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Evaluation of factors influencing the maximum crack width of pumice and scoria lightweight concrete one-way slabs

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Abstract

This paper presents an evaluation of two physical properties of pumice and scoria as coarse aggregates of lightweight concrete, namely high porosity and amorphous glass microstructure that comprises their solid masses. Due to these adverse properties, the tensile strengths of both lightweight concrete materials were low and the bond strengths were also diminished because they have a strong relationship with porosity and microstructure. This study experimentally investigated the influence of low bond strength on the maximum crack width of lightweight concrete one-way slabs using pumice and scoria as coarse aggregates. The tensile strengths were represented by compressive strengths, which are generally considered to be correlated and vary according to the concrete mix proportions. Additionally, the differences of tensile strengths were also evaluated according to the type of coarse aggregate used, i.e., pumice and scoria. Two principal factors influencing the maximum crack width, the ratio of reinforcement and reinforcement tensile stress, were also evaluated for comparison. The lightweight concrete compressive strengths as well as the ratio of reinforcement were varied such that the evaluation could be properly conducted. The results showed that the tensile strength and the type of lightweight coarse aggregate less significantly influenced the maximum crack width. Furthermore, the ratio of reinforcement and the reinforcement tensile stress remained the principal factors influencing the maximum crack width of both types of volcanic lightweight concrete one-way slabs. Hence, these adverse properties should not be taken into account in analysis and design.

Keywords: Pumice, Scoria, Lightweight concrete, One-way slab, Maximum crack width

1. Introduction

Natural or volcanic lightweight concrete is classified as a structural lightweight concrete [1] where the coarse lightweight aggregate includes pumice or scoria combined with river sand as a fine aggregate. Generally, structural lightweight concrete uses artificial coarse lightweight aggregates that are a factory products from sintering processes of natural materials or industrial wastes, like clay, slate, and fly ash, among others [2, 3]. Therefore, their production requires much heat energy, releases air pollution and the obtained lightweight concretes may be expensive. Additionally, no energy is saved and the products are less environmentally friendly. Volcanic coarse lightweight aggregates, pumice or scoria, are used as substitutes for those artificial products [4-6]. Their use is very advantageous because these materials are available in abundance in volcanic areas of the country. Thus, the obtained structural lightweight concretes are inexpensive, require less energy for production and are more environmentally friendly. Such product are called green lightweight concretes.

Several studies concerning the use of these vesicular rocks as coarse aggregates have been carried out by researchers in other countries. Lightweight concrete was made with pumice and scoria in Papua New Guinea [7, 8], Turkey [9], and Yemen [10]. Other studies investigated lightweight concrete made with pumice from Iran [11] and made with scoria in Saudi Arabia [12] and Cameroon [13]. These structural lightweight concrete materials showed a density reduction of about 20% to 23%. However, as with many natural materials, these volcanic lightweight coarse aggregates have two adverse physical properties. First, they have amorphous glass microstructures [14]. Their atomic bonds are weak making their physical and mechanical characteristics poorer [15]. Moreover, they have high porosities which also reduce their physical and mechanical characteristics [15] as well as provide for high absorption and an increased absorption rate [8]. Therefore, the workability of lightweight concrete mixtures decreases significantly and the resulting hardened concrete may become porous. For this reason, special treatments must be used when employing coarse aggregates. For example, presoaking these materials in various ways and at certain times is required. Some pretreatments involve presoaking for 24 hours, presoaking until the Saturated Surface Dry (SSD) condition or presoaking under a vacuum.

Two coarse lightweight aggregates used in Indonesia are medium-K basaltic andesitic pumice and scoria ejected from the Kelud volcano [16, 17], which is located in East Java Province. Although they are different in color, pumice is pale while scoria is black, both have practicaly similar physical characteristics. Their specific gravity [18], density and the compressive strength of intact rock core as well as oven dry density and bulk specific gravity of coarse aggregate [19] make them unique compared to the existing vesicular rocks. Physically, pumice is denser and stronger but rather heavy. Scoria has a lower density and is less strong, but it is lighter. This may be

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due to the combination between andesite and basalt minerals that comprises their solid masses. Their porosities were relatively high but the particle density are greater than one [18], so they immediately sink in water. Additionally, they are quite brittle with a rough and sharp surfaces. This may be caused by the amorphous glass microstructure which dominates their solid masses. Application of these vesicular rocks as coarse aggregates of lightweight concrete has been done previously by presoaking the materials for 18 hours and with no admixtures [19, 20]. Structural lightweight concrete materials were produced with compressive strengths that achieved 30 MPa at 28 days and their density was approximately 80% of that of normal weight concrete. However, the splitting tensile strength as well as the modulus of rupture are quite low, about 74% and 83%, respectively, of the splitting tensile strength and modulus of rupture of the normal weight concrete that was used as a control.

The application of lightweight concrete materials using both volcanic lightweight aggregates on structural elements was studied by researchers in several countries. Investigation of reinforced lightweight concrete beams made from commercial pumice in Singapore with water-reducing admixtures was investigated [21]. The results indicated that the parameters of flexural behavior can be predicted quite accurately with the ACI 318-99 code. A study of reinforced lightweight concrete beams with diatomic limestone as a coarse lightweight aggregate was performed in Iraq [22]. The results showed that the experimentally determined flexural behavior was similar to that of reinforced normal concrete beams and was verified using numerical simulation. An experimental investigation of lightweight concrete beams made with scoria coarse aggregate from Saudi Arabia was conducted [23] utilizing water-reducing and mineral admixtures. The results indicated the similarity of flexural behavior to the normal weight concrete beams and their suitability as structural elements with significant bending strength. An experimental investigation on lightweight concrete one-way slabs with typical pumice and scoria was done in Indonesia [17, 24]. The results indicated satisfactory performance as reinforced lightweight concrete structural elements with similar flexural behavior to normal weight concrete one-way slabs. However, the testing results of instantaneous deflection and the maximum crack width differed slightly when compared with calculational results.

The maximum crack width is one of the parameters of reinforced concrete structure in serviceability which must be evaluated due to low concrete tensile strength [25-27]. Its magnitude is determined by the service load on cracking behavior, which is expressed by the relationship between the load and the crack width obtained from bending tests. The steel reinforcement stress that occurs and the ratio of reinforcement in the cross-section of structural elements are the principal factors that significantly influence the maximum crack width as well as the cracking behavior [28, 29]. Other factors such as compressive strength and modulus of elasticity of the concrete, as well as the diameter of reinforcement, concrete cover and spacing of reinforcement also influence the maximum crack width, but less significantly. Analytically, the maximum crack width is determined by the maximum crack spacing which in turn depends on the bond strength between the steel bar with the surrounding concrete [30]. This bond strength is a function of the concrete tensile strength [31-33], so that it is practical and easy to calculate. The concrete tensile strength decreases, such that the bond strength is reduced, the maximum crack spacing increases and the maximum crack width becomes wider. The tensile strength of normal weight concrete is only 8% to 15% of its compressive strength [26] and the flexural strength is only 9% to 13% of its compressive strength [5]. For lightweight concrete using river sand as a fine aggregate, the tensile strength is approximately 80% to 100% of that of normal weight concrete [26] while its modulus of rupture is 85% of that of normal weight concrete [27, 34]. This tensile strength, as well as the flexural strength, are proportionally correlated to its compressive strength [35]. For pumice lightweight concrete, the tensile strength was also correlated as a linear function of its compressive strength [36]. Similarly, for pumice and scoria lightweight concretes, the splitting tensile strength as well as the modulus of rupture were proportionally correlated to their compressive strengths [37]. Generally, the failure mode of the lightweight concrete differs from the normal weight concrete. Failure occurs first in the coarse aggregate because it is weaker than the cement paste and the transition zone [3, 35]. Due to the presoaking of both volcanic coarse aggregates before mixing the concrete, their internal water contents significantly increased and interfacial transition zones formed. Hence, this failure mode may also occurs in these volcanic lightweight concretes when they are applied in reinforced lightweight concrete structural elements. Similarly, their amorphous glass microstructure may affect the cracking pattern indicated by the number of cracks.

Coarse aggregate occupies the largest portion of the total volume of normal weight concrete, in the range of 30% to 50% [4, 5] and this also applies to lightweight concrete. Therefore, the adverse properties in this volcanic lightweight aggregate must be properly considered when it is used as reinforced concrete structural elements. When external loads are applied to them, these coarse lightweight aggregates fail before the overall failure because they are weaker than the cement paste and transition zone. Therefore, the splitting tensile strength or modulus of rupture of pumice and scoria lightweight concrete were very low. The splitting tensile strength of lightweight concrete with pumice from Papua New Guinea was about 9% to 12% of its compressive strength [7, 36, 38]. The lightweight concrete splitting tensile strength with scoria from Papua New Guinea was about 11% of its compressive strength [8]. The splitting tensile strength of lightweight concrete with pumice from Iran was about 7% to 9% of its compressive strength [11]. The lightweight concrete splitting tensile strength with scoria from Saudi Arabia was about 8% to 12% of its compressive strength [12]. The modulus of rupture of lightweight concrete with pumice and scoria from Turkey were about 17% to 22% of its compressive strength [9]. The splitting tensile strength and modulus of rupture of lightweight concretes with typical pumice and scoria from Indonesia were about 9% and 12%, respectively, compared to their compressive strengths [19, 20]. Moreover, these were about 82% and 83%, respectively, of the splitting tensile strength and modulus of rupture of normal weight concrete. These percentages provide the reductions of tensile strength of about 17% to 18%, higher than the previously projected, about 15%. The bond strengths also become low and may eventually influence the maximum crack width obtained experimentally. An investigation like this has not been carried out before. The current study focuses on one-way slabs utilizing pumice and scoria lightweight concretes. So, it is necessary to evaluate whether low bond strength due to the adverse properties should be taken into account in the analysis and design.

The purpose of this work is to evaluate the influences of the tensile strength of pumice and scoria lightweight concrete on the maximum crack width of one-way slabs. These tensile strengths are described by the splitting tensile strength that are represented by their compressive strengths. Similarly, the influence of typical coarse lightweight aggregate, pumice and scoria, on the maximum crack width is also considered. For comparison, the maximum crack width is also evaluated for the two principal influencing factors, the specified ratio of reinforcement on the one-way slab and the experimentally measured reinforcement tensile stress. Several factors such as the diameter of steel bar used, concrete cover and steel bar spacing were kept constant so that their influences were not considered in this evaluation. Additionally, this study is an effort to promote the use of pumice and scoria from the Kelud volcano and other volcanic areas in Indonesia as construction materials for precast slab units.

2. Materials and methods

2.1 Materials

The structural lightweight concrete was made using two volcanic lightweight aggregates with no admixtures. Coarse lightweight aggregates were obtained by crushing two typical batches of pumice and scoria mined from the Badak river lava catchment areas of the Kelud volcano. Coarse aggregate gradation was designed to separate the material into four particle sizes with a 19 mm maximum size. This gradation met the requirement stated by ASTM Committee C330, 2004 [39] with a fineness modulus of 6.69. Normal-weight concrete was used as a control, where local crushed stone with a similar gradation was utilized as a coarse aggregate. Figure 1 presents images of pumice, scoria and their gradations. River sand of 4.75 mm maximum grain size was utilized as fine aggregates with a gradation that met the requirements of ASTM Committee C330, 2004 [39] with a fineness modulus was 2.61. Portland-Pozzolan Cement (PPC) and clean water were used as a binder in all concretes. For all one-way slabs, D13 deformed steel bar was used for longitudinal reinforcement, while the transversal reinforcements were ϕ6 mm plain steel bar. The testing results of three specimens steel bars showed that the average yield tensile strength was f_y = 457.45 MPa, ultimate tensile strength was f_u = 648.36 MPa, modulus of elasticity was E_s = 204.77 GPa, yield strain was ε_y = 0.00224 and ultimate strain was ε_u = 0.03341.

(a) (b) (c)

Figure 1 (a) Pumice and scoria, (b) Gradation of pumice, and (c) Gradation of scoria

2.2 Experimental design

There were two types of lightweight concrete mixtures. Group A represented pumice lightweight concrete whereas Group B consisted of scoria lightweight concrete. Both were designed utilizing the weight method presented by the practical standard of ACI Committee 211.2, 2004 [40]. Each group included three mixed proportions for designed compressive strengths of 20 MPa, 25 MPa and 30 MPa. In this method, the absorption of both coarse lightweight aggregates was precisely determined in the SSD condition at 96 hours [19, 20]. The slump value was specified to be between 60 to 70 mm and the air content in both lightweight concretes types was assumed to be about 3 to 4%. For a 1 m^3 volume of lightweight concrete, the approximate weight of mixing water can be determined. The average compressive strength was determined according to the Indonesian standard of Badan Standardisasi Nasional, 2019 [41]. Furthermore, the water-cement ratio can be determined and the weight of the cement components was obtained. The estimate volume of the oven dry coarse lightweight aggregate proportion was based on the maximum size of coarse aggregate and the fineness modulus of sand. The weight of the SSD coarse lightweight aggregate proportion can be converted using the oven dry density and absorption at 96 hours. Additionally, the weight of the SSD sand proportion can be determined from the estimated weight of the fresh lightweight concrete as a function of the air content and the specific gravity of coarse lightweight aggregate. Before mixing the concrete, the coarse lightweight aggregate was presoaked for 16 hours and its water content with the existing water content of sand was used to correct the weight of approximate amount of water in the concrete mixture. Group C was normal weight concrete used as a control, where the mixed proportion was designed according to the practical standard of ACI Committee 211.1, 2002 [42] with a designed compressive strength of 25 MPa. The results of the calculation of mix proportions are given in Table 1, where the coarse lightweight and normal-weight aggregates are in a damp condition.

Table 1 Calculated concrete mix proportions

Group	Typical coarse aggregate (CA)	Label	Designed compressive strength (MPa)	Mix proportions per 1 m^3 volume (kg)			
				PPC	Sand	CA	Water
A	Pumice	PLCS1	20	323	687	631	202
		PLCS2	25	377	633	626	190
		PLCS3	30	424	588	627	191
B	Scoria	SLCS1	20	323	711	704	182
		SLCS2	25	377	657	699	183
		SLCS3	30	424	612	694	199
C	Crushed stone	NCS2	25	377	780	988	200

The specimens included twenty-five one-way slabs. Of these, twelve pumice lightweight concrete slabs were classified in Group A and referenced as PLCS. Twelve scoria lightweight concrete slabs were in Group B and referenced as SLCS. Additionally, one normal weight concrete slab was used as a control in Group C and referenced as NCS. Three designed compressive strengths were determined for the two lightweight concrete types. Groups A and B were further divided into four typical slabs according to the specified ratio of reinforcement. All one-way slabs were analytically designed as reinforced concrete beams with a single reinforcement and the failure modes were a first yield reinforcement. Therefore, the ratios of longitudinal reinforcement were between ρ_{min} and ρ_{max}

so their numbers were 3, 4, 5 and 6 D13 steel bars. Practically, the transversal reinforcements did not contribute to the bending strength and were only considered as holders of longitudinal reinforcement. The detailed experimental design is described in Table 2.

Table 2 Experimental design

Group	Designed compressive strength (MPa)	Label	Steel bar number	Ratio of reinforcement ρ
A	20	PLCS11	3	0.00671
		PLCS12	4	0.00895
		PLCS13	5	0.01119
		PLCS14	6	0.01342
	25	PLCS21	3	0.00671
		PLCS22	4	0.00895
		PLCS23	5	0.01119
		PLCS24	6	0.01342
	30	PLCS31	3	0.00671
		PLCS32	4	0.00895
		PLCS33	5	0.01119
		PLCS34	6	0.01342
B	20	SLCS11	3	0.00671
		SLCS12	4	0.00895
		SLCS13	5	0.01119
		SLCS14	6	0.01342
	25	SLCS21	3	0.00671
		SLCS22	4	0.00895
		SLCS23	5	0.01119
		SLCS24	6	0.01342
	30	SLCS31	3	0.00671
		SLCS32	4	0.00895
		SLCS33	5	0.01119
		SLCS34	6	0.01342
C	25	NCS22	4	0.00895

2.3 Production of slab specimens

Molds were made of 12 mm thick multiplex with wooden ribs as stiffeners. The longitudinal reinforcements were assembled in accordance with the number of steel bars and held by five transversal steel bars. Figure 2 shows the details of reinforcement of one-way slab cross-sections. A strain gauge was placed in the center of one of the longitudinal reinforcement bars to measure the tensile strain in the reinforcement. The batching of concrete materials was conducted by weighing them according to the mix design. Before mixing the concrete, pumice and scoria coarse aggregate were presoaked for 16 hours and surface dried. This aimed to decrease their high absorption values at 24 hours, which were 16.2% for pumice lightweight aggregate and 12.3% for scoria lightweight aggregate. All concrete mixes were made using a mixer with a 1200 liter capacity and the slump values were determined as before. Each specimen was cast in two layers and was internally compacted using a vibrator. Similarly, the casting of five 150 x 300 mm cylindrical specimens was done to determine the density, compressive strength, modulus of elasticity and splitting tensile strength of hardened concrete. All specimens were covered by wet burlap during a seven-day curing period, then placed in a dry room until the testing was done. Demolding of the one-way slabs were done 21 days after casting.

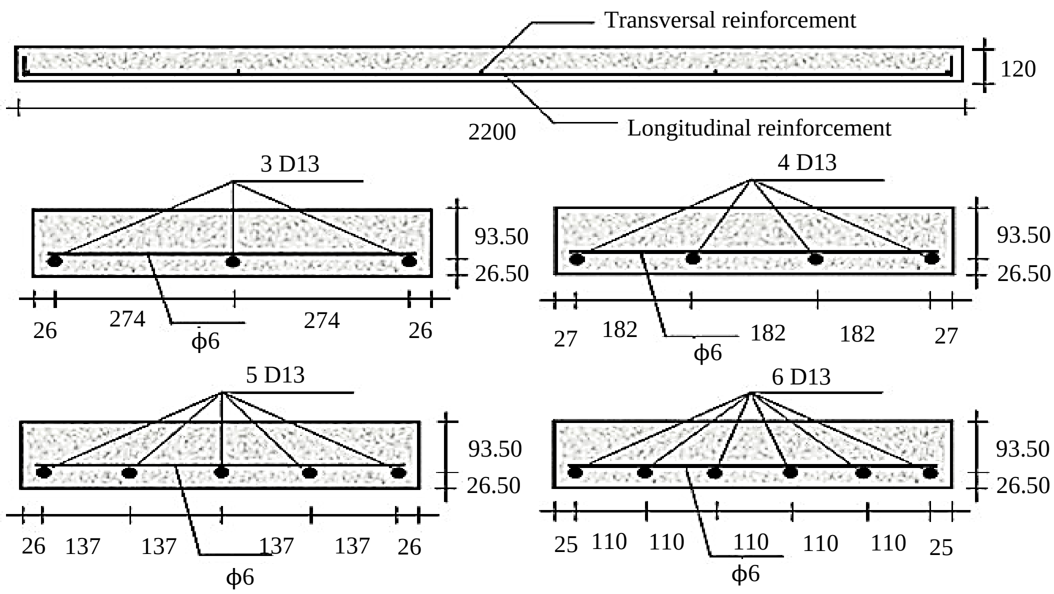

Figure 2 Scheme of reinforcement in the one-way slab cross-sections

2.4 Three point bending tests

All one-way slab specimens were tested as a simple beams placed on hinge and roller supports with a 2000 mm span. Three-point bending tests were carried out at 28 days after casting by applying a lateral line load at the slab midspan. The loads were gradually applied using a hand pump, while the load cell readings were recorded using a load indicator. The tensile strain in the reinforcement was measured using a strain gauge and recorded by a strain meter. An LVDT was placed at the center of the slab to monitor the resulting deflection. The widest cracks were selected on the side or bottom surface of one-way slabs and photographed using a Dino-Lite Edge Digital Microscope. Furthermore, the crack widths were measured at the maximum distance between two crack surfaces in these photographs using software provided by the microscope manufacturer. Prior to testing, 0.5 kN initial loading was applied to eliminate any movement at the supports. Then the equipment was re-initialized. The loads were gradually applied in 2 kN increments until failure was reached. Parameters that included reinforcement tensile strain and crack width were recorded and specimens were photographed at each interval. Simultaneously, cylinder tests were also done to measure the physical and mechanical characteristics described above. Figure 3 shows a schematic three-point bending test whereas Figure 4 presents an image of the instrument setup used in the current study.

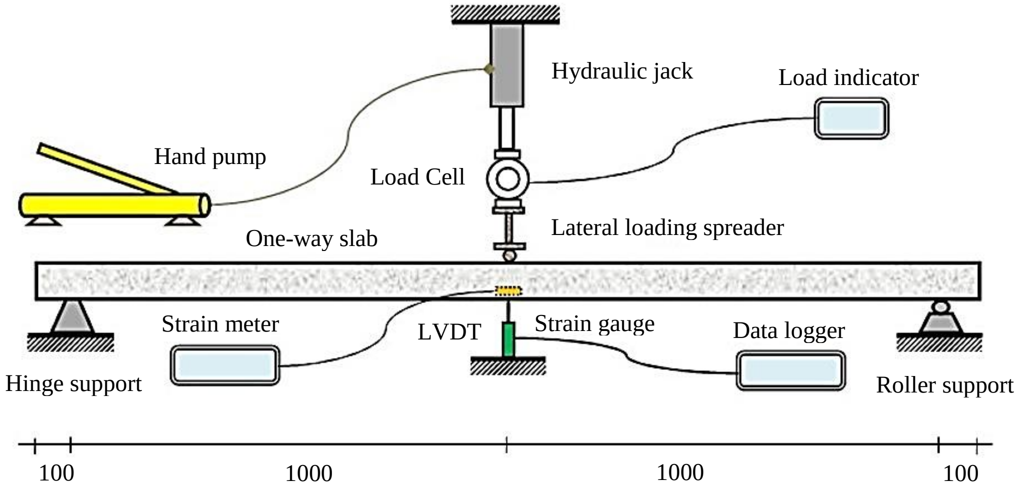

Figure 3 Scheme of the three-point bending testing apparatus

Figure 4 Instrument setup used

3. Results and discussion

3.1 Concrete characteristics

Table 3 shows that the average slump values of three typical concrete types meet the previously determined value with standard deviations (SDs) in the range of 0.14 mm to 0.20 mm. All concrete mixtures indicated satisfactory workabilities without exaggerated bleeding and segregation. The average equilibrium density for pumice and scoria lightweight concrete specimens meet the requirements for structural lightweight concrete of ACI Committee 213, 2014 [1] with SD values in the range of 21 kg/m^3 to 32 kg/m^3. The densities are about 75% and 77%, respectively, for pumice and scoria lightweight concrete of the normal- weight concrete used as control. The average compressive strengths meet those designed in the previous mix design with SD values in the range of 0.17 MPa to 0.28 MPa. The average moduli of elasticity are lower than that of the normal-weight concrete used as control with SDs in the range of 327 MPa to 420 MPa. These moduli of elasticity are about 72% and 75%, respectively, for pumice and scoria lightweight concrete of that of normal-weight concrete. The average splitting tensile strengths are also low with SD values in the range of 0.01 MPa to 0.03 MPa.

These splitting tensile strengths are about 76% and 80%, respectively, of normal-weight concrete and they are about 9% and 10% of their compressive strengths. Thus, these percentages are similar to values reported in earlier studies.

Table 3 Characteristics of fresh and hardened concrete

Group	Label	Slump value (mm)	Concrete density (kg/m^3)	Measured Compressive strength (MPa)	Modulus of elasticity (MPa)	Splitting tensile strength (MPa)
A	PLCS1	61	1787	22.2	12294	2.14
	PLCS2	61	1793	26.0	13414	2.55
	PLCS3	63	1808	30.1	14942	2.78
B	SLCS1	64	1812	23.0	12368	2.19
	SLCS2	63	1829	27.0	13982	2.69
	SLCS3	62	1835	31.1	15159	2.90
C	NCS2	64	2385	26.7	18630	3.36

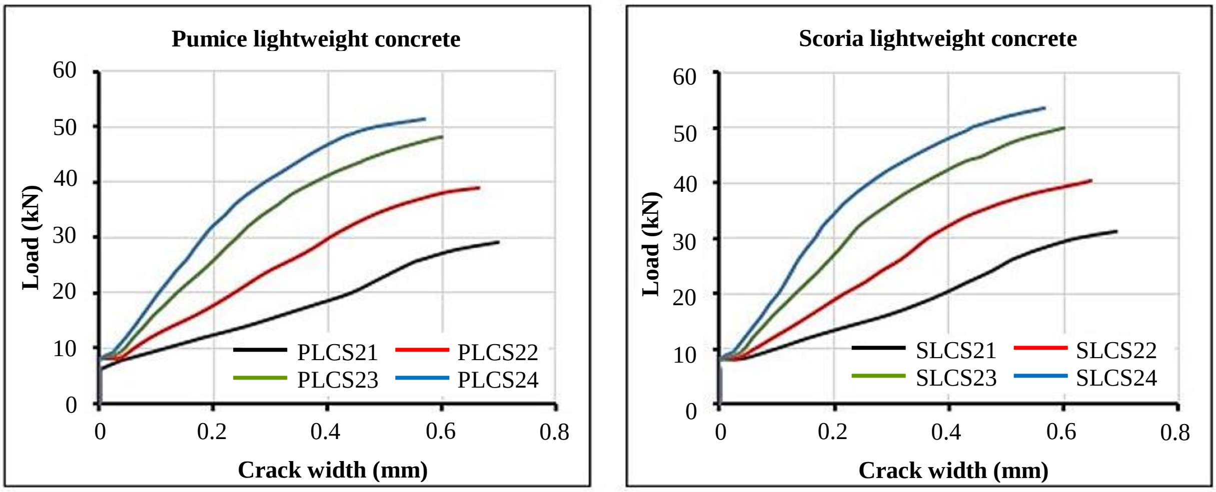

Figure 5 Diagram of load-crack width for both lightweight concrete one-way slabs

3.2 Diagrams of load-crack width

Figure 5 presents a diagram of load-crack width for one-way slabs with compressive strengths of 26.0 MPa and 27.0 MPa for pumice and scoria lightweight concrete. From these figures, it can be seen that the cracking behaviors vary significantly in accordance with the ratio of reinforcement. When the ratio of reinforcement increases, the slope of the curve significantly increases and the crack width decreases. Furthermore, when the type of coarse lightweight aggregate is considered, pumice and scoria, the cracking behaviors vary less significantly. Other compressive strengths indicate similar trends and also vary less significantly for variations of compressive strength. Thus, the cracking behavior of normal-weight reinforced concrete [25-27] is similar to that of reinforced lightweight concrete beams made using scoria coarse lightweight aggregate [23], and to that of reinforced lightweight concrete beams using Leca artificial coarse lightweight aggregate [43, 44].

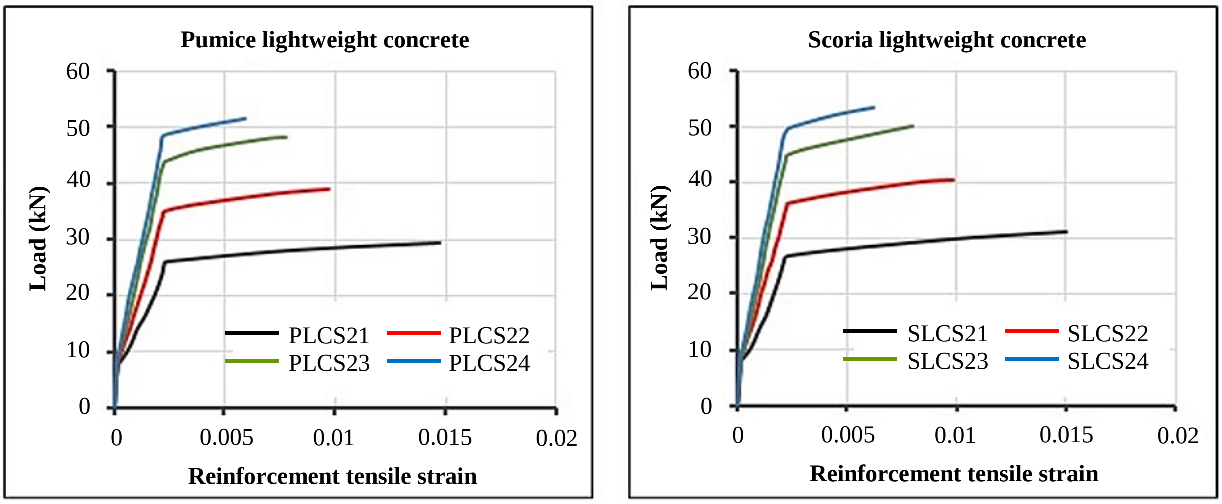

Figure 6 Diagram of load-reinforcement tensile strain

3.3 Diagrams of load-reinforcement strain

Figure 6 presents a diagram load-reinforcement tensile strain at midspan for one-way slabs using pumice lightweight concrete with a 26.0 MPa compressive strength and scoria lightweight concrete with 27.0 MPa compressive strength. From these figures, it can be seen that the tensile strain behaviors are comprised of three regions with different slopes, as is generally described for reinforced concrete structures. When only the second regions are considered, they vary significantly according to the ratio of reinforcements. The slope of the curve increases with the ratio of reinforcement so that tensile strain significantly decreases. However, when the type of coarse lightweight aggregate is considered, the tensile strain behaviors vary less significantly. Other compressive strengths indicate similar trends and vary less significantly. This is similar to the behavior of normal-weight reinforced concrete structures [28, 29].

3.4 Comparisons to the control

Figure 7 presents a comparison of cracking and reinforcement tensile strain behaviors of the control for the second concrete compressive strength. The behaviors are not significantly different, but the initial cracks in both lightweight concretes occur earlier than in normal-weight concrete. This may be due to the lower splitting tensile strengths of both lightweight concretes compared to normal-weight concrete, as shown in Table 3.

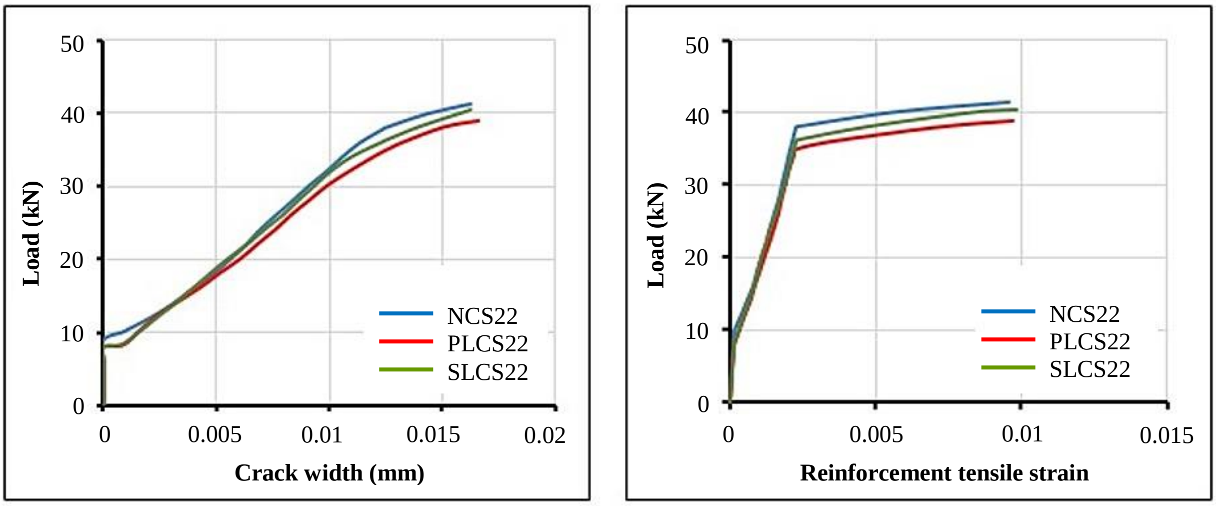

Figure 7 Comparison of crack width and reinforcement tensile strain to the control

Table 4 The results of the one-way slab bending tests

Group	Label	Cracking load (kN)	Service load (kN)	Ultimate load (kN)	Maximum crack width (mm)	Reinforcement tensile stress (MPa)
A	PLCS11	7.85	17.77	28.43	0.380	337.46
	PLCS12	7.98	23.33	37.32	0.335	316.37
	PLCS13	8.34	29.10	46.56	0.275	301.83
	PLCS14	8.96	31.64	50.63	0.225	284.43
	PLCS21	7.98	18.33	29.32	0.343	332.96
	PLCS22	8.25	24.28	38.84	0.308	312.89
	PLCS23	8.83	30.14	48.22	0.252	297.94
	PLCS24	9.38	32.35	51.76	0.213	283.20
	PLCS31	8.12	19.20	30.72	0.328	332.14
	PLCS32	8.51	24.86	39.78	0.287	311.46
	PLCS33	9.15	31.33	50.13	0.238	293.03
	PLCS34	9.78	32.95	52.72	0.205	281.56
B	SLCS11	8.16	18.21	29.14	0.373	337.05
	SLCS12	8.47	24.89	39.82	0.332	315.76
	SLCS13	8.72	29.76	47.61	0.268	303.88
	SLCS14	9.31	32.08	51.33	0.223	284.22
	SLCS21	8.14	19.54	31.26	0.341	331.73
	SLCS22	8.34	25.21	40.34	0.304	309.20
	SLCS23	8.77	31.25	50.00	0.245	296.92
	SLCS24	9.43	33.36	53.37	0.208	282.79
	SLCS31	8.24	20.43	32.68	0.316	329.68
	SLCS32	8.50	26.18	41.88	0.281	305.11
	SLCS33	9.26	32.13	51.41	0.237	290.77
	SLCS34	9.80	34.03	54.44	0.204	278.49
C	NCS22	9.98	25.84	41.34	0.304	307.97

3.5 Results of one-way slab bending tests

From the results of the three-point bending tests, the initial cracking loads, service loads and ultimate loads can be obtained. The service loads were considered to be the ultimate loads multiplied by 0.625 [44]. Then, the maximum crack widths and reinforcement tensile strains can also be determined. These results are presented in Table 4. The reinforcement tensile stress values at the service load were calculated based on the elastic properties of the steel reinforcement, where the modulus of elasticity was individually tested before experimentation.

3.6 Influence of the ratio of reinforcement

Figure 8 presents the influence of the ratio of reinforcement upon the maximum crack width for pumice lightweight concrete one-way slabs with three compressive strengths. It can be seen that when the ratio of reinforcement increases, then the maximum crack width is significantly reduced to values in the range of 18% to 22%. Similarly, this influence is also shown in scoria lightweight concrete one-way slabs, as presented in Figure 8. These values are in the range of 17% to 23%. The tensile forces due to bending, may spread according to the number of steel bars in the one-way slab cross-section. When the ratio of reinforcement increases, the number of steel bars is increased so that the tensile force resisted by each steel bar is less. Furthermore, its ability to remain embedded in lightweight concrete may be increased. Its tendency to slip is reduced, significantly decreasing the maximum crack width. Thus, the ratio of reinforcement significantly affects the maximum crack width, which is similar to observations of reinforced normal-weight concrete beams [25-27], and with reinforced lightweight concrete beams using artificial lightweight aggregates [43, 44].

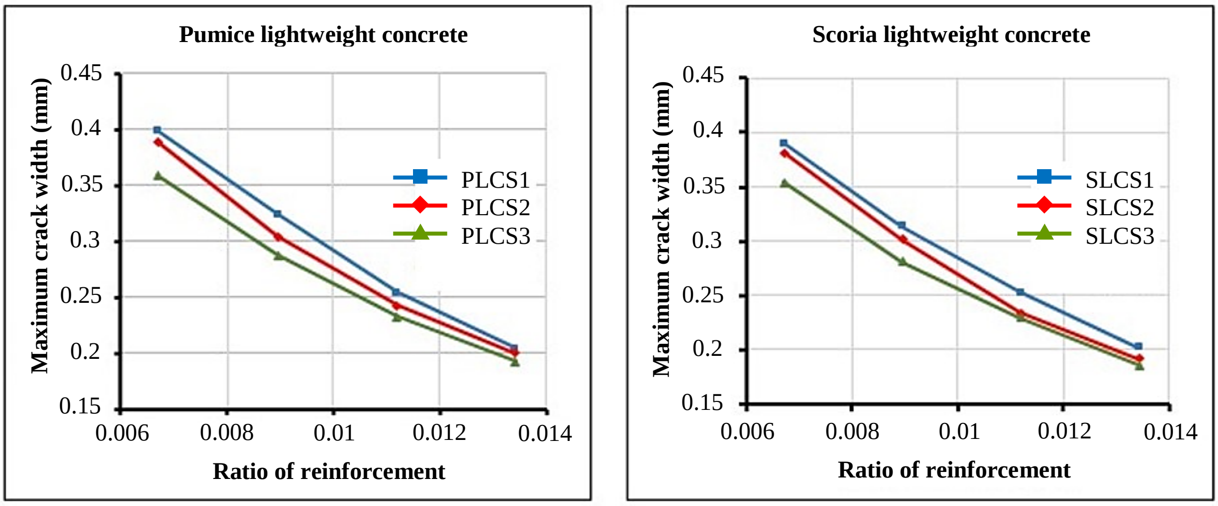

Figure 8 Influence of the ratio of reinforcement on the maximum crack width

3.7 Influence of compressive strength

Figure 9 presents the influence of the compressive strength of both lightweight concrete one-way slabs to the maximum crack width for the second ratio of reinforcement. When the concrete compressive strength increases, the maximum crack width is reduced less significantly, between 5% and 7% for pumice lightweight concrete and from 3% to 7% for scoria lightweight concrete. For other ratios of reinforcement, crack width decreases less significantly. From Table 3, it can be seen that when the concrete compressive strength increases, the tensile strength also increases. So, the bond strength qualitatively increases as well. Although, these increases are less significant, the ability of each steel bar to remain embedded in these lightweight concretes may increase. Its tendency to slip is reduced and the maximum crack width decreases, but less significantly. Thus, compressive strength less significantly affects the maximum crack width. This behavior is similar to that of reinforced normal-weight concrete [26-29].

3.8 Influence of reinforcement tensile stress

From Figure 6, it can be seen when the external load in the second region increases, the steel tensile strain increases so that the stress is also greater. The crack width also increased as shown in Figure 5. For the reinforcement tensile stress at the second compressive strength and ratio of reinforcement, the maximum crack width variation is presented in Figure 10. For pumice and scoria lightweight concretes, the results show that the maximum crack width significantly increases with the reinforcement tensile stress, with values in the range of 17% to 23%. Similarly, other compressive strengths also show similar tendencies. For increasing reinforcement tensile stress for each steel bar, the capability to remain embedded in the concrete significantly decreases. The tendency to slip increases and then the maximum crack width also significantly increases. Thus, the reinforcement tensile stress significantly affects the maximum crack width. This is similar to the behavior of reinforced normal-weight concrete [27, 29, 30].

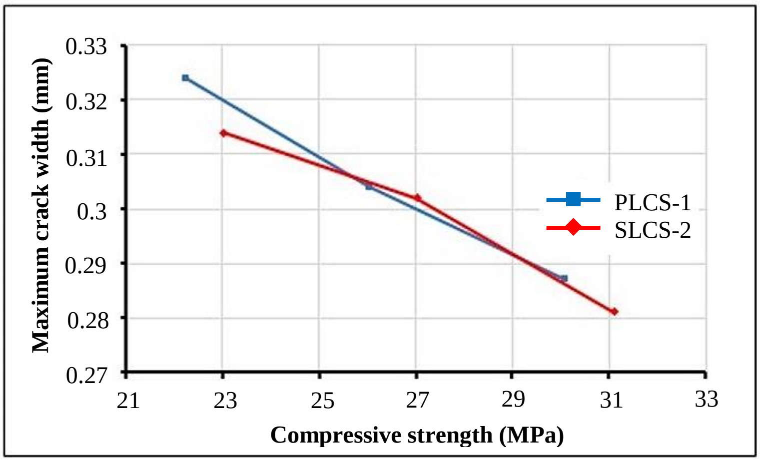

Figure 9 Influence of compressive strength on maximum crack width

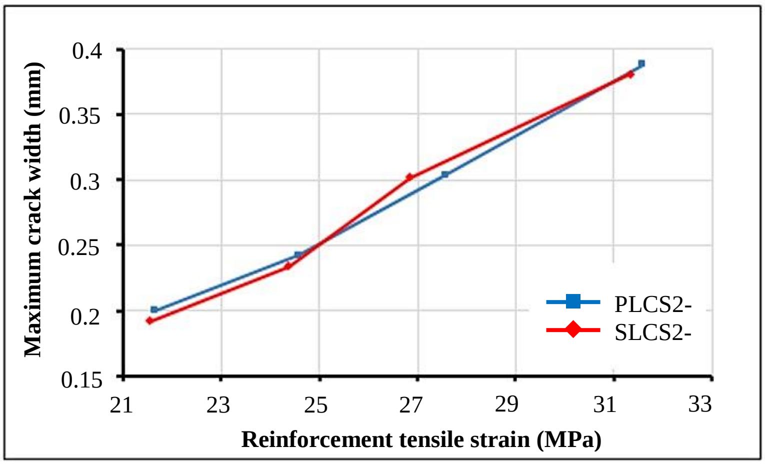

Figure 10 Influence of reinforcement tensile stress on maximum crack width

3.9 Influence of typical coarse aggregates

Figure 11 presents the influence of the typical coarse aggregate on the maximum crack width for typical coarse lightweight aggregates, pumice and scoria. This figure is for second compressive strength and it can be seen that the difference in maximum crack width between pumice and scoria lightweight concretes is less significant, in the range of 0.5% to 4%. Similarly, these differences are also less significant for other compressive strengths. This may be due to the less significant differences of splitting tensile strength, so that the maximum crack widths of both lightweight concretes do not vary significantly.

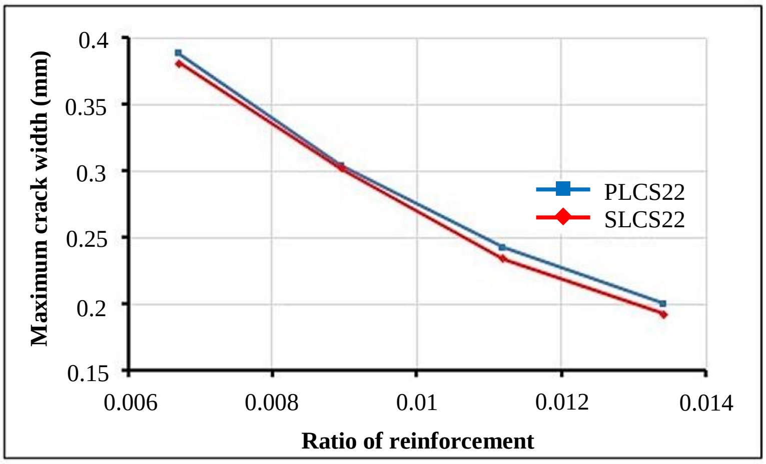

Figure 11 Influence of typical coarse aggregate on the maximum crack width

3.10 Cracking patterns

Figure 12 shows the cracking patterns of one-way slabs of lightweight pumice concrete PLCS22, scoria lightweight concrete SLCS22 and the normal-weight concrete NCS22 used as a control. From these results, it can be shown that the crack patterns are typical due to bending, i.e., the cracks are perpendicular to the slab axis. Similarly, other one-way slabs also show similar results. For the second compressive strength and ratio of reinforcement, the number of cracks on both sides was 17/18 for pumice lightweight concrete, 16/16 for scoria lightweight concrete and 16/16 for control. For other compressive strengths and ratios of reinforcement, it is in the range of 12 to 21. These results differ from those of earlier studies [43, 44] for lightweight concrete beams with artificial lightweight aggregate. The number of cracks was greater than the control and the maximum crack width was narrower than the control because the crack spacing was also lower. However, for pumice lightweight concretes, the maximum crack width was wider than the normal-weight concrete used as the control, while for scoria lightweight concrete, it was equal. This may have been due to the different types of coarse aggregate used. The coarse aggregates in lightweight concrete beams in earlier studies were Leca artificial lightweight aggregates. They have different microstructural characteristics than volcanic coarse aggregates. These artificial lightweight aggregates are composed of a strong crystalline microstructure, while both of volcanic lightweight aggregates examined in the current study are have a weak amorphous glass microstructure.

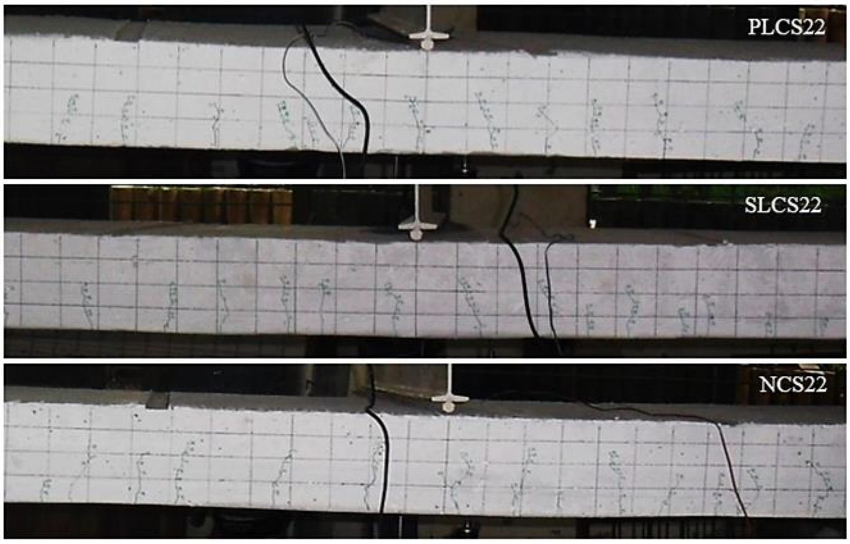

Figure 12 Cracking patterns of three one-way slabs

4. Conclusions

The paper presented an evaluation of the factors influencing the maximum crack width on one-way slabs produced from volcanic lightweight concretes. These lightweight concretes ulitized typical pumice and scoria, from the Kelud volcano in Indonesia, as coarse aggregates. Physically, both coarse lightweight aggregates have two adverse properties. They have high porosity and an amorphous glass microstructure that causes low tensile strengths. Furthermore, these properties are carried over into the lightweight concretes produced for one-way slabs. However, the low tensile strength that is represented by their compressive strengths less significantly influences the maximum crack width of pumice and scoria lightweight concrete one-way slabs, which is in the range of 3% to 7%. The typical coarse lightweight pumice and scoria aggregate less significantly influences the maximum crack width of lightweight concrete, which is in the range of 0.5% to 4%. The ratio of reinforcement significantly influences the maximum crack width, by 17% to 23%. Similarly, the reinforcement tensile stress significantly influences the maximum crack width by 17% to 23%. Thus, the ratio of reinforcement and reinforcement tensile stress remain the principal factors influencing the maximum crack width of pumice and scoria lightweight concrete one-way slabs. The adverse properties of pumice or scoria, which cause the low tensile strength, do not influence the maximum crack width and should not be taken into account in the analysis and design.

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