International Journal of GEOMATE, Oct. 2023, Vol. 25, Issue 110, pp.40-48
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.110.3921
Geotechnique, Construction Materials and Environment

MECHANICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE USING LIGHTWEIGHT AGGREGATES FROM CONSTRUCTION AND DEMOLITION WASTE

Hung Phong Nguyen[1], Ngoc Lan Le[2], Thi-Thanh Thao Nguyen[1], Cong Thang Nguyen[3], and *Van Tuan Nguyen[3]

[1]Faculty of Building and Industrial Construction, Hanoi University of Civil Engineering, Vietnam
[2]Department of Construction Management, Academy of Managers for Construction and Cities, Vietnam
[3]Faculty of Building Materials, Hanoi University of Civil Engineering, Vietnam

*Corresponding Author, Received: 23 April 2023, Revised: 18 July 2023, Accepted: 20 July 2023

ABSTRACT: In the era of sustainable development, lightweight concrete (LWC) manufactured from industrial waste becomes a potential material, particularly LWC using lightweight aggregates (LWA) from construction and demolition waste (CDW). However, there is a lack of study on this LWC manufacture, especially in terms of its mechanical properties and structural applications. This paper presents several experimental works that were conducted to assess the mechanical properties of lightweight concrete (LWC) made from construction and demolition waste (CDW), including the elastic modulus, compressive strength, splitting, and flexural tensile strength. The mechanical properties of this concrete have been impacted by the density, as well as the relationship between the tensile-compressive strengths and the relationship between the elastic modulus and compressive strength based on the elastic factor, as determined based on experimental results. In addition, this paper investigates bond behavior between steel reinforcement (ribbed rebar with a 12 mm diameter) and LWC according to the results of pull-out tests.

Keywords: Mechanical properties, Lightweight concrete, Recycled lightweight aggregate, Construction and demolition waste

1. INTRODUCTION

The usage of lightweight concrete (LWC) in long-span bridges, high-rise buildings, and earthquake resistant structures has become widespread. This is because LWC reduces the overall specific weight of the building in comparison to traditional concrete [1]. Besides, the lower thermal conductivity of LWC improves the fire resistance of buildings. However, the mechanical properties of LWC (i.e., compressive strength and modulus of elasticity) will differ depending on the type of lightweight aggregate (LWA) used [2].

On the other hand, the increasing industrialization has resulted in the development of construction and demolition waste (CDW), which has caused several major problems, such as environmental contamination, landscape degradation, and traffic congestion in many countries around the world. According to Menegaki and Damigos [3], the generation of CDW in Europe is estimated as approximately 333 million tons (excluding soils) in 2014, composed of 300 million tons of inert waste, 30 million tons of non-inert waste, and 3 million tons of hazardous waste. In the US, 534 million tons are generated, about 28.9 million tons during construction and 505.1 during demolition activities. For Australia, 19.5 million tons, and for China, approximately 1.13 billion tons are reported. In Vietnam, official statistics have shown that the total municipal solid waste generated in 2016 was about 33.2 thousand tons per day, i.e., approximately 12.1 million tons per year, of which the CDW accounts for approximately 10–15% [4].

One of the solutions is to recycle the CDW to make building materials, namely LWA, from the melting of bricks and mortar. Therefore, to create useable construction materials, recycling CDW has become a priority mission in several countries. Additionally, this can also prevent the over-exploitation of limited natural resources such as sand, clay, and limestone used in construction.

The manufacture of LWC with various types of lightweight aggregates, including construction waste, aluminum waste, expanded clay, rubber ash, and fly ash, was investigated by a number of researchers worldwide [5-7]. However, the focus of this study will be on research conducted by Mueller et al. [8-10]. The authors have presented an effective technique for manufacturing LWA from the crushed masonry walls of construction and demolition structures in buildings (i.e., brick and mortar). This is particularly important for development of LWC from CDW in the previous study of Nguyen et al. [11]. This work suggested that the combination of construction wastes and fly ash is suitable for manufacturing the LWA with a density of less than 1000 kg/m^3. Although LWC has been successfully manufactured from CDW, the mechanical properties of this concrete have not yet been investigated and assessed in this work.

The objective of this study is to evaluate the mechanical properties of LWC from CDW, including the elastic modulus, compressive strength, splitting, and flexural tensile strength, as well as the relationship between these properties. The stress and strain behavior of LWC and the bond strength between reinforced bars and LWC were also investigated. For these purposes, an experimental program was conducted at the laboratory LAS-XD 125 of Hanoi University of Civil Engineering on a type of LWC that used recycled lightweight aggregates from CDW with two different size ranges, namely A1 (with particle sizes of 4-8 mm) and A2 (with particle sizes of 8-16 mm). The experiments were carried out on three different types of mixtures of LWC, and the results were then analyzed and discussed.

2. RESEARCH SIGNIFICANCE

The significance of this study is to evaluate the mechanical properties of LWC from CDW, including the elastic modulus, compressive strength, splitting, and flexural tensile strength, as well as the relationship between these properties. In addition, the bond behavior between steel reinforcement and LWC, according to the results of pull-out tests, was studied.

3. EXPERIMENTAL PROGRAM

3.1 Materials

LWC consists of Portland cement PC40 as the binder; river sand as fine aggregates; recycled lightweight aggregates (LWA) with a maximum nominal size of 16 mm as coarse aggregates; coal-fired fly ash, superplasticizer Placc-air, and water as the other constituents. River sand has a density of 2630 kg/m^3, fineness modulus of 3.0, natural moisture content of 0.5%, and porosity of 43.7%. Two sets of recycled lightweight aggregates, A1 with a particle size of 4-8 mm and A2 with a particle size of 8-16 mm, that were used as coarse aggregates are shown in Fig.1. The relative density is 430 kg/m3 for A1 and 369 kg/m^3 for A2. After analyzing the physical parameters, the water absorption of LWA increased rapidly within 15 minutes of soaking in water. It reached 15.2% for particles A1 and 20.1% for particles A2 after 1 hour and remained stable after 24 hours. The hygroscopic coefficients for particles A1 and A2 were 28.3 and 32.0%, respectively. Therefore, the recycled LWA structure has a greater porosity compared to that of conventional LWA structures, resulting in a high water absorption capacity. Its capacity might improve the connection between aggregates and cement. In contrast, these LWA have lower particle strength with compressibility factors of 53.5% for particles A1 and 43.5% for particles A2. In order to enhance the compressive strength of LWC, coal-fired fly ash from Pha Lai coal-fired power plants was used. Besides, the utilization of fly ash also brings environmental and economic benefits for reducing cement use.

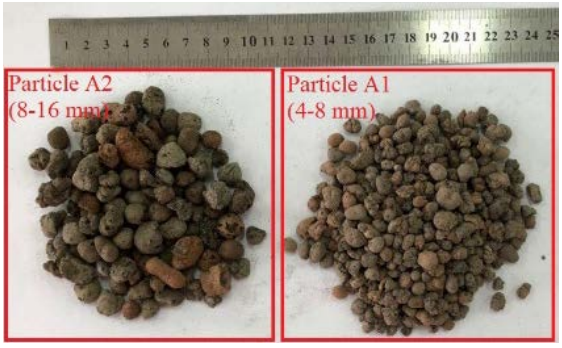


Fig.1 Recycled LWA made from CDW

According to ACI 211.2-98 [12], LWC mixes should include air-entraining admixtures to reduce separation and improve the homogeneity of fresh concrete. Superplasticizer was added to the mixture to ensure the reliable workability of recycled LWC. For these reasons, the deep brown admixture, which is a combination of superplasticizer and air-entraining admixture, may be used in the concrete mixtures in this study. Superplasticizer Placc-air producing according to ASTM C494 type G [13] was suitable for all types of cement to delay the setting time for concrete mixture including important properties, namely density of 1.08 g/cm^3 with a coefficient of variation of 0.2% and use the content of 0.7 to 1.4 liters per 100 kg of cement.

3.2 Concrete Mix Proportion

According to previous studies, the objective of this research is to manufacture LWC made from recycled LWA with a density ranging from 1400 to 1800 kg/m^3. Several concrete mixtures proportions used were determined corresponding to three target compressive strengths of 16, 20, and 30 MPa, corresponding to the strength classes of LWC: LC16/18, LC20/22, and LC30/33 according to EN 206-1:2003 [14]. After analyzing the influence of LWA content in LWC, three sets of LWC mix proportions were used in this study. The first and second sets (named M1 and M2) used only particles A1 or A2 as coarse aggregates, whereas the third set (named M3) included a combination of particles A1 and A2 as coarse aggregates.

3.3 Specimens and Experimental Procedure

After preparing the aggregates, cement, sand, and fly ash were mixed in a forced mixer for three minutes before adding water and superplasticizer Placc-air gradually. After that, LWA was added and mixed for around 5 minutes. Finally, the mixing product is controlled by the target slump to check the workability of the LWC mixtures. The workability of the fresh concrete was determined according to ASTM C143 [15]. The slump values, which ranged from 7 to 15 cm, increased when adding superplasticizer Placc-air.

In this study, Table 1 presents the mechanical properties of hardened LWC made from recycled LWA with various test specimen sets: (i) A set of cubes with dimensions of 150×150×150 mm was used as a specimen for dry density testing; (ii) Three sets of cylindrical specimens with dimensions of 150×300 mm were used as the standard specimen for compressive strength, and splitting tensile strength testing; (iii) a set of prism specimens with dimensions of 100×100×400 mm (i.e., the un-reinforced concrete beams subjected to a three-point bending test) was used for flexural tests to determine the tensile strength of LWC. Each set consists of nine specimens and was produced with three different concrete compressive strengths. After being cast and cured in the laboratory for 28 days, all cylindrical and prism specimens were dried on a saturated surface dry oven to remove water from the surface. Besides, pull-out tests were used to assess the bond behavior between steel reinforcement and LWC according to the guidelines for pull-out specimens from the RILEM standard [16-17]. The pull-out specimens are cubes with ribbed rebar of 12 mm in diameter (150×150×150 mm). Each cube has ribbed rebar with a 12 mm diameter at the center. The embedded rebar set into the PVC tubes with a length of 2 cm was attached to ensure an anchorage length. All pull-out specimens have an embedment length of 60 mm, which is five times the diameter of the rebar.

4. EXPERIMENTAL RESULTS

4.1 Density of Recycled Lightweight Concrete

In this study, the type of recycled LWA used was modified in three sets. When modifying the particle size of LWA A1 to the particle size of A2, the density of LWC decreases because particle A2 has a smaller density than particle A1. Besides, the density of specimens using the combination of particles A1 and A2 was higher than that of specimens using only particle A2. The average dry weight is 1684 kg/m^3 for the set M1. Meanwhile, it is 1746 and 1772 kg/m^3 for the sets M2 and M3, respectively.

Table 1 Testing and specimens' details

No.	Test	Specimen
1	For compressive strength	Cylinder (150×300 mm)
		
2	Flexural test for tensile strength	Prism (100×100×400 mm)
		
3	Splitting test for tensile strength	Cylinder (150×300 mm)
		
4	Test for static modulus of elasticity	Cylinder (150×300 mm)
		
5	Pull-out test for steel-LWC interface	Pull-out specimen: Cube (150x150x150 mm)
		

According to the status of Iffat [18] for the linear relationship between density and compressive strength of concrete, set M1 has the smallest value among the three sets, so it could be expected to be in the set with a compressive strength of 16 MPa.

4.2 Compressive Strength of Recycled Lightweight Concrete

According to the compression tests, the compressive strengths for set M1 ranged from 14.78 to 16.06 MPa. It varied from 20.66 to 23.54 MPa for the set M2 and from 29.92 to 31.59 MPa for the set M3. The coefficient of variation accounts for 3.10, 4.58, and 1.97% of all specimens for sets M1, M2, and M3, respectively. Therefore, the average compressive strength of all sets is in good agreement with the predicted value. When the density of LWC rose, the compressive strength of all specimens increased by around 30%. Therefore, the higher the compressive strength of LWC, the lower the content of LWA. Fig.2 illustrates failure models of cylinders after the compression test. All specimens were damaged at the weak cross-section between the aggregate and cement mortar. It shows that the cracks passed directly through LWA because of the good bond between LWA and cement mortar, as well as the low bearing capacity of LWA.

Fig.2 The failure of cylindrical specimens for compression tests

4.3 Tensile Strength of Recycled Lightweight Concrete

In this study, the flexural and splitting tests were conducted to evaluate the tensile strength of the recycled LWC. For the flexural tests, the average tensile strengths are 2.89, 3.46, and 4.12 Mpa, corresponding to the LWC mixtures M1, M2, and M3, respectively. For the splitting tests, they are 1.71, 2.07, and 2.50 MPa. The average tensile strength from the flexural tests was 60% as much as those from the splitting tests for all three sets of the LWC mixture.

Besides, the coefficients of variation from the flexural test were 1.55, 2.05, and 1.52% for three mixtures of LWC M1, M2, and M3, respectively. Meanwhile, these values from the splitting test were 1.70, 1.61, and 1.56%. These results indicate the reliable splitting-tensile strength of LWC. Figs.3-4 illustrate the failure mechanisms of prisms and cylinders in flexural and splitting tests. All specimens exhibited a primary crack along the loading diameter direction. The brittle failure mode of LWC was comparable to the mode of traditional concrete.

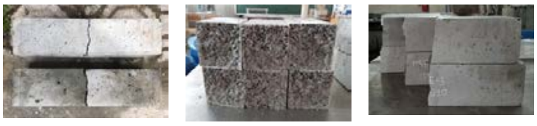


Fig.3 The failure mode of prisms in flexural tests

Fig.4 The failure mode of cylinders in splitting tests

$$f_{ct} = 0.56\sqrt{f_c} \tag{1}$$

$$f_{ct} = 0.3(f_c)^{2/3}\left(0.4 + 0.6\frac{\rho}{2200}\right) \tag{2}$$

$$f_{ct} = 0.23(f_c)^{2/3} \tag{3}$$

$$f_{ct,pv} = 0.5\sqrt{\frac{\rho}{2200}}\sqrt{f_c} \tag{4}$$

On the other hand, the relationship between the splitting tensile strength and the compressive strength of concrete is represented in previous empirical equations, as shown in Eqs. (1) and (2) [19-20]. On the other hand, Zhang and Gjorv [21] also proposed Eq. (3) for the splitting tensile strength/compressive strength relationship. Where f_{ct} and f_c are the tensile and compressive cylinder strengths, and ρ is the dry density of concrete. Fig.5 displays the relationship between compressive strength and splitting tensile strength of experimental LWC based on the experimental results and several given empirical equations.

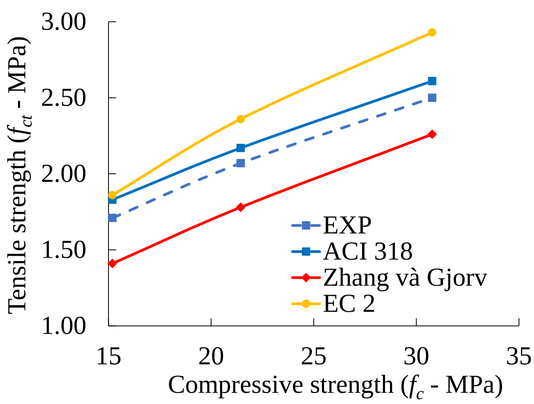


Fig.5 The relationship between the compressive and splitting tensile strengths

The results of the experiments gave a similar relationship as presented in the given empirical equations. The theoretical tensile strengths, which were calculated based on the present standards, were 1.8, 2.3, and 2.8 Mpa, corresponding to M1, M2, and M3 LWC mixtures. These theoretical values were higher than the experimental values for all three LWC mixtures. Meanwhile, these values obtained from the experiments were higher than the ones obtained from the empirical equation of Zhang and Gjorv [21], which were greater than 0.27 MPa.

After that, the experimental values for the splitting tensile strength of LWC were analyzed using a linear regression method. After determining the relationship between the splitting tensile strength and the form of different functions of compressive strength, the best-fit function of compressive strength is displayed in the proposed equation Eq. (4) with an empirical variance of 0.99. Besides, the coefficients of variation are 0.85, 1.59, and 0.43% for the LWC mixtures M1, M2, and M3. The splitting tensile strength calculated by Eq. (4) exhibits a deviation of 0.95% on average. There is a good agreement on the proposed value of splitting tensile strength ($f_{ct,pv}$) with a slight difference of around 1 %.

4.4 Modulus of Elasticity of Recycled Lightweight Concrete

LWC has a lower modulus of elasticity in comparison to traditional concrete, which ranged from 17300 to 22400 MPa due to the lower elasticity of LWA [21-22]. Besides, Neville investigated the influence of the volume fraction and physical properties of LWA on the modulus of elasticity of LWC [23]. This study estimated the modulus of elasticity based on the test for static modulus of elasticity on cylinders. As a result, the modulus of elasticity for recycled LWC ranged from 12333 to 18894 MPa, and the coefficient of variation varied from 1.84 to 1.97%. Fig. 6 shows the failure mode of cylinders for tests of the modulus of elasticity.

On the other hand, several empirical equations in the present standard presented the relationship between the modulus of elasticity (E_c) and the compressive strength (f_c). Eqs. (5), (6), (7), and (8) were proposed to determine the modulus of elasticity [19-20, 24-25]. Fig.7 illustrates the relationship between the modulus of elasticity obtained from the experimental data and empirical equations and compressive strength. The modulus of elasticity obtained in the experiments accounted for 60% of these values calculated based on the equation by Carrasquillo [24], while they were similar to these values determined based on the empirical equations recommended by the present standards. However, the theoretical values for LWC mixtures M1 and M2, which were calculated by Eq. (6), were 11577 and 14520 MPa. They were less than the experimental value for each LWC mixture.

Fig.6 The failure mode of cylinders in tests of modulus of elasticity

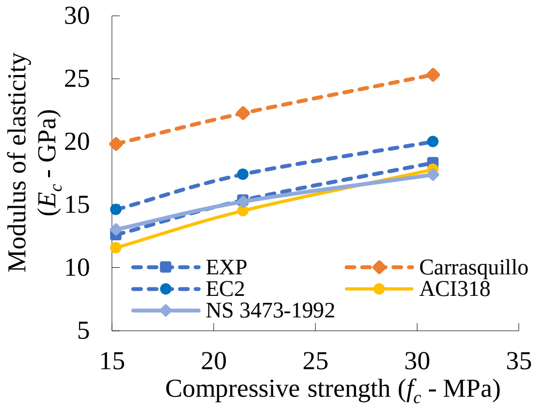


Fig.7 The relationship between the compressive strength and modulus of elasticity

Similar to the tensile strength, this study used a linear regression method to analyze the modulus of elasticity. After that, Eq. (9) was proposed to determine the modulus of elasticity based on the compressive strength obtained from experimental data. In which E_c, ρ, and f_c are the elastic modulus (MPa), the density (kg/m^3), and the compressive strength (MPa) of recycled LWC, respectively. There is a good agreement of the proposed value of modulus of elasticity with experiment data with a deviation of less than 3%.

$$E_c = 0.043\rho^{1.5}\sqrt{f_c} \quad (5)$$

$$E_c = 22000\left(\frac{f_c}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^2 \quad (6)$$

$$E_c = 3320 f_c^{0.5} + 6900 \ (21\text{ MPa} < f_c < 83\text{ MPa}) \quad (7)$$

$$E_c = 9500\left(\frac{f_c}{0.9}\right)^{0.3}\left(\frac{\rho}{2200}\right)^2 \quad (8)$$

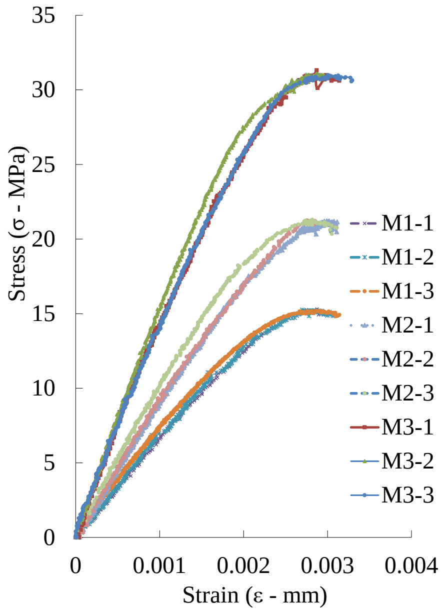
$$E_c = 19520\left(\frac{f_c}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^2 \quad (9)$$

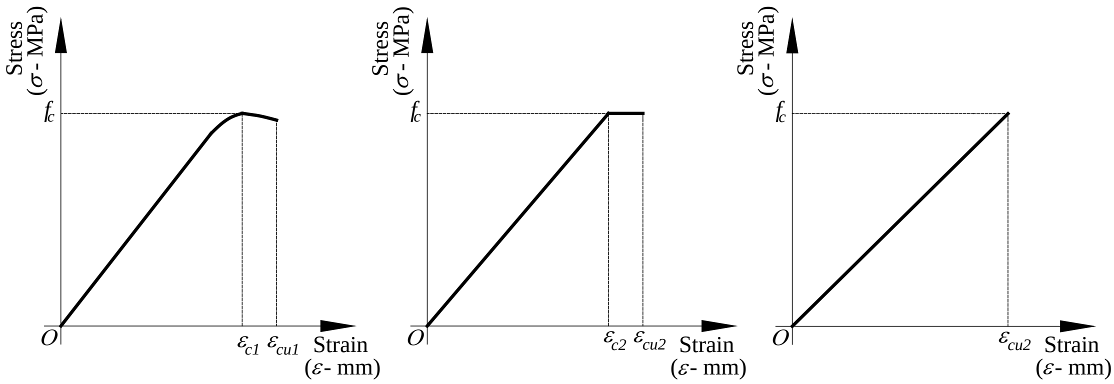
4.5 Stress-strain Relationship of Recycled Lightweight Concrete

From the results of tests for the modulus of elasticity, the strain ε_{c1} corresponding to the maximum stress was approximately 0.0028 mm for all three LWC mixtures. It is slightly lower than the recommended value, which is 0.003, according to present standards [20, 26-27]. Clarke [28] found that the relationship between stress and strain of LWC is more linear than that of traditional concrete because of the brittle behavior of LWC. The post-peak behavior of LWC, which is an unstable crack propagation stage of LWC, presents an immediate failure in LWC. In this study, there are two stages for the stress-strain curves for all three LWC mixtures, as depicted in Fig.8(a). Firstly, the pre-peak stage demonstrates the quasi-linear behavior of LWC. Because of the plastic strain development in LWC, after reaching 85% of the maximum stress, a stress-strain relationship progressively changes into a curve. Secondly, the post-peak stage is the immediate failure of concrete crushing after reaching the maximum stress, in which there is a total loss of bearing capacity. The strain (ε_{cu2}) corresponding to the ultimate stress at failure is relatively close to the strain ε_{c1} when reaching the maximum stress. The curve shown in Fig.8(b) illustrates the modeled curves for the stress-strain relationship of recycled LWC, and the curve depicted in Fig.8(c) was proposed to reflect the brittle behavior of this recycled LWC.

$$\varepsilon_{cu2} = 0.0035 \times \eta_1 \quad \left(\eta_1 = \frac{0.4 + 0.6\rho}{2200} \right) \tag{10}$$

On the other hand, the ultimate strain of concrete could be determined by Eq. (10) based on EC2 [21]. Then, this empirical equation was used to calculate the ultimate strain of recycled LWC in this study. Therefore, the average value of ε_{cu2} is approximately 0.0031, which is close to a 0.0028 strain when reaching maximum stress. In order to improve the simplicity and safety, the stress-strain relationship of recycled LWC was proposed, as shown in Fig.8(d), with an ultimate strain of 0.0031.





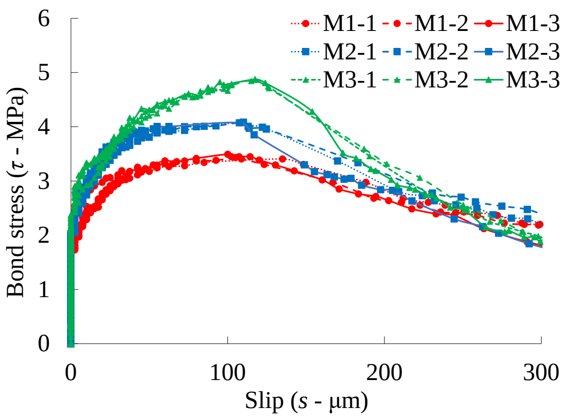
(b) The modeled curve (c) The proposed curve (d) The simplified curve

(a) The experimental curve

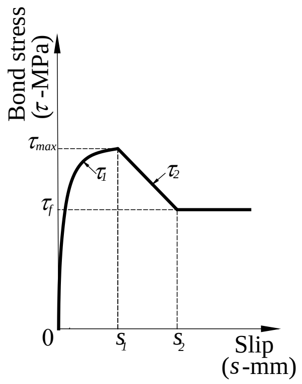
Fig.8 The stress-strain relationship of LWC

4.6 Bond Stress-Slip Relationship of Recycled Lightweight Concrete

Bond strength is an essential structural property of reinforced concrete components [29]. This study investigated the bond-slip relationship between recycled LWC and steel reinforcement (e.g., ribbed rebar with a 12 mm diameter). Fig.9(a) represents the bond stress and relative slip of LWC obtained from the experiments. In particular, the average slips corresponding to the maximum bond stress (denoted s_1) and the residual post-peak bond stress (denoted s_2) are 0.109 and 0.245 mm. As illustrated in Fig.9(a), there are four stages for the bond stress-slip relationship of LWC. In the first stage, the bond stress-slip relationship is linear because specimens have no cracks. Then, when increasing the bond strength, the slip of reinforcement on the concrete began to rise steadily. Simultaneously, cracks occurred around the reinforcement and developed outside the specimens. After reaching maximum bond stress (τ_{max}), the bond stress remained constant due to the yielding stage of the reinforcing bar. After bond stress and relative slip have plunged dramatically, the bonding stress would remain constant at τ_f until the reinforcing bar is pulled out of the concrete.



(a) The experimental curve



(b) The simplified curve

Fig.9 The stress-slip relationship of recycled LWC

On the other hand, several researchers observed that the bond properties of LWC are affected by aggregate characteristics, the water/cement ratio, the type and shape of steel reinforcing bars, and curing conditions [30]. Besides, others suggested the bond stress-slip constitutive law of LWC [31-32]. In this study, Eqs. (11) to (13) were proposed to describe the relationship between the bond stress and slip of the recycled LWC. As a result, the theoretical values of τmax were 3.42, 4.07, and 4.88 MPa, while the values of τ_f were 2.19, 2.52, and 2.93 MPa. These values correspond to the three different compressive strengths of LWC. In comparison with the experimental data, these theoretical values are quite satisfactory, with a slight difference of 0.65% for the maximum bond stress and 6.55% for the residual post-peak bond stress. Fig.9(b) demonstrates a simplified curve for the bond stress-slip relationship of recycled LWC with a good agreement between the experimental and theoretical values. This abrupt decline of recycled LWC presented the LWC mechanical properties (i.e., cracking properties and shear stiffness). In this study, Eq. (14) was proposed to determine the average bond stress of recycled LWC ($\bar{\tau}$) to evaluate the cracking distances in concrete structures. Within the scope of this paper, when the density of LWC varies from 1684 to 1772 kg/m^3, the ratio between the average bond stress and compressive strength stays relatively constant at around 1.8.

$$\tau = \tau_{max}\left(\frac{s}{s_1}\right)^{0.2} \text{ (for } 0 \le s \le s_1\text{)}$$
$$(\tau_{max} = 0.88\sqrt{f_c} \text{ with } s_1 = 0.109 \text{ mm}) \tag{11}$$

$$\tau = \tau_{max} - (\tau_{max} - \tau_f)\left(\frac{s - s_1}{s_2 - s_1}\right) \text{ (for } s_1 \le s \le s_2\text{)} \tag{12}$$

$$\tau = \tau_f \text{ (for } s_2 \le s\text{)}$$
$$(\tau_f = 0.62\tau_{max} \text{ with } s_2 = 0.245 \text{ mm}) \tag{13}$$

$$\bar{\tau} = 1.6\sqrt{\frac{2200}{\rho_c}}f_c \tag{14}$$

5. CONCLUSIONS

Based on the experimental data recorded during the tests to investigate the mechanical properties of recycled LWC using the LWA made from CDW, numerous conclusions can be derived from this study:

• In comparison to traditional heavy concrete, the recycled LWC has the degradation of stiffness and ductility (e.g., compressive and tensile strength, the modulus of elasticity).

• According to the suggested method for manufacturing recycled LWC by Nguyen et al. [4], concrete mixtures used were determined to have three different compressive strengths of 16, 20, and 30 MPa and a density ranging from 1400 to 1800 kg/m^3.

• The stress-strain relationship of recycled LWC has been proposed in the form of a straight line because the recycled LWC is more brittle than traditional concrete. When the maximum stress reaches about 85% of compressive strength, the relative strain is 0.0028. For the design of cross-sections, the simplified relationship may be used as a linear stress-strain relation with the value ultimate strain (ε_{cu2}) of 0.0031.

• The bond stress-slip relationship is formed in four stages. When reaching the maximum bond strength, the slip remains constant before quickly reducing. The average bond strength-to-compressive strength ratio for this recycled LWC, stays constant at 1.8.

• The proposed equations demonstrate the relationship between compressive strength and other properties of the recycled LWC, as calculated with several parameters (e.g., f_c: the compressive strengths (MPa) respectively; ρ: density (kg/m^3).)

(i) Splitting tensile strength ($f_{ct,sp}$ – MPa)

$$f_{ct,sp} = 0.5\sqrt{\frac{\rho}{2200}}\sqrt{f_c}$$

(ii) Modulus of elasticity (E_{cm} - GPa)

$$E_{cm} = 19.52\left(\frac{f_c}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^{2}$$

(iii) The average bond stress ($\bar{\tau}$- MPa)

$$\bar{\tau} = 1.8 f_c$$

6. ACKNOWLEDGMENTS

The research described in this paper was financially supported by the research project B2021-XDA-06 by the Ministry of Education and Training.

7. REFERENCES

[1] Mohamed S. H., Asran A. G., Noman M. T., and Azim M. A., Properties of structural lightweight high strength self-compacting concrete, International Journal of GEOMATE, Vol. 23, Issue 96, 2022, pp. 50–60.

[2] Yang C.-C. and Huang R., A two-phase model for predicting the compressive strength of concrete, Cement and Concrete Research, Vol. 26, Issue 10, 1996, pp. 1567–1577.

[3] Menegaki, M., and Damigos, D., A review on current situation and challenges of construction and demolition waste management. Curr. Opin. Green Sustainable Chem, Vol. 13, 2018, pp. 8–15.

[4] National Environmental Report, Waste Management Topic. 2017: Vietnam, pp. 45&55.

[5] Griño Jr A. A., Parametric modeling of recycled brick aggregate concrete using neural network and regression, International Journal of GEOMATE, Vol. 24(105), 2023, pp. 41–49.

[6] Tayeh B. A., Ibrahim O., and Mohamed O., Combined effect of lightweight fine aggregate and micro rubber ash on the properties of cement mortar, Advances in concrete construction, Vol. 10, Issue 10.6, 2020, pp. 537–546.

[7] Bajare D., Kazjonovs J., and Korjakins A., Lightweight concrete with aggregates made by using industrial waste, Journal of Sustainable Architecture and Civil Engineering, Vol. 4, Issue 5, 2013, pp. 67–73.

[8] Reinhold M. and Mueller A., Lightweight aggregate produced from fine fractions of construction and demolition waste, The CIB Task Group 39 – Design for Deconstruction and Materials Reuse - Deconstruction Meeting. CIB Publication 272, University of Karlsruhe, Karlsruhe, Germany, 2002, pp. 27–35.

[9] Mueller A., Schnell A., and Rübner K., The manufacture of lightweight aggregates from recycled masonry rubble, Construction and Building Materials, Vol. 98, 2015, pp. 376-387.

[10] Mueller A., Sokolova S., and Vereshagin V., Characteristics of lightweight aggregates from primary and recycled raw materials, Construction and Building Materials, Vol. 22, Issue 4, 2008, pp. 703–712.

[11] Nguyen H. P., Mueller A., Nguyen V. T., and Nguyen C. T., Development and characterization of lightweight aggregate recycled from construction and demolition waste mixed with other industrial by-products, Construction and Building Materials, Vol. 313, 2021, pp. 125472.

[12] ACI 211.2-98: Standard Practice for Selecting Proportions for Structural Lightweight Concrete, American Concrete Institute, 2004, pp. 1–18.

[13] ASTM C494: Standard specification for chemical admixtures for concrete, Annual book of ASTM standards, American society for testing and materials, Vol 04.02, 1988, pp. 245–252.

[14] EN 206-1: 2013 Part 1: Concrete. Specification, performance, production and conformity, European Committee for Standardization, 2003, pp. 1–46.

[15] ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM International, West Conshohocken, PA, 2020, pp. 1–4.

[16] RILEM: Technical Recommendations for the Testing and Use of Construction Materials, Taylor & Francis CRC, London, 2006, pp. 1–640.

[17] Evans R. and Marathe M., Microcracking and stress-strain curves for concrete in tension, Matériaux et Construction, Vol. 1, Issue 1, 1968, pp. 61–64.

[18] Iffat S., Relation between density and compressive strength of hardened concrete, Concrete Research Letters, Vol. 6, Issue 4, 2015, pp. 182–189.

[19] ACI 318-19: Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, Farmington Hills, MI, USA, 2019, pp. 1–628.

[20] EC2 (EN 1992-1-1): Design of concrete structures - Part 1-1: General rules and rules for buildings, European Committee for Standardization, 2004, pp. 1–227.

[21] Zhang M. H., and Gjvorv O. E., Mechanical

properties of high-strength lightweight concrete, Materials Journal, 88(3), 1991, pp. 240–247.
[22] B. E. I. The European Union, LWAC Material Properties State-of-the-Art, EuroLightCon, Economic Design and Construction with Light Weight Aggregate Concrete, Document BE96-3942/R2., 1998, pp. 1–132.
[23] Neville A. M., Propriétés des bétons, Eyrolles, 2000, pp. 1–824.
[24] ACI 363R-03: Report on High Strength Concrete, American Concrete Institute, 1997, pp. 1–55.
[25] NS 3473:1992: Concrete structures - Designs rules Norwegian Standards (Norges Standardiseringsforbund), 1992, pp. 1–136.
[26] fib-4: Lightweight aggregate concrete, Codes and standards, Bulletin-FIB, 4, 1999, pp. 1–47.
[27] ACI 213R-03: Guide for structural lightweight-aggregate concrete, American Concrete Institute, Michigan, 2003, pp. 1–38.
[28] Clarke J., Structural Concrete with Lightweight Aggregate, Blackie Academic & Professional, Glasgow, 2005, pp. 1–282.
[29] Prince M. J. R. and Singh B., Bond behaviour of deformed steel bars embedded in recycled aggregate concrete, Construction and building materials, Vol. 49, 2013, pp. 852–862.
[30] Mo K. H., Alengaram U. J., and Jumaat M. Z., Bond properties of lightweight concrete–a review, Construction and Building Materials, Vol. 112, 2016, pp. 478–496.
[31] Creazza G. and Di Marco R., Bending moment-mean curvature relationship with constant axial load in the presence of tension stiffening, Materials and Structures, Vol. 26, Issue 4, 1993, pp. 196–206.
[32] fib-8: Lightweight Aggregate Concrete. Recommended extensions to Model Code 90. Identification of research needs & Case Studies, Bulletin-FIB, 2000, pp. 1–144.