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Performance of lightweight concrete one-way slabs using medium-K basaltic andesite pumice and scoria

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Abstract

An investigation was conducted on bending tests of 24 reinforced lightweight concrete one-way slabs using medium-K basaltic andesite pumice and scoria and 1 reinforced normal concrete slab as a control. The compressive strengths and reinforcement ratios were varied to evaluate their flexural behaviors. The ultimate bending moment at failure, midspan deflections and maximum crack widths at assumed service, cracking patterns and failure modes were evaluated to indicate their performance. The results showed that medium-K basaltic andesite pumice and scoria as coarse aggregates can be used to produce pumice and scoria concrete one-way slabs with a relative satisfactory performance. Both behaved typically as reinforced concrete beams with first cracking load, ultimate load and stiffness were lower than the control. The reinforcement ratio was an important factor that influenced significantly the observed parameters compared to compressive strength and type of coarse aggregates. Theoretically, the ultimate bending moment can be estimated accurately by provision compared to midspan deflection and maximum crack width. Cracking patterns were a typical flexural crack, while failure modes were a reinforcement yielding without spalling on compressive concrete zone.

Keywords One-way slab · Pumice and scoria lightweight concrete · Performance · Flexural behavior

Introduction

Indonesia is an earthquake-prone zone where its geographic position occupies an active tectonic zone, three large tectonic plates, i.e., Indo-Australian Plate, Eurasian Plate and Pacific Plate meet each other in its territory (Team Works 2010). Therefore, the buildings especially high-rise buildings of reinforced concrete structures should be designed to be resistant from the possibility of earthquake (SNI 1726:2012 2012). One way to reduce the risk of earthquake hazard is by reducing the self-weight of the building so that the horizontal seismic force will also decrease. Using a lightweight concrete on its structural elements, it may be one effort to reduce the building's self-weight. This structural lightweight concrete is generally produced from lightweight artificial or natural aggregates so that its density is relatively light while the compressive strength still fulfills structural requirements (ACI 213.R-03 2003).

The artificial lightweight aggregates are factory products with controlled quality and most widely used in lightweight structural concretes. These aggregates are produced from a thermochemical sintering process of expanded natural materials or expanded industrial wastes such as clay or fly ash (Mehta and Monteiro 1993). The reduction of lightweight concrete density using these artificial aggregates to normal concrete is approximately 28% (Chandra and Berntsson 2003), thereby affecting the results of structural design and overall construction costs (ACI 213.R-03 2003). However, its production is relatively complicated, requires a high thermal energy and certainly produces air pollution

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so they are expensive, less energy saving and less environmentally friendly. As a substitute, natural lightweight aggregates such as pumice and scoria can be used; these aggregates are a volcanic eruption product that are abundant especially in volcanic areas and even easy to explore. Although their existences are only in certain areas and their qualities are very diverse, but the lightweight concretes obtained may be cheaper, conserve energy and be more environmental friendly (Suseno et al. 2017). Thus, both lightweight aggregates are natural resources that need to be considered as local construction materials for structural purposes, especially for developing countries that have not been able to produce artificial lightweight aggregates.

Several studies on the use of pumice and scoria as aggregates on lightweight concrete were conducted previously, such as pumice and scoria from Turkey (Kilic et al. 2009), pumice and scoria from Papua New Guinea (Hossain 2004a, b), scoria from Saudi Arabia (Shannag 2011), pumice breccia from Central Java Indonesia (Widodo et al. 2014) and pumice and scoria from Yemen (Al Naaymi 2015). The investigated results showed that the lightweight concretes obtained can be categorized as lightweight structural concretes by adding admixtures or prewetting aggregates. The average density reduction with the same compressive strength is approximately 20% compared to normal concrete, so it may be significant to reduce its self-weight when used on structural elements. However, studies on the use of pumice and scoria lightweight concretes on structural elements have not been widely conducted until now.

Medium-K basaltic andesite pumice and scoria are explosive eruption products that were produced simultaneously by Kelud volcano located in the southern part of East Java Indonesia. Both vesicular rocks differed only in color but they had similar chemical, mineralogical and texture compositions, whereas their specific gravities were greater than water (Bourdier et al. 1997). The study of both as coarse aggregates on lightweight concrete was carried out by (Suseno et al. 2017), the results showed that these two pyroclastic rocks were suitable as lightweight coarse aggregates and had unique physical characteristics that were different from the existing pumice and scoria. Their applications on the lightweight concrete using PPC and without admixtures, yielded 20% density reduction and compressive strengths can reached 30 MPa. While the coarse aggregates should be presoaked for 18 h in order to reduce their high absorption and high rate absorption. So these lightweight concrete may be categorized as structural lightweight concretes that were cheaper, energy-saving, environmental friendly and may be attempted for use on building structural elements.

Reinforced concrete slabs are a structural element with the most dominant volume in high-rise buildings so that their presences will contribute significantly in the self-weight (Juwana 2005). If the slab is designed from structural lightweight concrete while other structural elements remain in normal concrete, the self-weight may still be significantly reduced. This slab may be fabricated by reinforced pumice and scoria lightweight concretes in precast elements so that its quality is well controlled. Therefore, the flexural behavior subjected to static loads can be represented by precast slab segments considered as one-way slab. The one-way slab is a slab subjected to one directional flexure with a length–width ratio is greater than or equal 2 (Nawy 1985; Park and Gamble 1980; Setareh and Darvas 2017); when the slab only contains longitudinal reinforcements, its reinforced concrete section can be designed as a rectangular beam (McCormac 2001; McGregor 1997; Setareh and Darvas 2017) with single reinforcement.

The design of reinforced concrete structural elements subjected to flexure in limit state yields an ultimate bending moment, while the control of instantaneous deflection and crack width is their serviceability determined at service load (Eurocode 2 EN 1992-1-1 2004). From the reinforced concrete rectangular beam analysis, the reinforcement ratio is an important factor that will determine the bending strength capacity and the failure modes (McGregor 1997; Nawy 1985; Setareh and Darvas 2017), Whereas the flexural behavior can be observed from the result of the bending test expressed by the bending moment–curvature diagram or load–deflection diagram until failure. The bending moment or load at first cracking, at assumed service, at reinforcement yielding and at ultimate can be determined, respectively (Lim et al. 2011). Similarly, crack width, crack spacing, crack number, crack pattern and failure modes can also be observed in this bending test.

Study on the flexural behavior of reinforced pumice and scoria lightweight concrete structural elements is less when compared with lightweight concrete using artificial lightweight aggregates or other lightweight concretes. The result of the study of reinforced lightweight concrete beams using Leca coarse aggregate (Lim et al. 2006) or the coarse aggregates made from expanded reservoir sediments (Wu et al. 2011) showed similarities to the flexural behavior of normal weight concrete beams. The cracks also showed similar patterns but they appeared earlier than on the normal concrete; the total number of cracks was more than normal concrete so that the maximum crack width became smaller (Lim et al. 2011). Increasing the reinforcement ratio increased significantly the ultimate bending strength, while the concrete compressive strength also improved the bending strength but it was not significant (Al Mousawi 2011; Shafig et al. 2011). For rectangular reinforced concrete beam analysis, existing regulations were inadequate but a sufficient modification on the normal concrete codes yielded substantial accurate results (Tomicic 2012). The results of reinforced lightweight concrete beams using lightweight dolomite aggregates showed similarity of flexural behavior with normal concrete (Jomaa'h et al. 2012). Reinforced lightweight concrete beams using scoria lightweight aggregates also showed similarity of flexural behavior and the bending strength was so significant; therefore, it can be used for structural elements (Al Nasser et al. 2014). Other studies on flexural behavior have been carried out, such as reinforced geopolymer concrete beams using artificial lightweight aggregate lytag (Madheswaran et al. 2014). Reinforced lightweight concrete beams made with sawdust and coconut shell as fine and coarse aggregates (Palani and Sakthiswaren 2015) and reinforced lightweight concrete beams utilizing pumice and palm oil shell as coarse aggregates (Kumar and Polu Raju 2017). The result of these studies showed that their flexural behavior and cracking behavior also were similar to reinforced normal concrete beams. However, study on reinforced lightweight concrete one-way slabs using medium-K basaltic andesite pumice and scoria has not been conducted until now.

The objective of study is to evaluate the performance of lightweight concrete one-way slabs using medium-K basaltic andesite pumice and scoria as coarse aggregates. This study is an experimental investigation of the flexural behavior of pumice and scoria lightweight concrete one-way slabs with variation of compressive strength and longitudinal reinforcement ratio. The loading on three-point bending test was conducted gradually until failure occurs while the measured responses were midspan deflections, midspan reinforcement strains and the maximum crack widths. Observation of crack patterns and failure modes was also carried out during the loading process. The bending load, midspan deflection, midspan reinforcement strain and maximum crack width at first cracking, at assumed service, at yielding and at failure can be obtained from these results. Furthermore, ultimate bending moments and midspan deflection at assumed service were compared with theoretical calculations based on (ACI 318M-08 2008), while the maximum crack width at assumed service was compared with Gergely–Lutz formula (McGregor 1997; Park and Gamble 1980) and the accuracy was calculated to indicate their performances. In addition, this study will also used as a basic approach of design lightweight concrete to produce precast one-way slabs.

Experimental program

Materials and concrete mixes

Medium-K basaltic andesite pumice and scoria were collected from check dams of Badak and Putih rivers in the southern slope of Kelud volcano. Samples in cobbles size (100–250) mm were crushed into four different particle sizes of coarse aggregates (CA) with 19 mm maximum particle size. This designed grading fulfilled the requirements of lightweight aggregate with fine modulus which was 6.69 (Suseno et al. 2017). The commercial local crushed stone was used as normal coarse aggregate of the control with similar grading to the preceding requirement. All coarse aggregates were washed and dried so that they were relatively clean and free from deleterious substances. The photograph of pumice and scoria coarse aggregate is presented in Fig. 1. Fine aggregates were light river sand with 4.5 mm maximum particle size and its grading fulfilled the requirements with fine modulus which was 2.61 (Suseno et al. 2017). Portland Pozzolan Cement (PPC) fulfilled the requirements with specific gravity of 3.15, while clean water for drinking was used in all concrete mixtures. All kinds of admixtures were not used in order to keep their low production costs. Reinforcements were steel deformed bars D13 with 12.66 mm average diameter and plain bars with 6 mm diameter obtained from commercial market.

All mix designs of structural lightweight concrete and normal concrete were based on the previous study conducted by (Suseno et al. 2017). Two groups of structural lightweight concrete mix proportions were designed, Group A was pumice lightweight concrete (PLC), while Group B was scoria lightweight concrete (SLC). Each group consisted of three mix proportions with specified compressive strengths which were 20, 25 and 30 MPa, respectively, based on the average compressive strengths in accordance with Indonesian Standard (SNI 2847:2013 2013). Group C was a normal concrete (NC) using local crushed stone as the control designed with 25 MPa specified compressive strength. The slump values of all mix proportions were determined between (60–70) mm. The detail of both structural lightweight concrete mix proportions and the control are presented in Table 1.

One-way slab specimens

The total number of lightweight concrete one-way slab was 25; the size of each slab was 2200 mm in length, 600 mm in width and 120 mm in thickness. These specimens were divided into three groups, Group A comprised 12 pumice lightweight concrete one-way slabs (PLCS), Group B comprised 12 scoria lightweight concrete one-way slabs (SLCS) and Group C was 1 normal concrete one-way slab (NCS) as the control. Group A and B consisted of three specified compressive strengths mentioned previously and four reinforcement ratios. These reinforcement ratios were taken between $r_{\min} = 0.0058$ and $r_{\max} = 0.0323$, so that they produced 3, 4, 5 and 6 deformed bars, respectively,

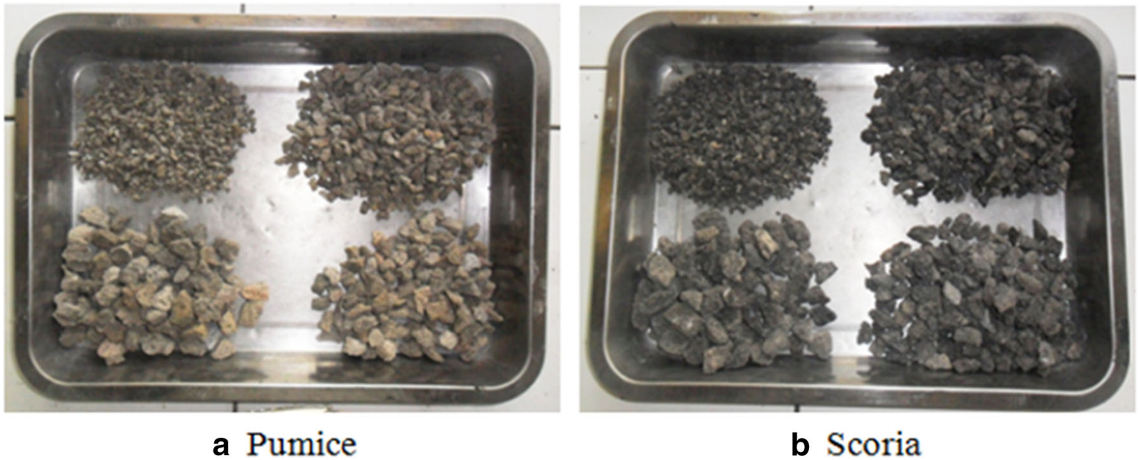

Fig. 1 Grading of pumice and scoria coarse aggregates

Table 1 Detail of structural concrete mix proportions

Group	Label	Specified compressive strength (MPa)	Average compressive strength (MPa)	Mix proportions per 1 m^3 volume (kg)			
				PPC	Dry sand	Wet CA	Water
A	PLC1	20	27.0	322.64	687.22	631.18	201.76
	PLC2	25	33.3	377.32	633.30	625.94	190.51
	PLC3	30	38.3	423.56	587.70	626.69	190.62
	SLC1	20	27.0	322.64	711.40	703.90	181.83
B	SLC2	25	33.3	377.32	657.47	699.40	182.57
	SLC3	30	38.3	423.56	611.78	693.91	199.48
C	NC2	25	33.3	377.32	779.61	987.77	200.30

and will indicated to fail in flexure. The transversal reinforcements were only assumed as assembler and did not contribute on their strength capacities. Concrete cover was constant, i.e., 20 mm from bottom side. Detail of one-way slabs is presented in Fig. 2, while the detail of experimental design of the research is presented in Table 2.

Fabrication of specimens

The longitudinal reinforcements were assembled according to the amounts mentioned previously and bounded by five transversal reinforcements of 6 mm diameter plain bar. Electrical strain gauge was pasted at midspan of the one of longitudinal reinforcement to measure the tensile strains. Before concrete mixing, pumice and scoria coarse aggregates were presoaked for 18 h and then dried their surfaces, whereas normal aggregate was only washed and dried their surfaces. One-way slab moulds were made from 12 mm thick plywood, concrete castings were performed in two layers and each layer was compacted carefully by a vibrator. Each casting of half one-way slab, three 150 × 300 mm cylinder was casted for quality control. All cylinders were internally compacted using a vibrating of steel rod, whereas demolding was carried out after 24 h casting. Curing for cylinder and one-way slab was conducted by covering all specimens within wet burlaps for 7 days and then stored in a dry room. Demolding of one-way slabs was performed after 21 days casting. Curing and testing for equilibrium density of both lightweight concretes were carried out in accordance with (ASTM C 567-00 2000).

Instrumentation and testing procedure

The tensile tests of steel bar were carried out by a universal testing machine for determining their mechanical properties. Three point bending tests were conducted at 28 days; all one-way slabs were simply supported in 2000 mm span and were precisely subjected to a line load at midspan. Loadings were manually given by handy pump, hydraulic jack and load cell, and then transferred to slab surface by a rigid lateral loading spreader. Deflections were measured by linear variable differential transducer (LVDT) installed at center of bottom side of the slab, while reinforcement strains were measured

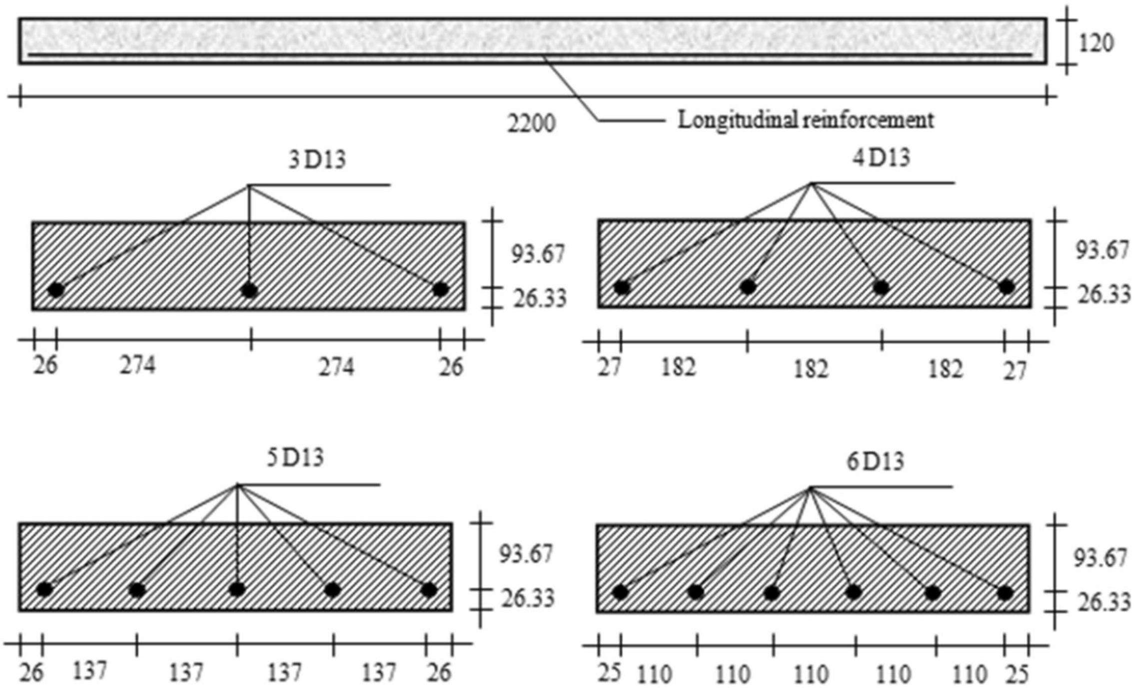

Fig. 2 Detail of reinforced concrete one-way slabs

Table 2 Detail of experimental design

Group	Type of coarse aggregate	fc′ (MPa)	Label	Number of bar	Area (mm^2)	ρ
A	Pumice	20	PLCS11	3	377.21	0.00671
			PLCS12	4	502.95	0.00895
			PLCS13	5	628.68	0.01119
			PLCS14	6	754.42	0.01342
		25	PLCS21	3	377.21	0.00671
			PLCS22	4	502.95	0.00895
			PLCS23	5	628.68	0.01119
			PLCS24	6	754.42	0.01342
		30	PLCS31	3	377.21	0.00671
			PLCS32	4	502.95	0.00895
			PLCS33	5	628.68	0.01119
			PLCS34	6	754.42	0.01342
B	Scoria	20	SLCS11	3	377.21	0.00671
			SLCS12	4	502.95	0.00895
			SLCS13	5	628.68	0.01119
			SLCS14	6	754.42	0.01342
		25	SLCS21	3	377.21	0.00671
			SLCS22	4	502.95	0.00895
			SLCS23	5	628.68	0.01119
			SLCS24	6	754.42	0.01342
		30	SLCS31	3	377.21	0.00671
			SLCS32	4	502.95	0.00895
			SLCS33	5	628.68	0.01119
			SLCS34	6	754.42	0.01342
C	Crushed stone	25	NCS22	4	502.95	0.00895

by electrical strain gauge pasted previously. Loading data outputs were recorded by load indicator, midspan deflections were recorded by data logger and reinforcement strains were recorded by strainmeter. Initially, all one-way slabs were preloaded approximately 0.5 kN to remove any slacking at the supports; the load was then released and all instruments were initialized. Furthermore, loadings were applied monotonically with 2 kN interval until failure and all responses were recorded at this loading interval. All parameters of disintegration of the compressed concrete process were difficult to record since three points bending test utilized a load rate procedure thus they were not plotted in diagrams. The maximum crack width for each load interval was photographed by a USB digital microscope and then measured with complementary software installed on the equipment. The total number of crack on the side of the slabs was precisely counted after failure. Compressive test of cylinders was also performed by compressive testing machine at the same day for determining compressive strength and chord modulus of elasticity. The Scheme and setup of instruments are presented in Figs. 3 and 4.

Results and discussion

Properties of materials

Table 3 shows properties of the pumice and scoria lightweight concretes and the control. All slump values fulfilled the specified values in the previous mix designs, i.e., (60–70) mm and all concrete mixtures showed a satisfactory workability, no segregation or excessive bleeding. The equilibrium density was a mean value of four cylinders and the testing results showed that they also fulfill the requirements of structural lightweight concrete, i.e., lower than 1920 kg/m^3 as defined by (ACI 213.R-03 2003). The density of control was the mean value of 6 cylinders measured at 28 days. Comparing with control, the reduction of densities of the pumice and scoria lightweight concretes are 21.42% and 19.98%, respectively. The compressive strength of the pumice and scoria lightweight concrete were the mean value of 20 cylinders casted for each fabrication of four slabs. The compressive strength of

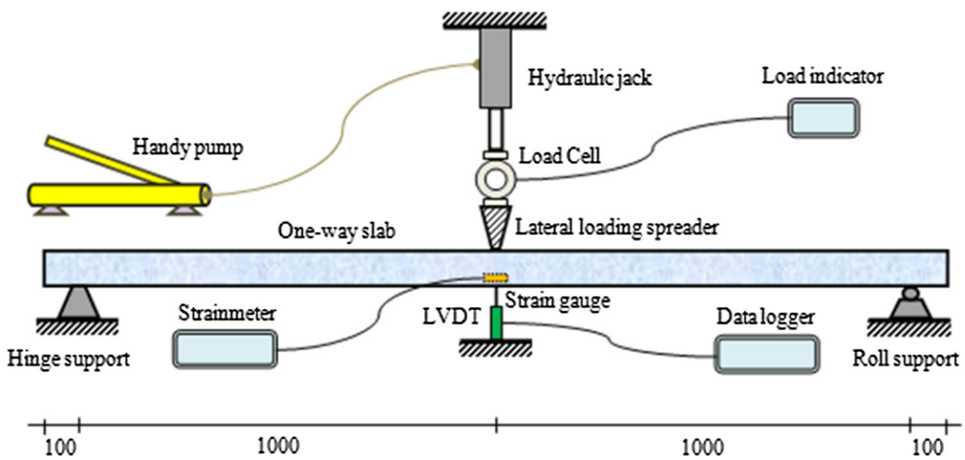

Fig. 3 Scheme of three-point bending test

Fig. 4 Testing setup of instrumentations

Table 3 Properties of both lightweight concretes and control

Group	Label	Specified compressive strength (MPa)	Slump value (mm)	Equilibrium density (kg/m^3)	Obtained compressive strength (MPa)	Modulus of elasticity (MPa)
A	PLCS1	20	61	1867.05	22.24	12293.56
	PLCS2	25	61	1873.76	26.03	13413.87
	PLCS3	30	63	1877.87	30.10	14941.80
	SLCS1	20	69	1891.36	23.01	12367.64
B	SLCS2	25	68	1908.18	27.03	13982.30
	SLCS3	30	62	1918.41	31.11	15158.52
C	NCS2	25	64	2384.52	27.74	18630.24

control was the mean value of six cylinders casted for fabrication of one slab. The testing results showed that the compressive strengths of both lightweight concretes and control obtained can achieve those specified in mix designs. However, the chord modulus of elasticity is lower than control, i.e., 72% for pumice lightweight concrete and 75.05% for scoria lightweight concrete. The result of tensile test of the steel deformed bar was the mean value of three specimens; the yield tensile strength, ultimate tensile strength, modulus of elasticity and yield tensile strain were 457.45, 648.36, 204,770 MPa and 0.0022, respectively.

Investigation of flexural behavior

Figure 5 shows the load-midspan deflection for four variations of the reinforcement ratio and the second compressive strength of the pumice and scoria lightweight concretes. It may be seen that they behave typically as reinforced concrete beams. All curves may be characterized by three different segments during the loading process until failure (McGregor 1997). The first segment is the stage where the cracks do not occur in the tensile concrete zone. The second segment is the stage where the concrete cracked but the reinforcement not yielding. Whereas the third segment is the reinforcement has yielded until the crushed compressive concrete zone. The slope decreases substantially from the first segment to the third segment; this indicates that the stiffness of the one-way slab also decreases during that loading process. From the curves, it can determine a first cracking point, a reinforcement yielding point and an ultimate strength point. Compared to the control (NCS22), the flexural behavior of both lightweight concretes is also similar but their slopes and also their stiffness are lower than it. Figure 6 shows the load-maximum crack width diagram for similar treatments mentioned previously. The maximum crack width of both lightweight concretes one-way slabs are lower than control but they do not differ significantly compared to it. It may be seen that all curves indicate a similar trend. The testing results comprising loads, midspan deflections and maximum crack width of three one-way slabs are presented in Table 4.

Figure 7 shows the load-midspan reinforcement strain diagram for similar treatments mentioned previously. It may be seen that all curves also indicate a similar typical flexural behavior, but their magnitudes do not differ

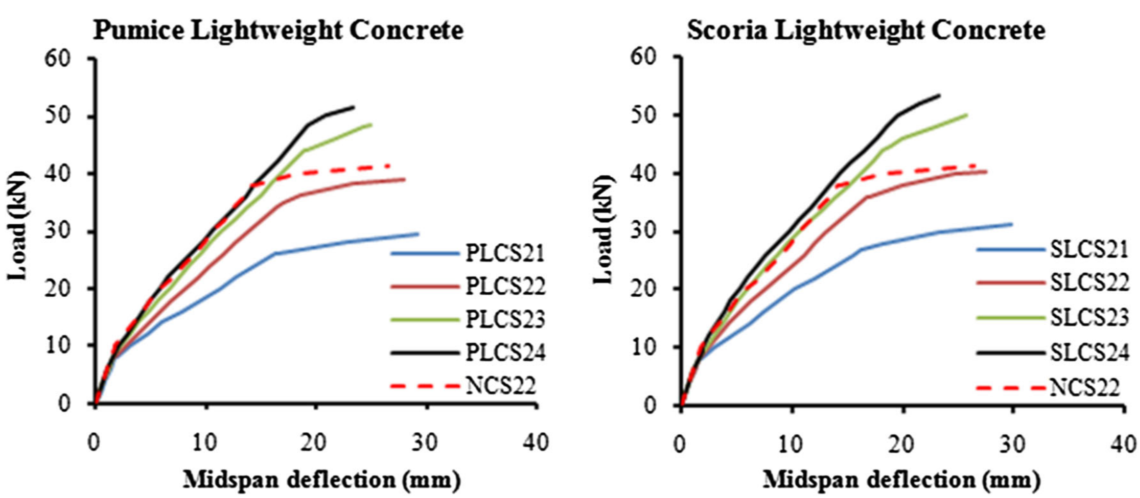

Fig. 5 Load-midspan deflection diagrams

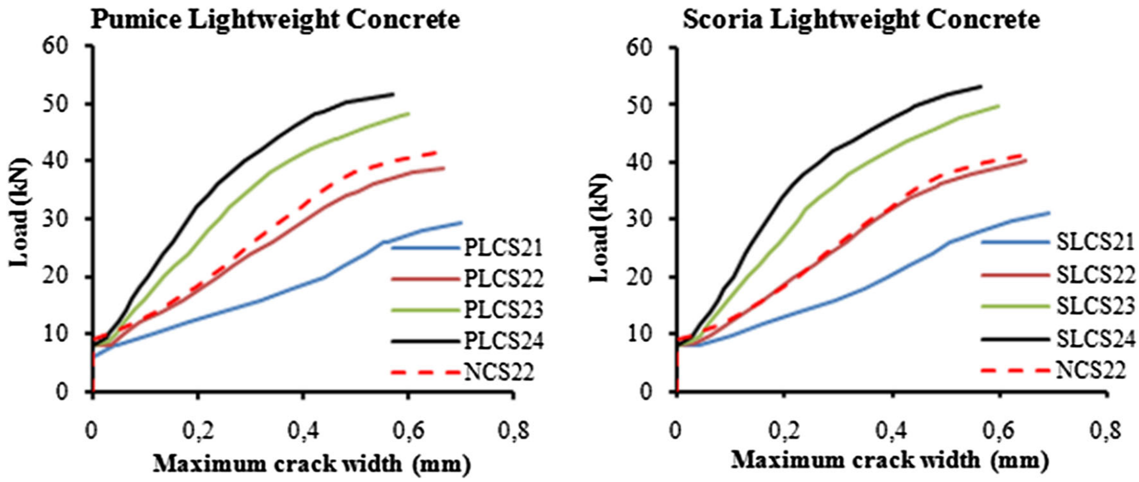

Fig. 6 Load-maximum crack width diagrams

Table 4 Testing results at different stage of loading

Group	Label	At first cracking			At yielding			At ultimate		
		P_c (kN)	Δ_c (mm)	w_c (mm)	P_y (kN)	Δ_y (mm)	w_y (mm)	P_u (kN)	Δ_u (mm)	w_u (mm)
A	PLCS11	7.85	1.73	0.044	24.84	16.70	0.557	28.43	30.33	0.718
	PLCS12	7.98	1.78	0.035	34.56	16.96	0.538	37.32	27.74	0.684
	PLCS13	8.34	1.84	0.029	42.95	19.18	0.483	46.56	25.31	0.625
	PLCS14	8.96	1.88	0.026	47.40	19.47	0.458	50.63	23.72	0.581
	PLCS21	7.98	1.72	0.042	25.80	16.23	0.532	29.32	29.22	0.698
	PLCS22	8.25	1.77	0.034	34.96	16.90	0.502	38.84	27.93	0.664
	PLCS23	8.83	1.82	0.028	43.84	19.05	0.461	48.22	25.03	0.601
	PLCS24	9.38	1.86	0.025	48.58	19.36	0.438	51.76	23.37	0.571
	PLCS31	8.12	1.71	0.039	27.87	15.96	0.508	30.72	29.75	0.672
	PLCS32	8.51	1.74	0.032	35.90	16.85	0.474	39.78	27.06	0.635
	PLCS33	9.15	1.81	0.024	45.50	18.89	0.452	50.13	24.58	0.582
	PLCS34	9.78	1.84	0.021	49.77	19.29	0.418	52.72	23.13	0.558
B	SLCS11	8.16	1.72	0.042	24.98	16.50	0.553	29.14	29.31	0.711
	SLCS12	8.47	1.74	0.034	35.52	16.80	0.534	39.82	27.67	0.682
	SLCS13	8.72	1.80	0.028	43.58	18.85	0.478	47.61	24.99	0.620
	SLCS14	9.31	1.86	0.025	47.96	19.32	0.452	51.33	23.47	0.576
	SLCS21	8.14	1.71	0.040	26.86	16.21	0.528	31.26	29.79	0.692
	SLCS22	8.34	1.75	0.032	36.13	16.86	0.497	40.34	27.46	0.648
	SLCS23	8.77	1.80	0.027	44.79	18.82	0.454	50.00	25.72	0.598
	SLCS24	9.43	1.85	0.025	49.44	19.21	0.434	53.37	23.29	0.567
	SLCS31	8.24	1.70	0.037	27.96	15.91	0.503	32.68	29.52	0.668
	SLCS32	8.50	1.73	0.031	36.80	16.74	0.471	41.88	26.97	0.628
	SLCS33	9.26	1.78	0.026	45.96	17.94	0.438	51.41	25.50	0.580
	SLCS34	9.80	1.82	0.024	50.78	18.80	0.416	54.44	23.10	0.552
C	NCS22	9.98	1.71	0.030	37.38	14.14	0.496	41.34	26.53	0.650

significantly compared to the control. The serviceability may lie in the second segment; the midspan deflection, maximum crack width and reinforcement strain can be determined by assuming that service load is the ultimate load divided by 1.6 (Lim et al. 2011). The reinforcement stresses may be calculated from these measured

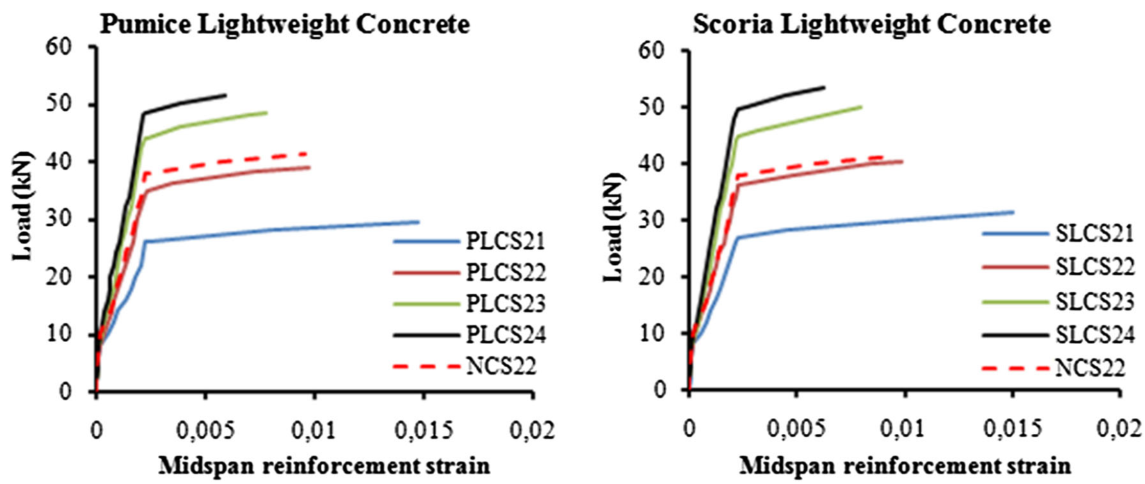

Fig. 7 Load-midspan reinforcement strain diagrams

Table 5 Testing results at assumed service

Group	Label	At assumed service				
		P_s (kN)	Δ_s (mm)	w_s (mm)	ε_s (10^{-2})	f_{ss} (MPa)
A	PLCS11	17.77	10.48	0.398	0.165	337.46
	PLCS12	23.33	10.87	0.324	0.155	316.37
	PLCS13	29.10	11.72	0.254	0.147	301.83
	PLCS14	31.64	11.84	0.204	0.139	284.43
	PLCS21	18.33	9.91	0.388	0.163	332.96
	PLCS22	24.28	10.61	0.304	0.153	312.89
	PLCS23	30.14	11.64	0.242	0.146	297.94
	PLCS24	32.35	11.79	0.200	0.138	283.20
	PLCS31	19.20	9.48	0.358	0.162	332.14
	PLCS32	24.86	10.53	0.287	0.152	311.46
	PLCS33	31.33	11.20	0.232	0.143	293.03
	PLCS34	32.95	11.29	0.192	0.138	281.56
B	SLCS11	18.21	10.37	0.390	0.165	337.05
	SLCS12	24.89	10.66	0.314	0.154	315.76
	SLCS13	29.76	10.99	0.253	0.148	303.88
	SLCS14	32.08	11.35	0.202	0.139	284.22
	SLCS21	19.54	9.90	0.381	0.162	331.73
	SLCS22	25.21	10.58	0.302	0.151	309.20
	SLCS23	31.25	11.24	0.234	0.145	296.92
	SLCS24	33.36	11.37	0.192	0.138	282.79
	SLCS31	20.43	9.46	0.354	0.161	329.68
	SLCS32	26.18	10.49	0.281	0.149	305.11
	SLCS33	32.13	11.18	0.230	0.142	290.77
	SLCS34	34.03	11.26	0.186	0.136	278.49
C	NCS22	25.84	8.96	0.302	0.151	307.97

reinforcement strains; all responses at assumed service are presented in Table 5.

All measured loads of the scoria lightweight concrete one-way slabs at loading stages mentioned previously are slightly higher than those of pumice lightweight concrete one-way slabs. While for the second compressive strength and reinforcement ratio, those loads are smaller than the control. This may be due to the mechanical characteristics of pumice lightweight concrete that does not vary significantly with those of scoria lightweight concrete, as well as both variations are also low compared to the control because their compressive strengths are not significantly different. For increasing the compressive strength of both lightweight concrete, the loads also increase but less significant. Furthermore, these loads increase significantly for increasing the reinforcement ratio of both lightweight concrete types. Thus, these testing results are similar with studies of lightweight concrete beams made of artificial coarse aggregates performed by (Al Mousawi 2011; Shafig et al. 2011; Wu et al. 2011). Both pumice and scoria lightweight concrete one-way slabs crack and also fail earlier than the control as presented by (Lim et al. 2006; Lim et al. 2011).

The responses of bending test, i.e., midspan deflection, reinforcement strain, reinforcement stress and maximum crack width at four different stage of loading also do not differ significantly to coarse aggregate types and compressive strengths, while all responses differ significantly for increasing reinforcement ratio. The midspan deflection of the pumice and scoria lightweight concrete in the second compressive strength and reinforcement ratio are also significantly different when compared to the control. This may be due to the modulus of elasticity of pumice and scoria lightweight concretes range about (72-75)% compared to normal concrete as the control. The nonlinear behavior of reinforced lightweight concrete one-way slabs appeared approximately before the yielding load until to ultimate load. This may be caused by the fast increase of cracks on the tensile concrete zone resulted by bond failure between reinforcement and lightweight concrete. However, other responses, i.e., maximum crack width, tensile reinforcement strain and tensile reinforcement stress, are not significantly different when compared to the control.

Ultimate bending moment

The ultimate bending moment of pumice and scoria lightweight concrete one-way concrete slabs can be calculated from the ultimate load (P_u) at ultimate presented in Table 4. These experimental results are then compared with theoretical calculations based on the analysis of reinforced concrete rectangular cracked section in accordance with (ACI 318M-08 2008). Comparison of experimental results with theoretical calculations is presented in Table 6. These results indicate a similar trend, i.e. their magnitude are significantly influenced by the reinforcement ratios, whereas the compressive strength and the coarse aggregate types affect them less significantly. The ratio of the experimental results and theoretical calculations varies and tends to overestimate and underestimate, but their difference range between (0.04–7.35)% with the average value is approximately 3.7%. So it may be said that these testing results are well predicted by theoritical calculation of ACI 318M-08 code.

Midspan instantaneous deflection

The experimental instantaneous midspan deflections are determined by taking the load at assumed service mentioned previously. These experimental results are then compared with theoretical calculations based on the analysis of reinforced concrete rectangular cracked sections in accordance with (ACI 318M-08 2008). Comparison of experimental results with theoretical calculations is presented in Table 6. These results also indicate the similar trend, i.e. their magnitude are significantly influenced by the reinforcement ratios, whereas the compressive strength and the coarse aggregate types less affect them. The magnitude of the experimental results ratio and theoretical calculations varies, but tends to underestimate with 14.95% maximum difference. Pumice and scoria are vesicular rocks and their groundmass are composed of dominant glassy amorphous structures; this may lead to low modulus of elasticity of the pumice and scoria lightweight concretes so that their stiffness is also low and then midspan deflections become large.

Maximum crack width

The experimental maximum crack widths are determined by taking the load at the same assumed service load as before. These experimental results are then compared with theoretical calculations based on Gergely–Lutz formula (McGregor 1997; Park and Gamble 1980). Comparison of experimental results with theoretical calculations is presented in Table 6. These results also indicate the similar trend, i.e. their magnitude are significantly influenced by the reinforcement ratios, whereas the compressive strength and the coarse aggregate types less to affect them. The magnitude of the experimental results ratio and theoretical calculations also varies, but tends to under estimate with 21.71% maximum difference. This may also be due to the physical characteristics of pumice and scoria mentioned previously so that the mechanical characteristics of both lightweight concrete differ from normal concrete.

Cracking patterns and failure modes

The testing results showed that the cracking patterns of pumice and scoria lightweight one-way concrete slabs as well as the control are flexural cracks and presented in Fig. 8. All cracks were flexural types with vertical direction and no diagonal crack appeared during loading conducted, this indicate that a bond failure occured between reinforcement and three types of concrete. The number of

Table 6 Comparison of experimental results with theoritical calculation

Group	Label	Ultimate bending moment		Ratio of M_{ue}/M_{ut}	Δ_{st} (mm)	Ratio of Δ_s/Δ_{st}	w_{st} (mm)	Ratio of w_s/w_{st}
		M_{ue} (kNm)	M_{ut} (kNm)					
A	PLCS11	14.22	14.85	0.9576	9.63	1.0883	0.367	1.2171
	PLCS12	18.66	19.22	0.9709	10.50	1.0352	0.312	1.1655
	PLCS13	23.28	23.29	0.9996	11.29	1.0381	0.277	1.0283
	PLCS14	25.32	27.08	0.9350	11.82	1.0017	0.245	0.9315
	PLCS21	14.66	15.04	0.9747	9.07	1.0926	0.362	1.2050
	PLCS22	19.42	19.56	0.9928	10.23	1.0372	0.309	1.1055
	PLCS23	24.11	23.82	1.0122	11.13	1.0458	0.273	0.9959
	PLCS24	25.88	27.84	0.9296	11.73	1.0051	0.244	0.9174
	PLCS31	15.36	15.19	1.0112	8.36	1.1340	0.361	1.1118
	PLCS32	19.89	19.83	1.0030	9.82	1.0723	0.308	1.0475
	PLCS33	25.07	24.25	1.0338	10.82	1.0351	0.269	0.9707
	PLCS34	26.36	28.45	0.9265	11.47	0.9843	0.243	0.8889
B	SLCS11	14.57	14.90	0.9779	9.57	1.0836	0.366	1.1963
	SLCS12	19.91	19.30	1.0316	10.49	1.0162	0.312	1.1295
	SLCS13	23.81	23.42	1.0167	11.31	0.9717	0.279	1.0202
	SLCS14	25.67	27.25	0.9420	11.87	0.9562	0.245	0.9266
	SLCS21	15.63	15.08	1.0365	8.84	1.1199	0.361	1.1869
	SLCS22	20.17	19.63	1.0275	10.07	1.0506	0.305	1.1103
	SLCS23	25.00	23.94	1.0443	10.99	1.0228	0.272	0.9669
	SLCS24	26.69	28.01	0.9529	11.60	0.9802	0.244	0.8848
	SLCS31	16.34	15.23	1.0729	8.23	1.1495	0.358	1.1097
	SLCS32	20.94	19.88	1.0533	9.75	1.0759	0.301	1.0485
	SLCS33	25.71	24.33	1.0567	10.78	1.0371	0.267	0.9705
	SLCS34	27.22	28.57	0.9528	11.45	0.9834	0.240	0.8692
C	NCS22	20.67	19.68	1.0503	8.53	1.0504	0.304	1.1144

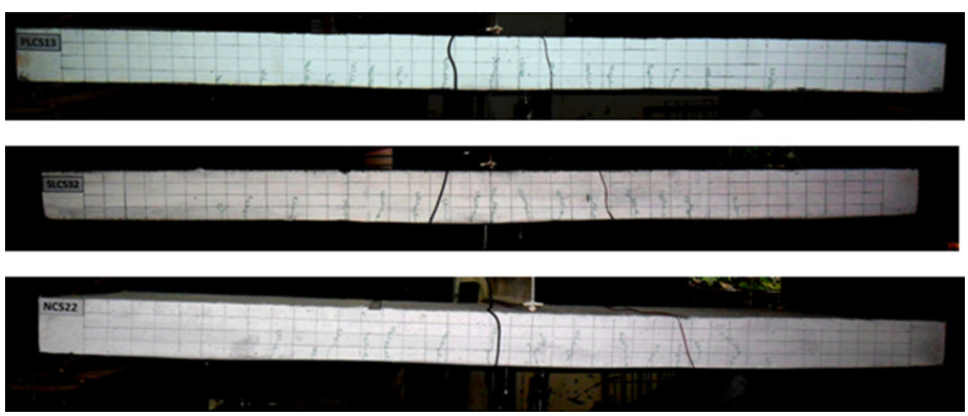

Fig. 8 Cracking patterns of three one-way slabs

cracks on the sides of pumice lightweight concrete one-way slabs ranged (13–21), while for scoria lightweight concrete one-way slabs ranged (12–20). For the second compressive strength and reinforcement ratio, the number of cracks of the pumice lightweight concrete one-way slab is greater than the control, while the scoria lightweight concrete one-way slab is the same number as the control. The maximum crack width of those lightweight concrete one-way slabs should be lower than the control but in reality was slightly higher than the control so this result is different from the previous studies conducted by (Lim et al. 2006, 2011). These differences may be due to differences in physical characteristics of pumice and scoria lightweight coarse aggregates with artificial lightweight coarse aggregates designed with accurate quality controls. All lightweight concrete one-way slabs as well as the control failed in the similar failure modes according to the previous designs, i.e., reinforcement yielding at the first time and then crushing concrete without any spalling on the concrete compressive zone.

Conclusions

This study proved that the medium-K basaltic andesite pumice and scoria as coarse aggregates can be used to produce lightweight concrete one-way concrete slabs with a relative satisfactory performance. From the experimental investigations reported on this paper, the following conclusions may be drawn:

1. All pumice and scoria lightweight concrete one-way slabs indicate typically the flexural behavior as reinforced concrete beams, while initial crack loads, ultimate loads and stiffness are lower than normal concrete one-way slabs as the control.
2. The reinforcement ratio is the most significant factor affecting the flexural behavior compared to the type of coarse aggregates and compressive strength.
3. Ultimate bending moment may be well predicted by theoretical calculations based on ACI 318-08 code.
4. The theoretical calculation of the instantaneous deflection based on ACI 318-08 code tends to underestimate with 14.95% maximum difference.
5. The theoretical calculation of the maximum crack width based on the Gergely–Lutz formula tends to underestimate with 21.71% maximum difference.
6. All one-way slabs show the cracking patterns due to flexure according to the design conducted previously, whereas the failure modes are indicated by reinforcement yielding at the first time and then crushing concrete without any spalling on the concrete compressive zone.

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References

ACI 213.R-03. (2003). *Guide for structural lightweight aggregate concrete*. Detroit: American Concrete Institute.

ACI 318M-08. (2008). *Building code requirements for structural concrete and commentary*. Detroit: American Concrete Institute.

Al Naaymi, T. A. (2015). Assessment of pumice and scoria deposits in Dhamar–Rada' volcanic field SW-Yemen, as a pozzolanic materials and lightweight aggregates. *International Journal of Innovative Sciences Engineering and Technology, 9*(2), 386–402.

Al Mousawi, A. N. (2011). Flexural and shear performance of high strength lightweight reinforced concrete beams. Philosophy Doctor Thesis, University of Illinois.

Al Nasser, S., Shannag, M. J., Charif, A. (2014). Flexural behavior of reinforced concrete beams made with natural lightweight aggregates. *Proceeding of The Second International Conference on Advanced in Civil, Structural and Environmental Engineering-ACSEE 2014*, Institute of Research Engineers and Doctors, Zurich, pp. 176–79.

ASTM C 567-00. (2000). *Standard test method for determining density of structural lightweight concrete*. West Conshohocken: ASTM International.

Bourdier, J. L., Indyo, P., Thouret, J. C., Boudon, G., & Vincent, P. M. (1997). Observation, stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano, Indonesia. *Journal of Volcanology and Geothermal Research, 79,* 181–203.

Chandra, S., & Berntsson, L. (2003). *Lightweight aggregate concrete: science, technology and applications*. New York: Noyes Publications.

Eurocode 2 EN 1992-1-1. (2004). *Design of concrete structures. Part 1-1: general rules and rules of buildings*. Brussel: European Committee for Standardization.

Hossain, K. M. A. (2004a). Properties of volcanic pumice based cement and lightweight concrete. *Cement and Concrete Research, 34,* 283–291.

Hossain, K. M. A. (2004b). Properties of volcanic scoria based lightweight concrete. *Magazine of Concrete Research, 34,* 283–291.

Jomaa'h, M. M., Daham, H. A., & Rao'of, S. M. (2012). Flexural behavior of lightweight concrete beams. *European Journal of Scientific Research, 4*(58), 582–592.

Juwana, J. S. (2005). *Panduan Sistim Bangunan Tinggi untuk Arsitek dan Praktisi Bangunan, (Guide of High Rise Building System for Building Engineer and Architect)*. Jakarta: Penerbit Erlangga.

Kilic, A., Atis, C. D., Teymen, A., Karahan, O., & Ari, K. (2009). The effect of scoria and pumice aggregates on the strengths and unit weights of lightweight concrete. *Scientific Research and Essay, 10*(4), 961–965.

Kumar, K. H., & Polu Raju, P. (2017). Comparative study on flexural behaviour of lightweight aggregate RC beams. *International Journal of Civil Engineering and Technology*, *8*(4), 1546–1561.

Lim, H. S., Wee, T. H., Islam, M. R., & Mansur, M. A. (2011). Reinforced lightweight concrete beams in flexure. *ACI Structural Journal, 1*(108), 3–12.

Lim, H. S., Wee, T. H., Mansur, M. A., Kong, K. H. (2006). Flexural behavior of reinforced lightweight concrete beams. *Proceeding of The 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006*), Kuala Lumpur, Malaysia, pp. 68–82.

Madheswaran, C. K., Ambily, P. S., Rajamane, N. P., & Arun, G. (2014). Studies on flexural behaviour of reinforced geopolymer concrete beams with lightweight aggregates. *International Journal of Civil and Structural Engineering*, *4*(3), 295–305.

McCormac, J. C. (2001). *Design of reinforced concrete* (5th ed.). New York: Wiley.

McGregor, J. G. (1997). *Reinforced concrete, mechanics and design*. New Jersey: Prentice-Hall Inc.

Mehta, P. K., & Monteiro, P. J. M. (1993). *Concrete structure properties and materials*. New Jersey: Prentice Hall Inc.

Nawy, E. G. (1985). *Reinforced concrete, a fundamental approach*. New Jersey: Prentice-Hall Inc.

Palani, S., & Sakthiswaren, N. (2015). Flexural behaviour of reinforced beam made with light weight aggregate concrete. *International Journal of Innovative Research in Science, Engineering and Technology*, *4*(6), 1751–1755.

Park, R., & Gamble, W. L. (1980). *Reinforced concrete slabs*. New York: Wiley.

Setareh, M., & Darvas, R. (2017). Concrete Structures. Switzerland: Springer International Publishing.

Shafig, P., Hassanpour, M. M., Razavi, S. V., & Kobraei, M. (2011). An investigation of the flexural behavior of reinforced lightweight concrete beams. *International Journal of the Physical Sciences, 10*(6), 2414–2421.

Shannag, M. J. (2011). Characteristics of lightweight concrete containing admixtures. *Construction and Building Materials, 25,* 658–662.

SNI 1726:2012. (2012). *Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Non Gedung, (Design Method of Earthquake Resistant for Building Structures and Non Building)*. Jakarta: Badan Standarisasi Nasional.

SNI 2847:2013. (2013). *Persyaratan Beton Struktural untuk Bangunan Gedung, (Building Code Requirements for Structural Concrete)*. Jakarta: Badan Standarisasi Nasional.

Suseno, H., Agoes Soehardjono, M. A., Wardana, I. N. G., & Rachmansyah, A. (2017). Suitability of Medium-K basaltic andesite pumice and scoria as coarse aggregates on structural lightweight concrete. *International Journal of Engineering and Technology, 4*(9), 3318–3329.

Team Works. (2010). *Peta Hazard Gempa Indonesia 2010, (Indonesian Earthquake Hazard Map 2010)*. Jakarta: Kementerian Pekerjaan Umum.

Tomicic, I. (2012). Analysis of lightweight aggregates concrete beams. *Gradevinar, 10*(64), 817–823.

Widodo, S., Satyarno, I., & Tujono, S. (2014). Experimental study on the potential use of pumice breccia as coarse aggregate in structural lightweight concrete. *International Journal of Sustainable Construction Engineering and Technology, 1*(5), 1–8.

Wu, C. H., Kan, Y. C., Huang, C. H., Yen, T., & Chen, L. H. (2011). Flexural behavior and size effect of full scale reinforced lightweight concrete beams. *Journal of Marine Science and Technology, 2*(19), 132–140.