The retained weight of these fractions consisted of 43% on 12.5 mm sieve, 28% on 9.5 mm sieve, 27% on a No. 4 sieve and 2% on No. 8 sieve, respectively. This grading fulfilled the requirement of lightweight aggregate according to ASTM C330-04 [25] or SNI 03-2461-2002 [26] with fine modulus was 6.69. Fine aggregate was a river light sand taken from Konto’s river on the northern slope of the same volcano. The maximum particle size was 4.75 mm and its grading was also according to ASTM C330-04 [25] or SNI 03-2461-2002 [26] with fine modulus was 2.61. A commercial PPC was used as a binder with the specific gravity of 3.15, while clean water for drinking was used in all concrete mixtures. Pumice, scoria and four different particle sizes of coarse aggregate are presented in Fig. 1.

Two groups of mix proportions of the structural lightweight concrete were designed by two methods of ACI 211.2-98 (R2004) [10] utilizing both coarse aggregates. Group A was pumice lightweight concrete while Group B was scoria lightweight concrete designed using Gravity and Volumetric Methods. The Gravity method used an assumption that maximum absorption of coarse aggregates can be determined precisely at 96 hours and then the mix proportion was determined by the water/cement ratio, while the mix proportion in the Volumetric Method was determined by trial and error based on the relationship between cement content and compressive strength. Each group consisted of four mix proportions based on average compressive strengths in accordance with Indonesian Standard SNI 2847: 2013 [27]. Slump values were specified between 60 to 70 mm while the air content was assumed 2 to 3%. Before concrete mixing, all dried coarse aggregates were presoaked for 18 hours to reduce high absorption and absorption rate. Concrete mixing was performed by a small mixer of 150 kg capacity and a slump test was carried out to ensure at given values.

Two kinds of specimens were utilized for this experimental investigation, 150×300 mm cylinder for compressive strength, static modulus of elasticity, splitting tensile strength, and equilibrium density tests, while 100×100×400 mm prism for modulus of rupture test. All specimens were compacted internally using a 12 mm diameter steel rod, whereas demolding was performed 24 hours after casting. Curing for all specimens of mechanical property tests were conducted by covering them within wet burlaps during 7 days and then stored in a dry room until testing time at 28 days. Curing and testing for equilibrium density were conducted in accordance with ASTM C567-00 [28]. Compressive strength and static modulus of elasticity tests were conducted according to ASTM C 39M-03 [29] and ASTM C 469M-02 [30], while splitting tensile strength and modulus of rupture tests according to ASTM C 496M-04 [31] and ASTM C78-02 [32], respectively. The magnitude of equilibrium density, splitting tensile strength and modulus of rupture were mean values of three specimens, while for compressive strength and modulus of elasticity were mean values of five specimens. Specimens and mechanical properties tests are presented in Fig. 2, while their properties of hardened lightweight concrete are presented in Table 1.

a. Pumice b. Scoria

Fig. 1. Pumice, scoria and four different particle sizes of coarse aggregates.

Fig. 2. Specimens and mechanical properties tests.

Table 1. Properties of hardened pumice and scoria lightweight concrete.

Group	Label	Equilibrium density (kg/m^3)	Compressive strength (MPa)	Modulus of elasticity (MPa)	Splitting tensile strength (MPa)	Modulus of rupture (MPa)
A	PLC01	1864.27	20.96	10245.81	1.89	2.39
	PLC02	1866.24	21.17	10385.39	1.91	2.42
	PLC03	1867.56	22.24	12506.02	2.13	2.63
	PLC04	1869.98	22.63	12823.43	2.15	2.76
	PLC05	1873.68	27.87	13778.36	2.53	3.35
	PLC06	1878.30	27.89	13944.25	2.56	3.39
	PLC07	1879.76	31.01	14775.61	2.88	3.58
	PLC08	1885.24	31.05	14825.20	2.93	3.60
B	SLC01	1880.88	21.71	11049.99	1.95	2.50
	SLC02	1886.99	21.92	11640.92	1.97	2.53
	SLC03	1892.68	23.82	12874.75	2.15	2.79
	SLC04	1896.77	24.07	12914.72	2.19	2.82
	SLC05	1909.83	28.10	14103.20	2.62	3.34
	SLC06	1911.36	28.48	14590.88	2.64	3.37
	SLC07	1920.03	32.36	14846.03	2.92	3.83
	SLC08	1922.43	32.92	15295.41	3.04	3.87

2.2. Relationships between mechanical properties

In this study, three relationships between mechanical characteristics were evaluated for each pumice and scoria lightweight concretes, i.e., the relationship between modulus of elasticity and compressive strength, the relationship between splitting tensile strength and compressive strength and the relationship between modulus of rupture and compressive strength. The forms of relationship are similar functions given by previous studies and codes. The modulus of elasticity is expressed in terms of the square root of compressive strength and combination of a power function of equilibrium density and the square root of compressive strength. The splitting tensile strength and modulus of rupture are expressed in terms of square root and power function of compressive strength. The empirical formulas are obtained by regression analysis using measurement data of both lightweight concretes, then the empirical coefficients obtained are compared to those given by ACI 213R-03 [9], ACI 318M-08 [22], BS DD ENV 1992-1-1 [23] and EN 1992-1-1 [33].

3. Results and Discussion

3.1. Modulus of elasticity

The relationships between modulus of elasticity and compressive strength of the pumice and scoria lightweight concrete are expressed in general form by two following empirical formulas:

$$E_c = C_1 \sqrt{f_c'} \tag{1}$$

$$E_c = C_2\, w^{1.5} \sqrt{f_c'} \tag{2}$$

where E_c is the modulus of elasticity in MPa, C_1 and C_2 are empirical coefficients, f_c' is compressive strength in MPa and w is equilibrium density in kg/m^3. The plotting data from Table 2 is presented by Figs. 3 and 4.

The results of regression analysis of pumice and scoria lightweight concrete from Kelud volcano, the results of pumice lightweight concrete conducted by

Hossain et al. [24] and the results recommended by codes ACI 213R-03 [9] and ACI 318M-08 [22] are presented in Table 2.

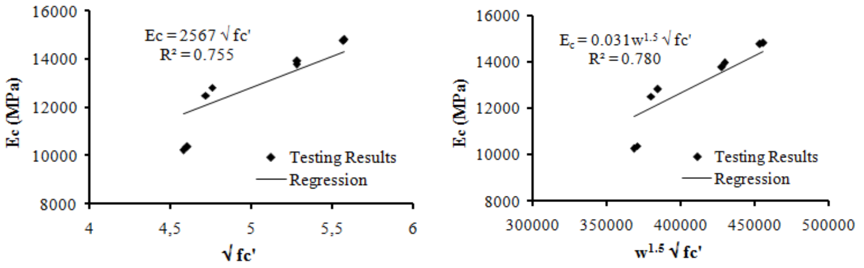

Fig. 3. Relationships between modulus of elasticity and compressive strength for pumice lightweight concrete.

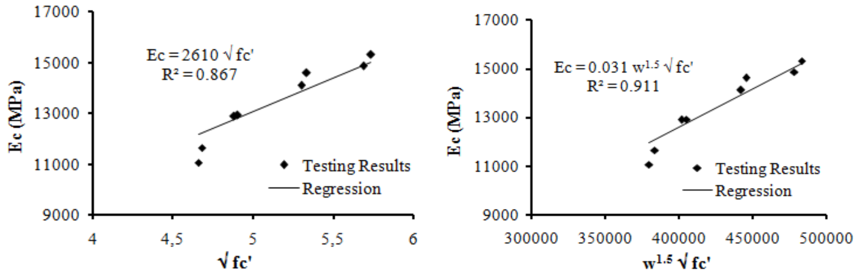

Fig. 4. Relationships between modulus of elasticity and compressive strength for scoria lightweight concrete.

Table 2. Coefficients of regression of modulus of elasticity.

Type of lightweight coarse aggregates	Eq. (1)		Eq. (2)	
	C_1	R^2	C_2	R^2
Pumice from Kelud volcano	2567	0.755	0.031	0.780
Scoria from Kelud volcano	2610	0.867	0.031	0.911
Pumice by Hossain et al. [24]	2004.6	0.9419	0.030	0.9599
ACI Committee [9, 22]	4700	-	0.043	-

As compared by ACI Committee [9, 22], the difference of C_1 coefficient on lightweight concretes with pumice and scoria from Kelud volcano as coarse aggregates, are approximately 45% and 44%, respectively, while for the C_2 coefficient are similar, i.e., approximately 28%. These differences are significant and it may be due to the magnitude of the porosity of both coarse lightweight aggregates as indicated by their equilibrium densities or maximum absorptions. The maximum absorption of the pumice and scoria coarse lightweight aggregates are relatively high and approach the 20% recommended value, i.e., 19.17% and 15.26%, respectively, but their equilibrium densities still fulfil the requirements [6]. Due to the high porosities, the modulus of elasticity of the coarse aggregates becomes low and the modulus of elasticity of both lightweight concrete may be low. Another cause of these significant differences may the type of coarse aggregates used in structural lightweight concrete. ACI Committee [9, 22] explained, it may utilize artificial coarse aggregates, used commonly and they compose of crystalline microstructure, while pumice and scoria coarse aggregates are amorphous glass.

The natural pozzolan content of pumice and scoria coarse aggregates from Kelud volcano is high and potentially reactive, it may be a pozzolanic reaction between the surfaces with CH and water so that the quality of the transition zone on both lightweight concrete increases [34, 35]. The transition zones become strong while the coarse aggregates become weak and then the strength limit of both lightweight concretes are determined by their coarse aggregates. In the same time, their stress transfer capacities of the cement paste to the aggregates or vice versa increase so that their stiffness and modulus of elasticity also increase [15]. However, both moduli of elasticity of the coarse aggregate is low due to the weakness of the atomic bonds in the amorphous glass microstructure [7]. Thus, the modulus of elasticity of both lightweight concrete may remain low and lower than structural lightweight concrete with artificial coarse aggregates. The Eqs. (1) and (2) are valid as compared by ACI Committee [9, 22], while Eq. (2) yields a coefficient of determination R^2 that is greater than Eq. (1) for pumice and scoria lightweight concretes. Thus, Eq. (2) may be more suitable to predict their modulus of elasticity since it incorporates equilibrium density as a correction of the high porosity of both coarse lightweight aggregates.

As coarse aggregates studied by Hossain et al. [24], for lightweight concrete with pumice from Papua New Guinea and ACI Committee [9, 22], the difference of C_1 and C_2 coefficients to are approximately 57% and 30%, respectively. These differences are greater than lightweight concrete with pumice from Kelud volcano so that the predicted modulus of elasticity becomes low. The absorption of pumice from Papua New Guinea is greater than pumice from Kelud volcano so that its porosity may be higher and its modulus of elasticity becomes lower. The modulus of elasticity of the scoria lightweight concrete from Kelud volcano is slightly greater than pumice lightweight concrete because the maximum absorption of scoria coarse aggregate is lower than pumice coarse aggregate so that its porosity may become lower. Thus, the modulus of elasticity of the pumice lightweight concrete is not significantly different to that of the scoria lightweight concrete and the empirical formula expressed by Eq. (2) may be considered to predict the modulus of elasticity of the pumice and scoria lightweight concretes together.

3.2. Splitting tensile strength

The relationships between splitting tensile and compressive strengths of the pumice and scoria lightweight concrete are expressed in general form by two following empirical formulas:

$$f_s = C_3 \sqrt{f_c'} \tag{3}$$

$$f_s = C_4\, f_c^{2/3} \tag{4}$$

where f_s is the splitting tensile strength in MPa, C_3 and C_4 are empirical coefficients. The plotting data from Table 3 is presented by Figs. 5 and 6.

The results of the regression analysis of pumice and scoria lightweight concrete from Kelud volcano are presented in Table 3. Similarly, the mean values of C3 coefficient of the general lightweight concrete taken from Picard [21] and C4 coefficient recommended by codes ACI 213R-03 [9] and ACI 318M-08 [22] for general lightweight concrete with river sand as fine aggregate, are also presented in Table 3.

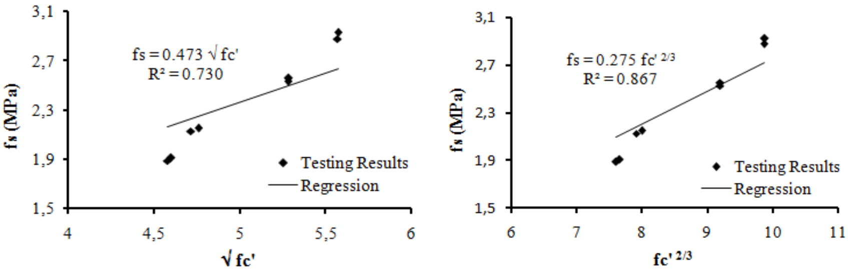

Fig. 5. Relationships between splitting tensile and compressive strengths for pumice lightweight concrete.

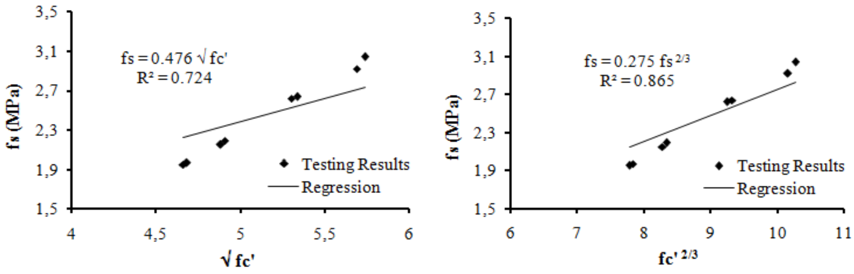

Fig. 6. Relationships between splitting tensile and compressive strength for scoria lightweight concrete.

Table 3. Coefficients of regression of the splitting tensile strength.

Type of lightweight coarse aggregates	Eq. (3)		Eq. (4)	
	C_3	R^2	C_4	R^2
Pumice from Kelud volcano	0.473	0.730	0.275	0.867
Scoria from Kelud volcano	0.476	0.724	0.275	0.865
General by Picard [21]	0.375	-	-	-
General by European Committee for Standardization [23, 33]	-	-	0.283	-

3.3. Modulus of rupture

The relationships between the modulus of rupture and compressive strength are expressed in general form by two following empirical formulas:

$$f_r = C_5 \sqrt{f_c'} \tag{5}$$

$$f_r = C_6\, f_c^{2/3} \tag{6}$$

where f_r is the modulus of rupture in MPa, C_5 and C_6 are empirical coefficients. The plotting data from Table 4 is presented by Figs. 7 and 8.

The regression analysis results of pumice and scoria lightweight concrete from Kelud volcano and two comparable results from the same previous references are presented in Table 4.

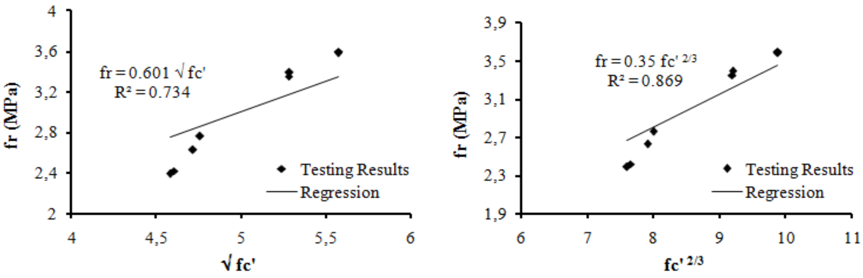

Fig. 7. Relationships between modulus of rupture and compressive strength for pumice lightweight concrete.

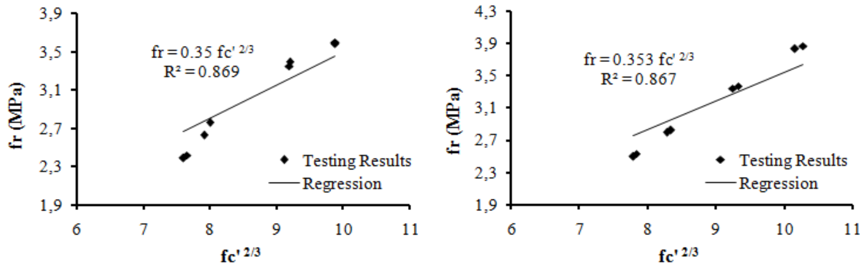

Fig. 8. Relationships between modulus of rupture and compressive strength for scoria lightweight concrete.

Table 4. Coefficients of regression of the modulus of rupture.

Type of lightweight coarse aggregates	Eq. (5)		Eq. (6)	
	C_5	R^2	C_6	R^2
Pumice from Kelud volcano	0.601	0.734	0.350	0.869
Scoria from Kelud volcano	0. 612	0.725	0.353	0.865
General by Picard [21]	0.585	-	-	-
General by European Committee for Standardization [23, 33]	-	-	0.510	-

As compared by to Picard [21], the difference of C_5 coefficient on lightweight concretes with pumice and scoria from Kelud volcano as coarse aggregates, are approximately 3% and 4%, respectively. While the difference of C_6 coefficient is approximately similar, i.e., 31%. As mentioned above that the cohesion of both coarse aggregates is significantly low. Furthermore, due to maximum tensile stress on the prism specimen of four bending test, the coarse aggregates in the bottom tensile zone will be failed first so that their tensile strength may be low and lower than lightweight concrete with artificial aggregate as coarse aggregates. Thus, Eq. (6) may be more suitable for predicting the modulus of rupture of the pumice and scoria lightweight concretes because it also yields a greater coefficient of a determinant than Eq. (5) and as stated by the European Committee for

Standardization [23, 33] their magnitudes of C_6 coefficient are lower. However, the difference of C_6 coefficients to these references is relatively large, this may be due to the non homogeneity and linearity assumptions of the tensile stress distribution on the cross section so that their accuracy become low [15]. It can be showed that Eq. (6) yields C_6 coefficients that are not significantly different so it may be considered to predict the modulus of rupture of the pumice and scoria lightweight concrete together.

4. Conclusions

This study has demonstrated the relationship between mechanical characteristics of structural lightweight concrete using medium-K basaltic andesitic pumice and scoria as coarse aggregates. These relationships yield empirical formulas, which may be considered for predicting the static modulus of elasticity, splitting tensile strength and modulus of rupture in the design of lightweight concrete structures. From the analysis presented previously, the following conclusions can be drawn:

- The modulus of elasticity of pumice and scoria lightweight concretes are directly related to compressive strength and equilibrium density as control of large aggregate porosity. These relationships are more precisely expressed in term of a combination of the power function of equilibrium density and the square root of compressive strength. Both empirical formulas are expressed by a similar coefficient, they can be validated by codes and may be considered to predict them together.
- The splitting tensile strength of pumice and scoria lightweight concretes are directly related to the compressive strength and more precisely expressed in term of the power function of compressive strength. Both empirical formulas are also expressed by the similar coefficient and they may be considered to predict them together and their results can be accurately validated by the codes.
- The modulus of rupture of pumice and scoria lightweight concretes are directly related to the compressive strength and more precisely expressed in term of the power function of compressive strength. Both empirical formulas are expressed by the coefficients, which are significantly different, they can be validated by codes with relatively low accuracy and may be considered to predict them together.

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Nomenclatures

C_i	Empirical coefficient (i = 1 to 6)
E_c	Static modulus of elasticity
f_c'	Compressive strength
f_r	Modulus of rupture
f_s	Splitting tensile strength

R^2	Coefficient of determination
w	Equilibrium density

Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing Materials
BS	British Standard
CH	Calcium Hydroxide
EN	Europaïsche Norm (European Standard)
LA	Los Angelos
PLC	Pumice Lightweight Concrete
PPC	Pozzolan Portland Cement
SLC	Scoria Lightweight Concrete
SNI	Standar Nasional Indonesia (Indonesian National Standard)

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