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# Compressive Strength of Lightweight Concrete

*Saman Hedjazi*

## Abstract

This chapter has been prepared with the hope that its readers will become interested in lightweight concrete (LWC). Therefore, after a brief background of lightweight concrete, different types of LWC will be introduced and then LWC made of lightweight aggregates (LWA) will be specifically discussed. Compressive strength and density of LWC are the main points of interest in this chapter. In addition to conventional compression test, a nondestructive test (NDT) method will be used to assess the compressive strength of a variety of lightweight concrete mixes. A case study has been designed and conducted including an experimental program on the LWC made of expanded glass aggregate. The experimental program includes about 150 specimens, incorporating different unit weight for the entire specimens. In the end, it can be observed that the properties of LWC depend on the properties of the used LWA, and therefore for each specific type of lightweight aggregate, a brand new equation will be required for prediction of concrete compressive strength. The author hopes that the present chapter and the discussed case study on LWC would attract the attention of researchers to the importance of LWC in the future of construction industry.

**Keywords:** lightweight aggregate, lightweight concrete, nondestructive testing, compressive strength, expanded glass aggregate

## 1. Introduction

Concrete is a mixture made of aggregates, water, cement, and different additives. The “lightweight” term can be added to different types of concrete which are all common in one specification, and that is “lower density” than normal weight concrete (NWC). This reduction in density is achievable by different methods such as using lightweight aggregate (LWA) in concrete, foamed concrete (FC), and autoclaved aerated concrete (AAC) or by any other techniques that reduce the final specific weight of the product, and thus the achieved weight is less than what we have in NWC mixtures. Whereas NWC weighs from 2240 to 2450 kg/m<sup>3</sup>, lightweight concrete weighs ~300–2000 kg/m<sup>3</sup>, but the practical range of density for lightweight concrete is 500–1850 kg/m<sup>3</sup>. Before talking about the background of LWC, we prefer to explain a little more about the different types of LWC and their mechanical properties.

### **1.1 Lightweight aggregate concrete (LWAC)**

There are a variety of lightweight aggregates that can be used in the production of LWAC, such as natural materials, like volcanic pumice, and the thermal-treated natural raw materials like expanded glass, clay, shale, etc. LECA is an example of expanded clay and Poraver is an example of expanded glass aggregates. There are also other types, which are aggregates made of industrial by-products such as fly ash, like Lytag. The final properties of the LWC will depend on the type and mechanical properties of LWA used in the concrete mixture.

### **1.2 Foamed concrete (FC)**

With incorporation of considerable amount of entrained air (20% to 50%) in concrete, foamed concrete is produced which is a workable, low-density, pumpable, self-levelling, and self-compacting LWC. Foamed concrete is used more as a nonstructural concrete for filling voids in infrastructures, a good thermal insulation, and filler for space in buildings with less increase in the dead load.

### **1.3 Autoclaved aerated concrete (AAC)**

AAC, or also named as autoclaved gas concrete, to which a foaming agent is added, was first produced in 1923 in Sweden and is one of the oldest types of LWC. AAC construction systems were then popular all around the world because of its ease of use.

### **1.4 Structural and nonstructural lightweight concrete**

Lightweight aggregate concretes (LWAC) can be used for structural applications, according to the American Concrete Institute (ACI). To be considered as structural lightweight concrete (SLWC), the minimum 28-day compressive strength and maximum density are 17 MPa and 1840 kg/m<sup>3</sup>, respectively. The practical range for the density of SLWC is between 1400 and 1840 kg/m<sup>3</sup>. LWC made of a material with lower densities and higher air voids in the cement paste are considered as nonstructural lightweight concrete (NSLWC) and will most likely be used for its insulation and lower weight properties. LWC with compressive strength less than 17 MPa is also considered as NSLWC. There are several benefits with using LWAC such as improved thermal specifications, better fire resistance, and dead load reduction which results in lower cost of labor, transportation, formworks, etc., especially in precast concrete construction industry. With the reduction of the concrete density, the properties of the concrete change fundamentally. For two specimens of concrete with the same compressive strength, but one made of LWC and the other one made of NWC, the tensile strength, ultimate strains, and shear strengths are all lower in LWC than NWC, while the amount of creep and shrinkage is higher for LWC. LWC are also less stiff than the equivalent NWC. However, there are benefits in using LWC such as reduction in dead load that results in slight reduction in the depth of a beam or slab. It is also observed that the elastic modulus of LWC is lower than the equivalent strength of NWC, but when considering the deflection of a slab or beam, this is counteracted by the reduction in dead load.

In the present chapter after the discussion about the lightweight concrete and its properties, we will study about the compressive strength of LWC and the

methods for evaluation and prediction of compressive strength of LWC. Further a case study of LWC made of LWA will be conducted and presented for a better understanding of the properties of LWC. In the end the conclusion of the chapter will be drawn.

## **2. Background of lightweight concrete**

Concrete is a relatively heavy building material; therefore many experiments have been conducted throughout the twentieth century to decrease its weight without impairing other properties. During the 1920s and 1930s, many different types of lightweight concrete were developed, e.g., Durisol, Siporex, Argex, and Ytong. Probably the most famous and first type of autoclaved gas concrete was Ytong. It was invented by the Swedish architect, Johan Axel Eriksson, assistant professor at the Royal Institute of Technology in Stockholm. In the early 1920s, Eriksson experimented with different samples of gas concrete and put the mixtures in an autoclave to speed up the curing process. In November 1929, the industrial production of Ytong blocks began. The name combines the y of Yxhult, the town where the first Swedish factory was located, and the end of betong, the Swedish word for concrete. The material was very popular in Sweden from 1935 onward, with a true breakthrough immediately after World War II, when it became one of the most important building materials in the country. Also, the manufacturing process was exported to other countries such as Norway, Germany, the UK, Spain, Poland, Israel, Canada, Belgium, and even Japan. The autoclaved gas concrete Siporex was developed in Sweden in 1935. The LWAC, Argex, was first produced in Denmark in 1939 under the international brand name Leca. Starting with an annual production in Copenhagen of 20,000 m<sup>3</sup>, the total production throughout Europe had increased by 1972 to nearly 6 million m<sup>3</sup> per year (adopted from postwar building materials “postwarbuildingmaterials.be”).

The later type of LWC which is called LWAC is one of the most popular one among them and from that time until today has been the subject of many research works around the world. Even today there are many ongoing extensive research programs on SLWC and NSLWC made of LWA. In the present chapter, we focus on LWAC, and for the case study, we will discuss a part of the ongoing research of the author on LWAC [1]. Categorized examples of the research works conducted recently have been discussed below:

### **2.1 LWC including recycled lightweight aggregate**

In 2013, a research was conducted on producing concrete containing recycled aggregates obtained from crushed structural and nonstructural lightweight concrete [2]. The mechanical properties of this concrete were investigated. Concrete compositions made of recycled lightweight concrete aggregates (RLCA) were measured for their compressive strength, modulus of elasticity, tensile strength, and abrasion resistance. The influence of the properties of the aggregates on concrete properties were discussed including concrete density, compressive strength, structural efficiency, splitting tensile strength, modulus of elasticity, and abrasion resistance. This research proved that it is possible to produce structural recycled lightweight concrete from crushed, structural, and nonstructural LWC with densities below

2000 kg/m<sup>3</sup>. Improvements in mechanical properties can be seen when the LWA is replaced with RLCA. The study concluded that recycled lightweight aggregate is a potential alternative to conventional LWC.

## **2.2 LWC including expanded clay aggregates**

In 2015, other researchers studied the properties of LWC consisting of cinder and light expanded clay aggregates (LECA) [3]. By replacing coarse aggregate with blended lightweight aggregates such as cinder and LECA, there was a reduction in weight and, respectively, a decrease in compressive strength, but they were able to use cinder and LECA as a replacement for normal coarse aggregate to reduce the cost, while the compressive strengths were close to the strengths of NWC. The average compressive strength for samples that included the abovementioned LWA was 39.2 N/mm<sup>2</sup>, while the average compressive strength for NWC was 43.4 N/mm<sup>2</sup>. The density of the LWC varied from 1800 to 1950 kg/mm<sup>3</sup> and the density for the NWC was 2637 kg/m<sup>3</sup>. The slump from the fresh concrete mix and the average compressive and tensile strength of the hardened concrete were analyzed in the research.

## **2.3 LWC including foam glass aggregates**

Similar research presented on waste materials showcased that waste materials can be reused as construction materials, in 2016 [4]. Foam glass and high-impact polystyrene (HIPS) are materials they collected through the processing of waste materials. The glass foam is found from a glass cutlet, and the polystyrene is collected from butadiene modified rubber. They investigated the compressive and flexural strength, water absorption, and bulk density of the proposed concrete mixtures. LWC with foamed glass aggregates was affected by the amount of aggregate. Larger amounts of aggregate cause a decrease in compressive and bending strength and an increase in absorption. The addition of HIPS improved the compressive strength; however, it did not have a significant influence on water absorption. In 2017, Kurpinska and Ferenc studied on the physical properties of lightweight cement composites consisting of granulated ash aggregate (GAA) and granulated expanded glass aggregate (GEGA) [5]. This study showcased the significant impact of grain type and size on the physical properties of lightweight concrete. After the mechanical properties of 15 different mixtures were calculated and measured, they utilized a finite element modeling program to study the possibility of applying this type of LWC in structural elements, extenders, and insulation material.

## **2.4 LWC including expanded glass aggregates**

In 2017, the material properties and effects of crushed and expanded waste glass aggregates on LWC properties were evaluated [6]. In this study, an image-based approach is used to extract the characterization of the materials. Pore measurement and pore structures of each material type were evaluated using a microscope, 3D, and X-ray micro-computed tomography. Thermal conductivity for the material was measured. There results showed that crushed and expanded waste glass aggregates are supported as alternatives for lightweight aggregates. LWC with a density less than 2000 kg/m<sup>3</sup>, including crushed waste aggregate, have shown to have a compressive strength over 38 MPa. This was considered as effective lightweight concrete, and it satisfied the desired mechanical properties.

## 2.5 LWC including expanded glass aggregates and expanded clay aggregates

An experimental investigation on the compressive strength and durability of LWC with fine expanded glass (FEG) and expanded clay aggregates (ECA) using different micro-fillers including ground quartz sand and silica fume was conducted in 2018 [7]. Based on their research, ECA is one of the most popular aggregates for SLWC, and using this aggregate is important for sustainable development in the construction industry. The relationships between compressive strength and density of concrete mixtures with different proportions of LWA were explored. The effects of fine LWA on density and compressive strength of LWAC were also analyzed. They could reach to compressive strengths of 39.5–101 MPa for the mixtures containing EGA and 43.8–109 MPa for mixtures containing ECA. The density of the mixtures containing EGA and ECA are 1458–2278 and 1588–2302 kg/m<sup>3</sup>, respectively. Different compressive strength-density relationships were obtained for LWC containing EGA and LWC containing ECA even though the compositions had the same amount of cement, water to cement ratio, micro filler, and total volume of LWA. While understanding the basic mechanical properties (density and compressive strength) of concrete containing LWA such as ECA and EGA was the main goal of this study, it was concluded that the application of expanded glass aggregate (EGA) in concrete is still in its early stages.

As in the present book, compressive strength of concrete is the main subject of discussion; later in this chapter, we will discuss a case study on compressive strength of a specific type of LWC containing EGA implementing a NDT method in addition to the conventional compression test. Therefore in the next section, we will briefly talk about the usage of NDT in the evaluation of compressive strength and properties of concrete.

## 3. Nondestructive testing methods

Nondestructive testing (NDT) methods are widely used in the investigation of the mechanical properties and integrity of concrete structures. As seen in **Table 1**, provided by AASHTO [8], the following techniques are used for detecting defects in

The capability of defect detection						
Method based on	Cracking	Scaling	Corrosion	Wear and abrasion	Chemical attack	Voids in grout
Strength	N	N	P	N	P	N
Sonic	F	N	Gb	N	N	N
Ultrasonic	G	N	F	N	P	N
Magnetic	N	N	F	N	N	N
Electrical	N	N	G	N	N	N
Nuclear	N	N	F	N	N	N
Thermography	N	Gb	Gc	N	N	N
Radar	N	Gb	Gc	N	N	N
Radiography	F	N	F	N	N	F

*G = good; F = fair; P = poor; N = not suitable; Gb = beneath bituminous surfacing; Gc = detects delamination.*

**Table 1.**  
 Capability of investigating techniques for detecting defects in concrete structures in field use [8].

concrete structures for field use. In the present study, ultrasonic pulse velocity (UPV) method is used to evaluate the properties of LWC. Ultrasonic techniques measure the velocity of a pulse, generated from a piezoelectric transducer in concrete, and this measurement assesses the mechanical properties of a concrete. Based on research and correlations, the pulse velocity relates items such as compressive strength or corrosion [1]. As seen in **Table 1**, UPV detects corrosion in reinforcement; however, it is not studied in this report.

### 3.1 Ultrasonic pulse velocity (UPV)

AASHTO states that the accurate measurement of the concrete's strength depends on several factors and is best determined experimentally [8]. In the present work in addition to the conventional compression test, UPV is utilized to explore the properties of concrete. In general UPV tests are used to distinguish the material and integrity of concrete sample being tested. This technique enhances quality control and detection of defects. In the field, UPV verifies concrete uniformity, detects internal imperfections and finds the imperfections' depth, estimates the deformation moduli and compressive strength, and monitors characteristic variations in concrete throughout time [9]. From observations, certain factors influence UPV. The theory for elasticity for homogeneous and isotropic materials states that the pulse velocity of compressional waves (P-waves) is indirectly proportional to the square root of the dynamic modulus of elasticity,  $E_d$ , and inversely proportional to the square root of its density,  $\rho$  [10]. The aggregate type used in a mixture has a significant influence on the elastic modulus; therefore for our current LWA, a significant change in the pulse velocity is expected. To differentiate results, correlations need to be analytically determined. As an example an expression for the modulus of elasticity of concrete and its relation between the compressive strength ( $f_c$ ), the oven-dried density, and the  $E_c$  itself is suggested by EN 1992-1-1, Eurocode 2 [11]. This relationship suggests that UPV and  $f_c$  are not unique and are affected by factors such as the type and size of aggregate, physical properties of the cement paste, curing conditions, mixture composition, concrete age, voids/cracks and moisture content [12]. Factors influencing the UPV method are presented in **Table 2** [13]. Constituents of the concrete and its moisture content, age, and voids/cracks impact UPV significantly. Previous works have shown that a correlation between the compressive strength in concrete and the ultrasonic pulse velocity must be determined for each particular concrete mix [13, 14]. Finding a general

Constituents of concrete	Aggregate	Size	Average influence
		Type	High influence
Cement		Percentage	Moderate influence
		Type of cement	Moderate influence
Other constituents		Fly ash content	Average influence
		Water/cement ratio	High influence
Humidity degree/moisture content			Average influence
Other factors		Reinforcements	Moderate influence
		Age of concrete	Moderate influence
		Voids, crack	High influence

**Table 2.**  
*Influencing factors for UPV method.*

correlation between  $f_c$  and UPV will be an enhancement for inspection and assessment of structures made of LWC.

Therefore based on the previous studies, it is recommended that for each type of LWA used in LWC, the researchers conduct an experimental program to drive a brand new relation between UPV and compressive strength of concrete, which is not the focus of the present chapter. Hence in the present chapter, we have presented some of the most recent proposed equations, relating UPV to compressive strength of LWC, and presented some of the available equations relating UPV to compressive strength of LWC and NWC for those interested to compare the configurations of the equations and to initial their research for the specific types of LWA of interest.

### 3.2 Utilizing UPV to find the compressive strength

During the last decades, many researchers presented different methods for the evaluation of compressive strength for LWA concrete versus UPV. The LWA in those studies consists of different types of natural or man-made LWA such as recycled lightweight concrete aggregates (RLCA), light expanded clay aggregate (LECA), high-impact polystyrene (HIPs), granulated ash aggregate (GAA), granulated expanded glass aggregate (GEGA), foam expanded glass aggregate (FEG), expanded clay aggregate (ECA), and expanded glass aggregate (EGA). In the literature several factors that influence the relation between compressive strength and UPV were examined. Most important analyzed factors included the cement type and content, amount of water, type of admixtures, initial wetting conditions, type and volume of aggregate, and the partial replacement of normal weight coarse and fine aggregates by LWA. As a result, simplified expression was proposed to estimate the compressive strength of different types of LWAC and its composition. The dependence of UPV and the modulus of elasticity were also explored in many of works [13]. They presented the expression below for a wide range of SLWC with compressive strength varying from 20 to 80 MPa. UPV and density are measured in meters per second and  $\text{kg/m}^3$ . From the regression analysis,  $K_{upv}$  can be a constant equal to 54.6, 54.3, 0.86, etc. and is a correlation coefficient. Values of UPV and strength measurements were performed on cubed concrete specimen in their study:

$$f_c = \left( \frac{UPV}{K_{upv} * \rho^{0.5}} \right)^{\frac{2}{3}} \quad (1)$$

where  $f_c$  is the compressive strength of concrete (MPa), UPV is the ultrasonic pulse velocity (m/s), KUPV is a constant representing the correlation coefficient, and  $\rho$  is the dry density of specimen ( $\text{kg/m}^3$ ). In the research presented elsewhere [9], equations for LWC containing fibers were proposed to estimate the concrete compressive strength from respective UPV values. The equations presented below are the compressive strength of concrete at days 7 and 28, respectively:

$$f_c = 1.269 \exp.(0.841v) \quad (7 \text{ days}) \quad (2)$$

$$f_c = 0.888 \exp.(0.88v) \quad (28 \text{ days}) \quad (3)$$

where  $f_c$  is the compressive strength of concrete (MPa) and  $v$  is the pulse velocity (m/s). Other types of equations were presented in 2015 [10], which contributed the coarse aggregate content as a ruling factor in the relationships presented. In the developed equations, the  $f_c$  was represented for a compressive cube strength measured in MPa. The variable,  $v$ , is UPV and it was measured in



No.	Proposed equations	Author, year
1	$f_c = 1.2 \times 10^{-5} \times UPV^{1.7447}$	Kheder, 1999
2	$f_c = 36.75 \times UPV - 129.077$	Qasrawri, 2000
3	$f_c = 21.5 \times UPV^2$	AIJ, 1983
4	$f_c = 0.6401 \times UPV^{2.5654}$	Ali-benyahia, 2017
5	$f_c = 0.0316 \exp(1.3 * UPV)$	Atici, 2011
6	$f_c = 0.5208 \times UPV^5$	Khan, 2012
7	$f_c = 50.163 \times UPV - 178.2$	Kim, 2012
8	$f_c = 0.0136 \times UPV - 21.34$	Najim, 2017
9	$f_c = 38.05 \times UPV^2 - 316.76 \times UPV + 681.62$	Rashid, 2017
10	$f_c = 0.854 \exp(1.28882 \times UPV)$	Trtniket et al., 2009

**Table 3.**

*Proposed equations for finding the compressive strength of concrete using UPV [15].*

kilometers per second. The expressions are presented below for different coarse aggregate (CA) contents:

For CA (coarse aggregate content) = 1000 kg/m<sup>3</sup>

$$f_c = 8.88 \exp(.0.42v) \quad (4)$$

For CA = 1200 kg/m<sup>3</sup>

$$f_c = 0.06 \exp(.1.6v) \quad (5)$$

For CA = 1300 kg/m<sup>3</sup>

$$f_c = 1.03 \exp(.0.87v) \quad (6)$$

For CA = 1400 kg/m<sup>3</sup>

$$f_c = 1.39 \exp(.0.78v) \quad (7)$$

**Table 3** showcases some of the different equations generated by researchers in the last decades to predict compressive strength of concrete,  $f_c$ , in terms of UPV [15].

## 4. Experimental program

In this section an experimental program was developed and conducted by the author and his graduate student to investigate the compressive strength of LWAC containing a specific type of expanded glass aggregate (EGA), to better showcase the properties of LWAC [1].

### 4.1 Lightweight and normal weight aggregates

#### 4.1.1 NWA

**Tables 4** and **5** consist of the sieve analyses for the normal weight gravel and coarse sand, respectively, which were measured according to ASTM C136-01 [16].

The NWA's absorption capacity, specific gravity, and moisture content are evaluated according to ASTM C 127-01 [17] and ASTM C 566 [18]. **Table 6** includes aggregate properties such as specific gravity, absorption capacity, moisture content, and fineness modulus (FM). In **Figures 1** and **2**, the individual aggregates are shown. The maximum normal weight aggregate size was 9.53 mm (3/8").

Sieve analysis		Sample size (SS): 2.27 kg		
Sieve size	Weight retained (kg.)	% retained	% coarser	% finer
19 mm	0	0	0	0
13 mm	0	0	0	0
9 mm	0.047	2.073	2.073	97.93
No. 4	1.6	70.49	72.56	27.4
No. 8	0.5	21.622	94.18	5.82
No. 10	0.021	0.92	95.1	4.9
Passing	0.112	4.9023	99.99	0.001
Sum of SS	2.27			

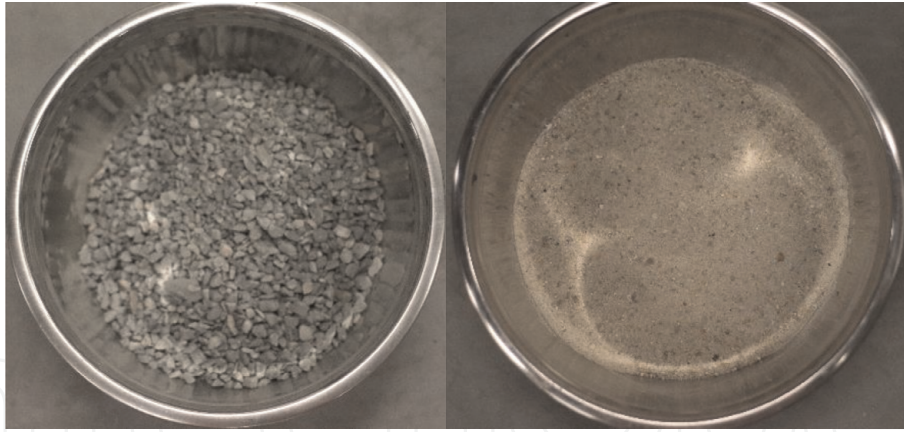
**Table 4.**  
*Sieve analysis for normal weight gravel mix.*

Sieve analysis		Sample size (SS): 1000 g	
Sieve no.	Weight retained (g)	% retained	% finer
8	5	0.5	99.5
10	49.5	5.45	94.55
16	283	33.75	66.25
20	286.5	62.4	37.6
30	364.5	98.85	1.15
40	11	99.95	0.05
pan	0.5	100	0
Sum of SS	1000		

**Table 5.**  
*Sieve analysis for normal weight coarse sand.*

Property	Normal weight aggregates		Lightweight aggregates		
	Gravel mix (GM)	Coarse sand (CS)	Poraver (0.25–0.5 mm)	Poraver (1–2 mm)	Poraver (2–4 mm)
Specific gravity (ton/m <sup>3</sup> )	2.4	2.75	0.55	0.36	0.32
Absorption capacity (%)	2.3	1.87	19	9	9
Moisture content (%)	4.5	6.4	0.5	0.5	0.5
Fineness modulus	3.64	2.9	1.92	3.81	4.7

**Table 6.**  
*LWA and NWA properties.*



**Figure 1.**  
*NWA, from left to right, normal weight gravel mix, and coarse sand.*



**Figure 2.**  
*LWA, from left to right, Poraver 0.25–0.5, 1–2, and 2–4 mm.*

#### 4.1.2 LWA

The LWA used in this study is Poraver, [19] which is an expanded glass granule. The material is pressure resistant, durable and dimensionally stable, 100% mineral, spherical in shape, ecological, and not hazardous to health. According to the Poraver technical data sheet, the aggregate is lightweight according to ASTM C330, C331, and C332 and DIN EN 13055-1. Mineral casting and polymer concrete, plaster and dry mortar, lightweight panels, automotive, 3D printing, and other additional practices are practical applications of this material. The aggregate sizes and properties of the LWA are presented in **Table 6**. The Poraver technical data sheet provided the absorption capacity and moisture content on delivery and specific gravity for the LWA [19].

#### 4.2 Mix proportion

The experimental work includes various concrete mixes consisting of lightweight EGA, and these concrete mixes were created with partial or total replacement of NWA with LWA. The ACI 211.2-98 guide for LWC was followed for mix designing [20]. In this study, the control of the cement content is intended to properly understand the compressive strength for different concrete mixes without being influenced by the cementitious material effects. Many combinations of aggregates were tested and the optimum aggregate sizes to increase the compressive strength were selected. The mix proportions of the LWAC mixes are found in **Table 7**. The cement type used was Ordinary Portland cement CEM I 42.5 N. In the presented tables, Poraver size 0.25–0.5 is referred to as LWA (fine), while the LWA sizes, 1–2 and 2–4 mm, are considered as LWA (coarse).

Mix label	w/c	Cement (g)	Water (g)	GM (g)	CS (g)	LWA	LWA	LWA
						(0.25–0.5 mm) (g)	(1–2 mm) (g)	(2–4 mm) (g)
1	0.29	685	199	304	2545	—	—	154
2	1.88	576	1084	658	1275	—	—	2631
3	0.31	576	177	3284	508	—	—	767
4	0.47	576	272	2631	1021	—	658	254
5	0.47	576	272	658	1021	254	658	—
6	0.7	576	404	1973	767	508	329	—
7	0.7	576	404	658	1021	254	658	—
8	0.47	576	272	3284	1021	181	—	—
9	0.47	576	272	3284	767	167	—	—
10	0.47	576	272	3284	508	253	—	—
11	0.47	576	272	3284	254	340	—	—
12	0.47	576	272	3284	340	421	—	—

**Table 7.**  
 Mix proportions.



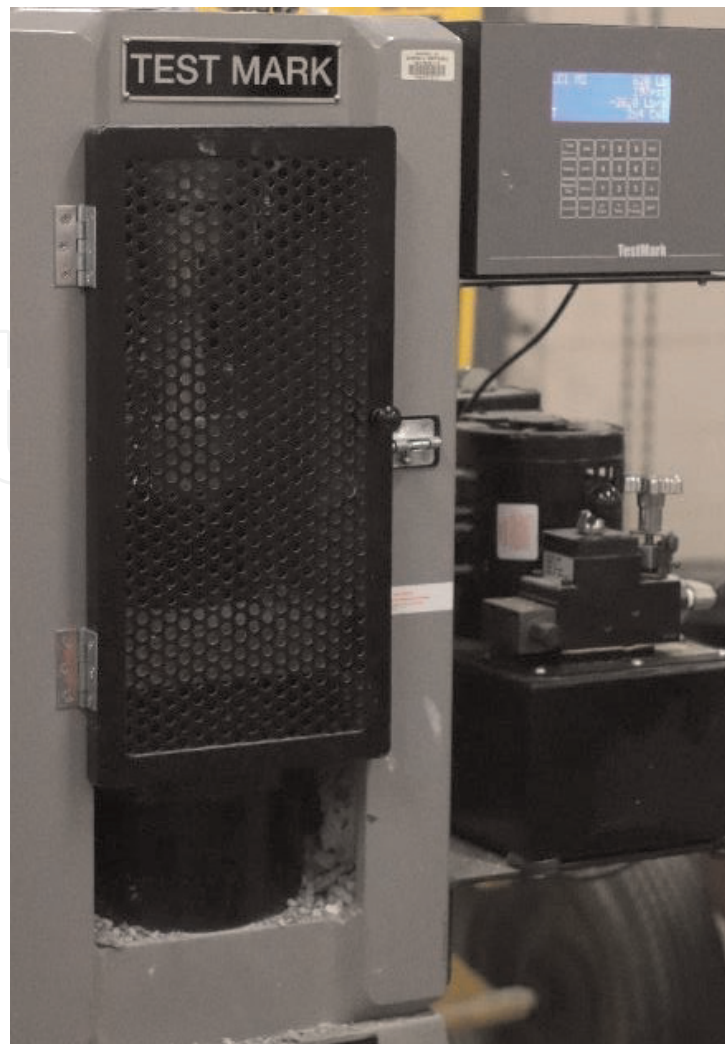
**Figure 3.**  
 Ultrasonic pulse velocity instrument.

### 4.3 Test methods

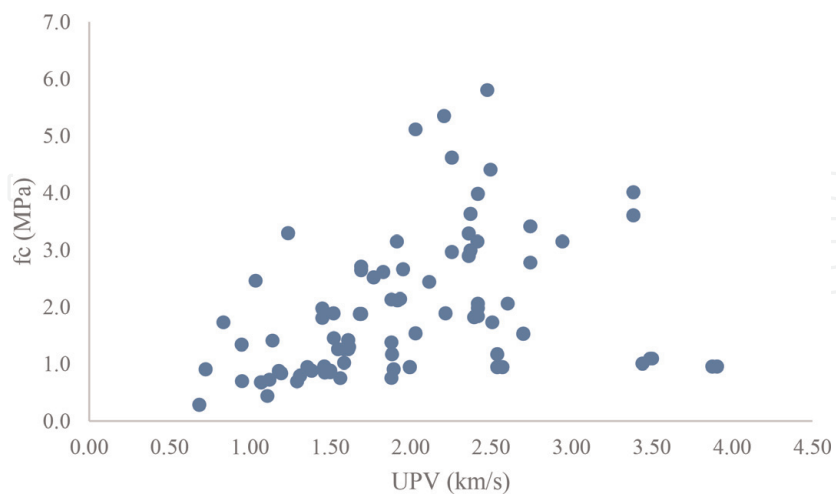
ASTM C 192 was used as the guide for making and curing concrete test specimens in the laboratory [21]. The specimens were demolded after 24 hours and submerged underwater until a day before testing. UPV (**Figure 3**) and the axial compression machine (ACM) in **Figure 4** were used to determine the compressive strength of concrete at days 7 and 28.

### 4.4 Results and discussion

In general it was observed that with increase in the amount of LWA in the concrete mixture, the compressive strength and UPV of LWC decrease, which was expected. In **Figure 5**, the relationship between UPV and  $f_c$  (measured with ACM), at the age of 7 and 28 days for the LWC is presented. It can be observed that the results are scattered and more tests and specimens and concrete mixtures will be



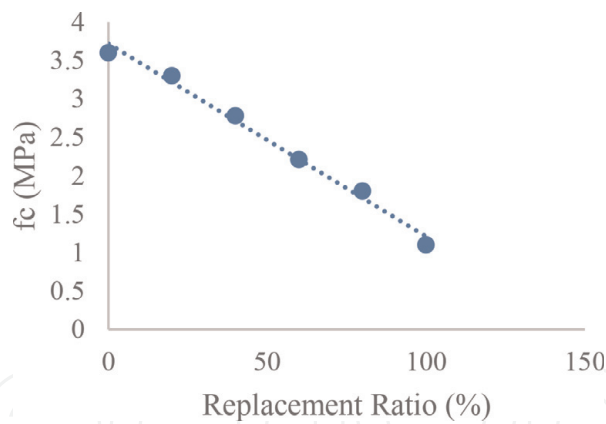
**Figure 4.**  
*Compression test machine.*



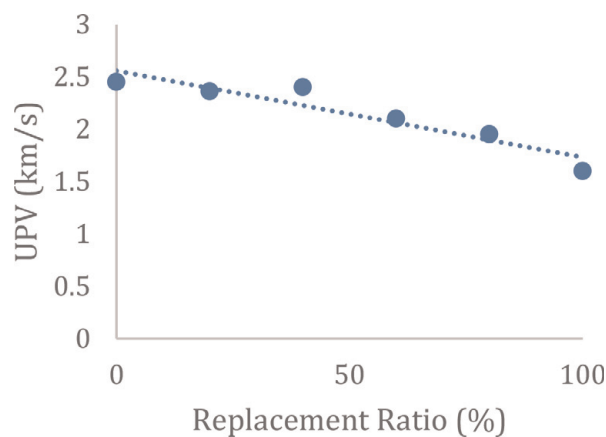
**Figure 5.**  
*UPV versus  $f_c$  for LWC tested at days 7 and 28.*

required to be able to establish a solid relationship between UPV and compressive strength for this type of LWAC. The best empirical relation obtained from curve fitting analyses for this study can be written as below:

$$f_c = 0.8 \exp (0.335v) \quad (8)$$



**Figure 6.**  
*fc versus RR for LWC.*



**Figure 7.**  
*UPV versus RR for LWC.*

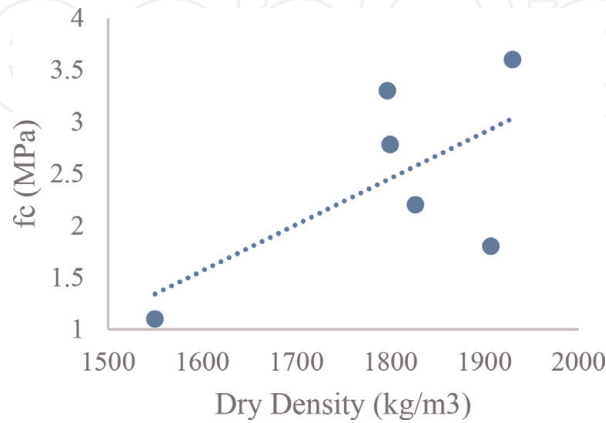
where  $f_c$  is the compressive strength of concrete (MPa) and  $v$  is the pulse velocity (km/s).

To be able to investigate the effect of the LWA content in the mix proportions, we have selected the mixes with constant w/c ratio of 0.47 and gradually replaced the NWA with LWA (Table 8). Figure 6 depicts the relation between  $f_c$  and replacement ratio (RR) or LWA content for these individual mix proportions. From this figure, it can be observed that for the LWC in this study, as the LWA content increases,  $f_c$  decreases. Figure 7 shows the relation between UPV and RR or LWA content for these individual mix proportions. From this figure, it can be observed that for the LWC in this study, as the LWA content increases, UPV decreases as expected.

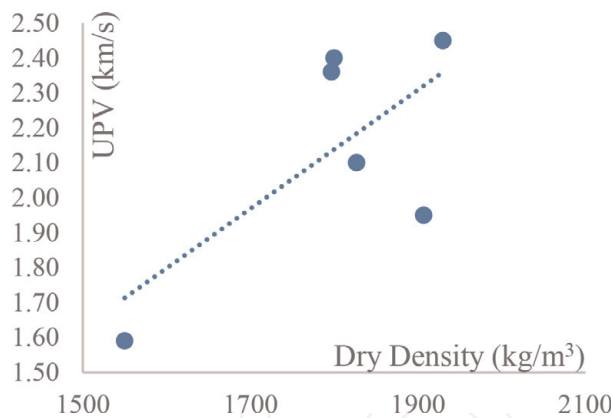
Mixes	RR	w/c	Cement (g)	Water (g)	GM (g)	CS (g)	LWA, coarse (g)	LWA, fine (g)
12a	0	0.47	576	272	3284	1275	—	0
12b	20	0.47	576	272	3284	1021	—	254
12c	40	0.47	576	272	3284	767	—	508
12d	60	0.47	576	272	3284	508	—	767
12e	80	0.47	576	272	3284	254	—	1021
12f	100	0.47	576	272	3284	0	—	1275

**Table 8.**  
*Comparison between different LWA contents.*

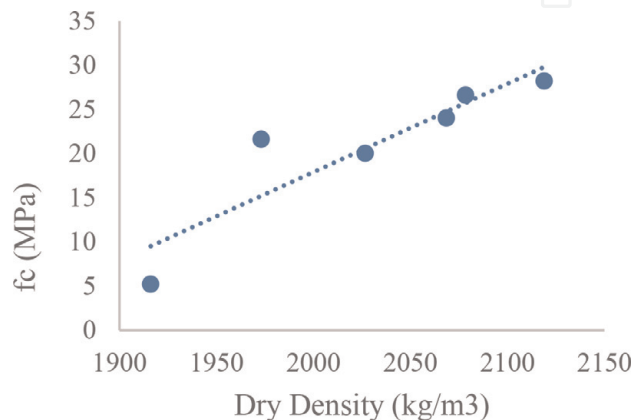
The relationship between UPV,  $f_c$  (compressive strength), and dry density for the mix proportions in **Table 8** is presented in **Figures 8** and **9**. It can be observed that for the LWC in this study, as the dry density increases, UPV and  $f_c$  also increase, but the results are scattered when working with LWC. To be able to compare these results from those of NWC, mixes of NWC with similar compositions but without any LWA were produced, and results were presented in **Figures 10** and **11**. It is observed that the result for the relationship between UPV,  $f_c$  and, dry density for LWC is more scattered than similar test result for NWC.



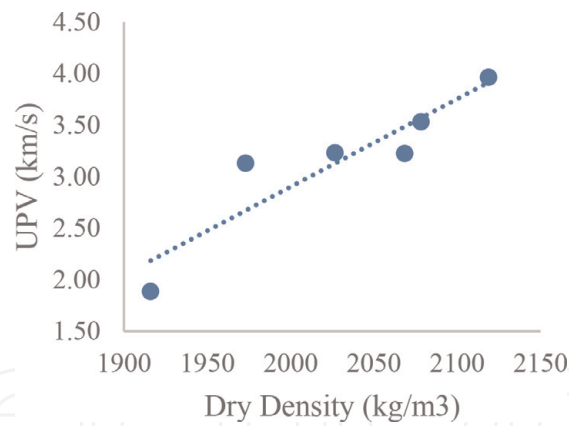
**Figure 8.**  
 *$f_c$  versus dry density for LWC.*



**Figure 9.**  
*UPV versus dry density for LWC.*



**Figure 10.**  
 *$f_c$  versus dry density for NWC*



**Figure 11.**  
*UPV versus dry density for NWC.*

## 5. Conclusions

There are different types of LWC available in the industry that depending on the method which is used for production of each type, the properties of the LWC can be completely different. Lightweight aggregate concrete (LWAC), foamed concrete (FC), and autoclaved aerated concrete (AAC) are among the most common types. On the other hand, structural and nonstructural lightweight concrete can be produced for different purposes. Lightweight aggregate concrete, such as the one discussed in this study, are being used nowadays in the advancement of concrete technology, but it is proven that each type of LWA needs to be tested before being used in structures and even for nonstructural purposes. Compressive strength of LWC is an important characteristic of LWC that can be measured or predicted with few methods such as NDT methods. Ultrasonic pulse velocity was utilized to assess the compressive strength,  $f_c$ , of the LWC containing EGA in the present study. In this chapter it was observed that LWA can replace NWA to achieve smaller bulk densities and UPV can be used as a method for evaluation of compressive strength of LWC. Based on the case study conducted in the present chapter, it was shown that as the dry density of the LWC decreased, UPV and  $f_c$  decreased, respectively. Comparisons of actual  $f_c$  values obtained from CTM proved UPV can be related to  $f_c$ , and the results showed similar characteristics to previous works, while the previous work's equations cannot be used for the aggregates used in this study. The results of the present study are limited to the mix design and materials that were used in this work, and it should be noted that these results cannot be extended to other types, sizes, etc. of aggregates and different mix designs.



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### **Author details**

Saman Hedjazi

Department of Civil Engineering and Construction, Georgia Southern University,  
Statesboro, GA, USA

\*Address all correspondence to: [shedjazi@georgiasouthern.edu](mailto:shedjazi@georgiasouthern.edu)

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