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Investigation of production and Performance Evaluation of High-Strength Lightweight Concrete (HSLWC) Produced with Regional Volcanic Aggregates(RVA)

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Abstract

This study investigates the feasibility of producing high-strength lightweight concrete using regional volcanic aggregate (RVA) and examines the performance of the produced concrete. Various mix designs conforming to ASTM and TS EN standards were applied to achieve the targeted strength and density. The study also investigated the effect of water/cement ratio (W/C) and cement content on the mechanical and physical properties of high-strength lightweight concrete. Experimental tests such as compressive strength, tensile strength, density, water absorption, and elastic modulus were conducted to determine the effect of cement content and lightweight aggregate on the overall behavior of the concrete. To ensure adequate workability, superplasticizer was added to all mixes at a rate of 1.5% of the cement weight. The slump values of fresh concrete met modern requirements for good workability, pumpability, and high strength. The results showed that, provided a superplasticizer is used, high-strength concrete with a density range of 1830 to 1915 kg/m³ can be produced using 450 kg/m³ of cement. The results show that the porous structure and pozzolanic properties of RVA significantly increase the mechanical strength of concrete and, thanks to its porous structure, reduce its unit weight by 20-25%. The highest compressive strength recorded within 90 days for a mixture containing 650 kg/m³ of cement was 87 MPa. It was concluded that the W/C ratio and cement content have a

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significant effect on the mechanical and physical properties of these concretes.

Keywords: Lightweight aggregate concrete, Sustainable concrete, Regional volcanic aggregate, high strength lightweight concrete, shrinkage, elastic modulus, compressive and tensile strength, Unit volume weight, Water absorption rate

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1. Introduction

Lightweight aggregate concrete (LWAC) is increasingly used in civil engineering applications due to its contribution to sustainable construction and environmental protection (Hong et al., 2023). Concrete is the most widely used construction material worldwide due to its ease of production, low cost, and abundance of raw materials (Wang et al., 2020). However, the self-weight of concrete remains a critical parameter determining the economy and seismic performance of structures, especially in earthquake areas (Lu, 2023). Compared to normal concrete, LWAC offers a significantly lower unit weight while maintaining an appropriate strength-to-weight efficiency (Kayali et al., 2003).

The use of lightweight concrete dates back to ancient civilizations. It is known that natural lightweight aggregates were used as early as 3000 BC (Peck, 2006; Artioli and Addis, 2019). Roman engineers and craftsmen widely used lightweight concrete in monumental structures such as temples and statues and many of these structures have survived to this day (Artioli and Addis, 2019). Similarly, lightweight concrete was also used in the construction of Babylonian palaces, early Anatolian structures including Hagia Sophia, and monumental structures in Central America between the 7th and 10th centuries (Entidhar et al., 2012). These historical applications were mostly composed of natural volcanic aggregates such as pumice, scoria, tuff, and perlite, and these were used as both coarse and fine aggregates. In reinforced concrete structures, structural high-strength lightweight aggregate concrete (HSLWAC), typically defined by a unit volume weight below 1950 kg/m^3 and a 28-day compressive strength exceeding 40 MPa, has become increasingly important for high-rise and ultra-high-rise buildings due to its ability to reduce dead loads and lateral seismic forces (Zhang et al., 2011). Volcanic lightweight aggregates currently used worldwide have become particularly preferred due to the natural pozzolanic activity exhibited by most of them (Abdelfattah et al., 2023; Mouli and Khelafi, 2008). Puzzolanic lightweight aggregates react with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), which improves the

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aggregate's pore structure while increasing the density and strength of the aggregates and cement matrix(Mizaal et.al., 2024). This mechanism has a significant positive contribution to the mechanical properties, durability, and long-term performance of lightweight concretes (Mouli and Khelafi, 2008; Nie et al., 2017; Hossain, 2006; Chandra and Berntsson, 2003; Hossain, 2004). Erdoğan (2003) attributes the fact that historical structures in regions such as Ephesus and Milas have remained intact to the present day to the pozzolanic nature of the aggregates and binders used.

Its lightweight structure and advanced durability have led to increased demand for high-strength lightweight concrete and prompted extensive research aimed at improving its mechanical and physical performance. Unlike normal-weight aggregates, volcanic lightweight aggregates have a porous surface structure that allows the cement paste to partially penetrate into the aggregate during mixing, transport, and placement, resulting in a stronger interfacial transition zone and less stress concentration at the aggregate-matrix interface. This strong adhesion prevents the formation of weak zones, resulting in higher strength and durability (Nie et al., 2017; Chandra, 2003; Hossain, 2004; Neville, 2006). Although the results of studies on lightweight aggregate concrete are promising, the behavior of lightweight aggregate concrete varies significantly depending on the aggregate source, mineralogy, and pore structure, requiring research specific to the aggregate (Chandra and Berntsson, 2003; Hossain, 2005; R. S. Fakhri and E. T. Dawood, 2023).
Previous studies have recommended binder contents ranging from 400 to 600 kg/m³ to produce high-strength lightweight concrete; the upper limit of this range has been defined as the dosage beyond which no further increase in strength can be achieved. However, these recommendations vary depending on the properties of the lightweight aggregate used. In this context, regional lightweight volcanic aggregates (RVA) have rarely been used for structural concrete applications before. This is particularly important for regions such as Erzincan, Turkey, where seismic activity is

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intense and locally available traditional aggregates (Fırat aggregates) exhibit unfavorable chemical, physical, and mechanical properties. Therefore, the development and evaluation of suitable alternative regional aggregates for earthquake-resistant structural concrete is both a scientific necessity and a practical engineering requirement. Adhesion, the physical and mechanical bond between the aggregate and the cement matrix, is the most important factor affecting the mechanical and physical properties of concrete (Aïtcin. 1998; Neville,2006). Compressive strength tests performed on concretes produced with Fırat aggregate revealed that fracture occurred as a result of the cement paste peeling off the smooth, rounded aggregate surface. Some aggregates were also observed to fracture. In normal-strength concrete, it is desirable that fracture does not occur due to aggregate fracture (Aïtcin. 1998; Neville,2006). These two observations suggest that Fırat aggregate is mechanically and physically unsuitable for concrete production. In the 1992 earthquake of magnitude 6.6 that struck Erzincan, it was determined that the cause of the damage and collapse of the buildings that were destroyed or severely damaged was due to aggregate materials. In addition to mechanical and physical drawbacks, the disadvantages of extracting aggregate from the Fırat River include causing erosion along the riverbanks and the destruction of aquatic life and the ecosystem (Lim et al. 2024). The reason for this study is that RVA has not been used in the production of structural concrete before in 1992, which is where severe earthquakes often occur. The Fırat aggregate used in concrete in this region is not chemically, physically or mechanically suitable for the production of concrete. Thus, there is a need for an alternative aggregate for the production of concrete which can be used in buildings in this region.

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2. Materials and Method

2.1. Materials

2.1.1. Superplasticizer

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In the production of high-strength light weight concrete, the most important principle is to use a low w/c ratio. To provide the desired workability at low w/c ratios, superplasticizer should be used at a high rate (Kayali et al. 2003; Abdelfattah et al. 2023; Moali and Khehafi 2008). In this study, to provide the desired workability at a low w/c ratio, Polycarboxylic ether-based plasticizer was used. This plasticizer can be used with any type of cement. It conforms with TS EN 934-2 and ASTM C 494 Type F.

2.1.2. Aggregate

Aggregate is the most important factor affecting the mechanical and physical properties of concrete. Aggregate, which is harder and more durable than mortar, generally maintains the dimensional stability of concrete by limiting the deformation of the cement matrix (Mehta and Monteiro 2006). Coarse aggregate reduces the volume change caused by creep deformation, and this effect increases as the aggregate volume content increases. However, lightweight aggregates behave slightly differently from normal aggregates due to their porous structure. Porous lightweight aggregates cannot resist external forces to the same degree as normal-weight aggregates, leading to greater volume changes in the cement matrix and resulting in higher creep (Lopez et al. 2006).

In this study, RLWA with a Dmax of 12.5 mm and gronometry conforming to the Fuller equation was used. The aggregate's gronometry curve is shown in Figure 1. Figure 2 shows a view of fine RVA and Figure 3 shows a view of coarse RVA.

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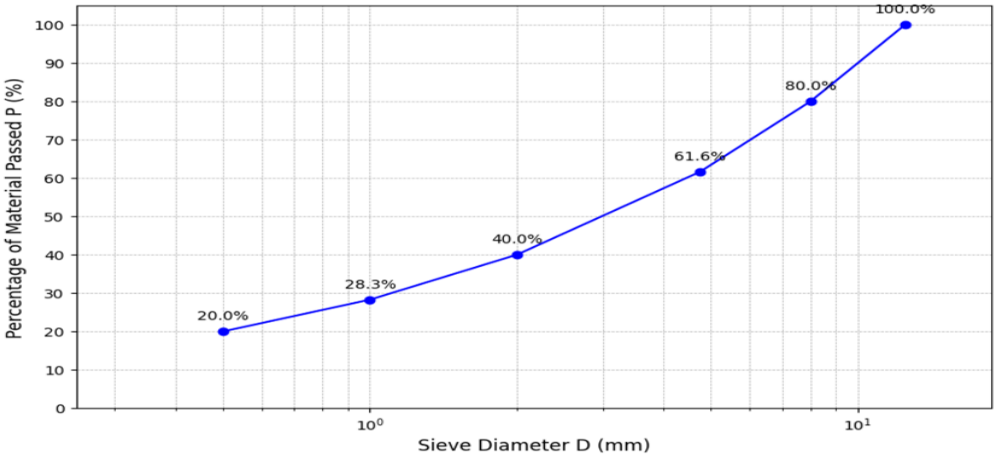


Fig. 1 Granulometer curve of RVA



Fig. 2 A view of fine aggregate



Fig. 3 A view of coarse aggregate

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2.1.3. Cement

In this study, CEM I 52.5 N cement, which was produced in the Ankara Factory of Set ciment in accordance with TS EN 197-1, was used as the binder. The properties of this cement are shown in Table 1.

Table 1. Chemical Composition, Physical and Mechanical Properties of CEM I 52.5 N

Components (%)	**CEM I 52.5 N**	**TS EN 197-1**
CaO	61.7-66.6	---
SiO_2	18.7-21.6	---
Al_2O_3	5.64	---
Fe_2O_3	3.27	---
MgO	1.64	≤ 5.00
SO_3	2.86	≤ 4.00
K_2O	0.80	---
Na_2O	0.32	---
Loss of ignition	0.90	≤ 5.00

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Insoluble residue		0.31	≤ 5.00
Main components			
C_3S		55.55	---
C_2S		16.50	---
C_3A		9.41	---
C_4AF		9.95	---
Free CaO		1.48	---
Physical and Mechanical Properties			
Specific gravity (g/cm^3)		3.11-3.21	---
Specific surface		3600-4500	---
Above 200 µm (%)		---	---
Above 90 µm (%)		0.30	---
Above 40 µm (%)		8.40	---
Volume expansion (mm)		2.00	≤ 10
Setting time (min)	Initial set	145	≥ 60
	Final set	230	---
Compressive Strength (MPa)	7 days	35-45	---
	28 days	54-65	≥ 52.5

3. Method

In this study, the total required amount of aggregate is taken according to the loose air-dry unit weights of the aggregates. Although this amount varies between lightweight aggregates, generally 1 to 1.2 m^3 of lightweight aggregate is sufficient for 1 m^3 of concrete. Many researchers such as Neville (1994), Aitcin (1998), Zhong and Gjorv (1991) and Kayali et al. (2003) suggest limiting the maximum aggregate size to 12.5 mm in the production of high-strength lightweight concrete, depending on the type of lightweight aggregate used. The reason for the limitation of lightweight aggregate particle size is that as the diameter increases, the workability and strength of the concrete decrease. One of the most important factors that will affect the properties of the concrete to be obtained is the granulometry of the fine and coarse aggregates and their proportions. Well-graded aggregates have a uniform grain distribution and a minimum void ratio, and so require minimum cement paste. This provides very economical cement usage. For an ideal mixture and workability, the required fine aggregate amount is recommended to be between 40% and 65% of total aggregate. Aitcin (1998), Neville (1994), Hossain (2004) and many other researchers state that the fine aggregate

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ratio should be 50% or more for the production of workable high-strength lightweight concrete. In this study, Dmax was chosen as 12.5 mm as the maximum aggregate particle size and, for the aggregate gronometry, the relation suggested by the Fuller equation and ASTM No:4, ASTM C330 and previous studies was taken into account.

3.1. Design of High-strength Lightweight Concrete

The design of lightweight concrete differs considerably from the design of normal concrete (Bahmani et al. 2025; Lu et al. 2021; Chandra and Berntsson 2002; Zhang et al. 1991). The relationship between strength and workability, which is one of the functional requirements, has not previously been considered important in the design of lightweight concretes. However, in the design of normal concrete, there is a very close relationship between these two properties and designs are made to incorporate them. Therefore, it is recommended to use different methods in different lightweight concrete designs. A lot of work has been done on the factors that will affect the properties of normal concrete with useful information being obtained. Conversely, adequate studies have not yet been carried out on the factors that will affect the properties of lightweight concrete and so sufficient information has not been obtained (Nie et al. 2017; Chandra 2003; Chandra and Berntsson 2002; Zhang et al. 1991). Recently, with the increase in the need for lightweight concrete around the world, studies on this subject have increased. One of the basic principles in the design of lightweight concrete is that the concrete has the desired workability, but this is very difficult to produce. The coarse surface texture and the shape of both the lightweight aggregate and the fine lightweight aggregate reduce the workability of these concretes (Lu et al. 2021; Chandra and Berntsson 2002; Neville 1998; Wilson and Malhotra 1998). To avoid this problem, the fine aggregate volume should be at least 50% of the total aggregate volume (Chandra and Berntsson 2002; Zhang et al. 1991; Aïtcin 1998). The workable characteristics of

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lightweight aggregate concrete are quite different from those of concrete produced with normal aggregate. While a wide range of workability is achieved with a range of water content in concrete produced using normal aggregates, workability can be very low when the same amount of water is used in lightweight aggregates. If the workability of lightweight concrete is too low, it will not be possible to place the concrete by compaction or bottling. When a vibrator is used, the light coarse aggregates float to the surface and cause segregation in the concrete (Lu et al. 2021; Aïtcin 1998). If the amount of water in the mixture is too high, segregation occurs during concrete casting. A high amount of cement should be used in the production of high-strength concrete (Lu et al. 2021; Chandra and Berntsson 2002; Zhang et al. 1991; Aïtcin 1998). Most researchers recommend the use of a binder between 400 kg/m^3 and 650 kg/m^3. Aïtcin (1998) and many researchers define the maximum amount of cement as the final amount that increases the strength of the concrete. A value above this will have no effect on compressive strength because it is the strength of the coarse aggregate that is effective on the compressive strength of high-strength lightweight concrete. For this reason, the maximum amount of cement varies from lightweight aggregate to lightweight aggregate. The maximum amount of binder in previous studies carried out varied between 630 and 750 kg/m^3. In this study, concrete was produced at three different w/c ratios and five different cement dosages in order to produce high-strength lightweight concrete and to see the change in the physical and mechanical properties of the concretes produced depending on the w/c ratio and the amount of binder.

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3.2. Mixing Ratios of Concrete

In this study, the mixtures given in Table 2 were prepared in order to determine the physical and mechanical properties of the concrete obtained. Forty-five samples were prepared for each group.

Table 2. Concrete mix ratios

Mixture number	Concrete mix ratios			
	Water	Cement	W/C	Super plasticizer
1	135	450	0.3	1.5
2	150	500	0.3	1.5

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3	165	550	0.3	1.5
4	180	600	0.3	1.5
5	195	650	0.3	1.5
6	180	450	0.4	1.5
7	200	500	0.4	1.5
8	220	550	0.4	1.5
9	240	600	0.4	1.5
10	260	650	0.4	1.5
11	225	450	0.5	1.5
12	250	500	0.5	1.5
13	275	550	0.5	1.5
14	300	600	0.5	1.5
15	325	650	0.5	1.5
C.C	195	650	0.3	1.5

The aggregate amount is the same in all mixtures with D_{max} from 12.5 - 4.75 mm (500 kg/m^3), and 4.75-0 mm (700 kg/m^3).

3.3. Mixing and Molding of Concrete

Putting all of the mixing materials into the concrete mixer at the same time causes the cement to clump due to the rapid absorption of water by the lightweight aggregates. This reduces the binding property of the cement paste and its homogeneous distribution in the mixture (Mouli and Khelafi 2008; Nie et al. 2017; Lu et al. 2021; Chandra and Berntsson 2002). No rule is specified by the standards as to which of the materials, whose mixing ratios have been determined, will be placed into the mixer vessel first, nor which ones should be placed gradually or all at once, provided that the mixing ratios are complied with. On the other hand, according to practical application experience, both the order of placing the materials in the mixer vessel and the applied method affect the homogeneity of the concrete to a certain extent (Chandra 2003; Lu et al. 2021; Chandra and Berntsson 2002). In this study, a conventional rotary drum concrete mixer with a capacity of 150 dm^3 was used to mix the concrete. First, coarse and fine aggregates were placed in the mixer and water was added in equal measure to the water absorption amount of the aggregates. Then the mixer was operated for 10 minutes, after which the mixture was allowed to sit for one hour. Later on, cement was added, and the mixer ran for another three minutes. Then two-thirds of the mixing water was added to the mixture within two minutes while the mixer was running. The remaining water was mixed with the superplasticizer and added to the mixer, and the mixing process continued for three more minutes.

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The most important goal in the placement of fresh concrete is to ensure that the concrete goes into the molds without losing its homogeneous feature and without segregation. In order to determine the mechanical properties of concrete, molds were filled with mixed concrete samples according to ASTM C 192: for the compression strength, 100x100x100 mm^3 steel cube molds were used; for the splitting strength, 100/200 mm cylindrical plastic molds; for the elasticity modulus test, 100/200 mm cylindrical plastic molds; and for the tensile strength in bending, 150x150x500 mm steel was used.

4. Results and Discussion

4.1. Properties of RVA

The RVA was ground into powder and its mineral structure was determined by FEI Quanta field emission scanning electron microscope (FESEM). As shown in Fig. 4 and Table 3, the aggregate has high amounts of SiO_2 and Al_2O_3 and very small amounts of Fe_2O_3, FeO, MnO, MgO, CaO and K_2O. According to these results, there is no mineral in the aggregate that would damage either concrete or reinforced concrete. Furthermore, there is no chemical that would cause a problem in the use of this aggregate in concrete. According to the mineral structure and porous surface texture, the aggregate is a volcanic rock. In structural concrete, the rapid increase in the use of lightweight aggregates may present a number of challenges for material engineers. Comprehensive information is required regarding the various properties of lightweight aggregates. The Los Angeles abrasion test, ASTM Method C 131, does not contain any provisions regarding the density of aggregates, as it requires a specific sample size by weight, regardless of the material's weight-to-volume ratio. Consequently, in very light aggregates, the volume filled into the drum is greater, which may affect the results due to the buffering effect of the volume, and the wear value may be lower than expected (Rushing 1963). As RVA is not very light, the buffering effect specified for very light aggregates does not occur. In the abrasion test conducted on the aggregate using the Los Angeles test machine in accordance with ASTM C131-06, the abrasion value was found to be 39%. The reason for the high wear value is that the aggregate surface has a porous structure. During the concrete mixing process, the pores are filled with cement paste, thereby eliminating any negative effects that the pores might cause. According to ASTM C131-06 standard, the wear value for D_{max} 19 mm and smaller particle sizes may be between 10-45%. Since the wear value found

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is 39% and falls within the range specified in ASTM C131-06, there is no problem with the wear resistance of the aggregate for use.

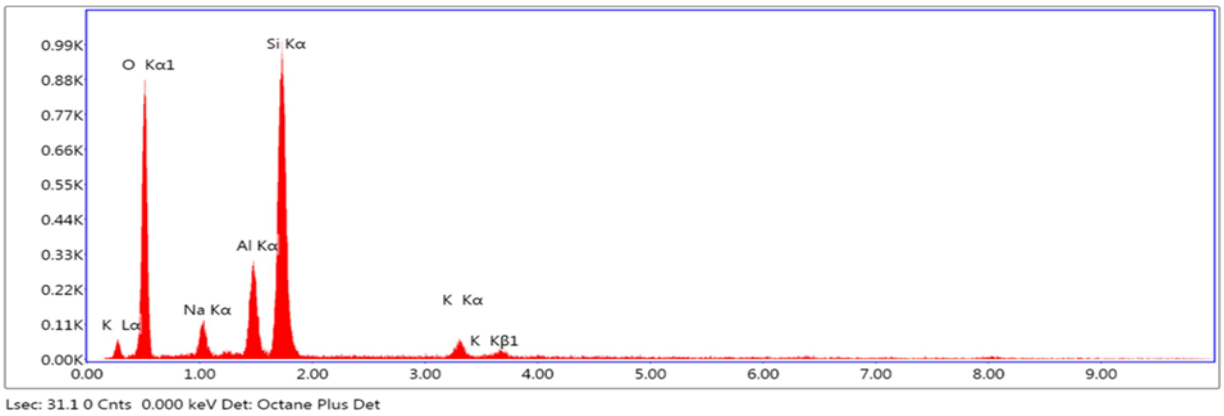


Fig. 4 Mineral analysis of RVA

Table 3 Chemical composition of RVA

Element	Weight	Atomic %	Net Int.	Error %	Kratio	Z	R	A	F
O	48.09	61.75	311.4	8.03	0.22	1.06	0.98	0.43	1
Na	5.04	4.50	45.52	10.44	0.03	0.96	1	0.54	1.01
AL	9.31	7.08	141.75	5.83	0.07	0.93	1.01	0.78	1.02
Si	33.81	24.72	503.88	4.18	0.26	0.95	1.02	0.81	1
K	3.75	1.97	32.28	8.65	0.03	0.88	1.05	0.93	1.01

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The physical properties of the aggregate were performed according to ASTM C29/C29M-07 and the results obtained are given in Table 4. It is recommended that the maximum water absorption rate is up to 10% for lightweight concrete with high durability. Similar advice from Wilson and Malhotra (1998), Chandra and Berntson (2002), Kayali et al (2003), Domagala (2015), Abdelfattah et al. (2023) and many other researchers have stated that the water absorption rate of lightweight aggregates to be used in the production of lightweight concrete with high durability should be below 10%. Based on the results in Table 4, there is no problem in using this aggregate in the production of high-strength lightweight concrete. In terms of specific gravity and unit volume weight, this aggregate can be considered as a lightweight aggregate.

Table 4 Physical properties of RVA

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Properties	Sieve grade (mm)				
	12.5-9.5	9.5-6.75	6.75- 4.75		4.75- 1.2 1.2-0
Loose unit weight	960	1010	1050	1080	1130
Compact unit weight	1020	1090	1130	1195	1260
Specific gravity	1.91	1.93	1.96	1.99	2.01
Water absorption	7.2	6.6	6	4.50	2.7
30-minute water absorption	3.4	3.2	2.8	2.2	1.8
Organic matter	-	-	-	absent	absent

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4.2. Properties of Fresh Concrete

High cohesiveness was observed in all of the high strength lightweight concrete with RVA and the measured slump values varied between 100 and 200 mm. Figure 5 shows the way the concrete collapses. As seen in Fig. 5, despite the high slump value, the fresh concrete retained its conical shape due to its high viscosity. In the measurements made 30 minutes after the mixing, it was observed that the concrete was highly workable and the slump value decreased by an average of 10-15 mm. As the w/c ratio and cement amount in the mixture was increased, the consistency increased and as the w/c ratio and cement amount was decreased, the consistency decreased. Many researchers such as Bahmani et al. (2025), Zhang et al. (2022), Domagala (2015), Shafigh et al. (2011), Hossain (2006), Kayali et al. (2003) and Aïtcin (1998) state that workable high-strength lightweight concretes must have a slump value of 100 to 200 mm.

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Fig. 5. Slump of concrete

4.3. Properties of Hardened Concrete

4.3.1 Unit Weight

The unit weight of HSLWC produced with RVA varied between 1830 and 1915 kg/m^3. As seen in Fig. 6 and Table 5, the unit weight of HSLWC varies depending on the w/c ratio and the amount of cement. If the weight of ordinary concrete in 2400 kg/m^3 is compared, there is a saving in the dead load between about 20.2% and 23.75%. This provides a substantial reduction in the dead loads of buildings and a reduction in the size of the reinforced concrete elements, and ensures that less earthquake load is exerted on structures during an earthquake, all resulting in a reduction in the cost of the structure. The unit weight values of the concretes obtained are very similar to the values found by other researchers such as Smadi and Migdady (1991), Hossain (2004), Shaligh et al. (2011) and Sajedi and Shafigh (2012), who used aggregates of natural volcanic origin in their studies and obtained very close unit weight values with the results obtained by other researchers. Small differences between the unit weights of high-strength lightweight concretes obtained in different studies are due to various factors: the unit weight of the aggregate, the moisture condition of the aggregate before mixing, the w/c ratio of the mixture, and the amount and type of binder. In general, the unit weights of aggregates of volcanic origin used in the production of structural concrete are slightly

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higher than the unit weights of aggregates obtained as a result of thermal processing.

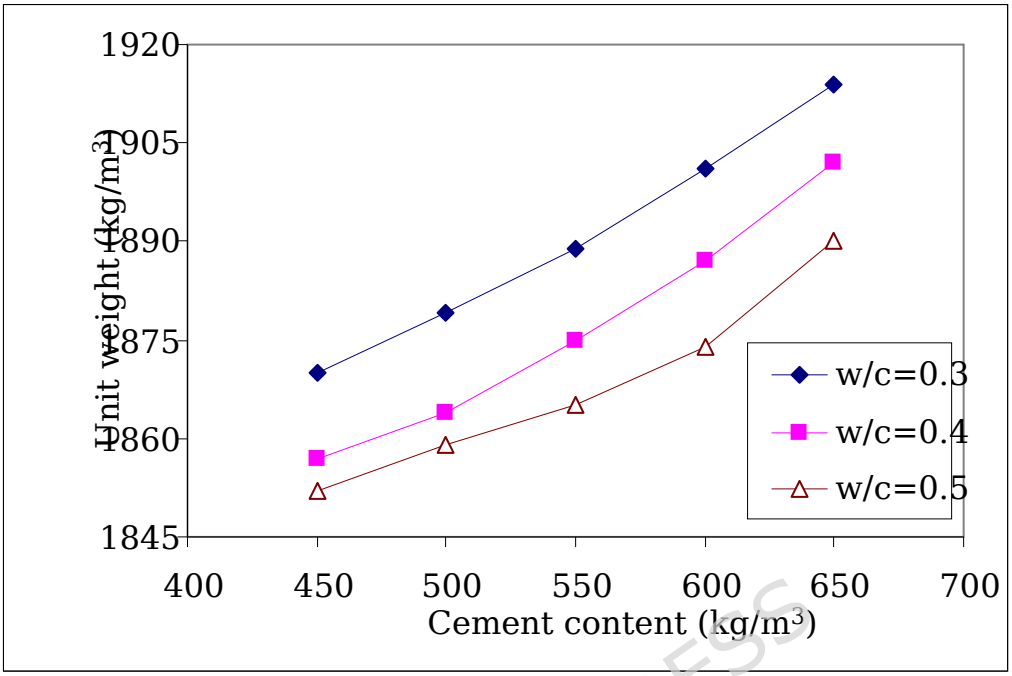


Fig. 6 Relationship between cement content and unit weight

A new concept called efficiency has emerged to evaluate the produced concretes, especially lightweight concretes, more accurately and to measure the performance of the material used. Efficiency is obtained by dividing the compressive strength of concrete by its unit weight.

Table 5 Efficiency of HSLWC

Mixture No	Amount of cement	w/c	Dry unit weight (kg/m^3)	Compressive Strength	Efficiency (MPa*dm^3/kg)	Water absorption (%) Cure type	
1	450	0.3	1870	64	34.22	6.90	7.20
2	500	0.3	1880	67	35.64	6.50	6.80
3	550	0.3	1890	70	37.04	5.20	5.50
4	600	0.3	1900	73	38.42	4.60	4.90
5	650	0.3	1915	77	40.21	4.40	4.75
6	450	0.4	1832	60	32.75	7.00	7.20
7	500	0.4	1840	65	35.33	6.85	7.10
8	550	0.4	1850	68	36.76	6.62	7.00
9	600	0.4	1874	71	37.88	6.45	6.85
10	650	0.4	1881	73	38.80	6.35	6.70
11	450	0.5	1830	60	32.80	7.75	8.15
12	500	0.5	1837	64	34.84	7.40	7.65
13	550	0.5	1841	66	35.85	7.60	7.40
14	600	0.5	1846	70	37.92	6.50	7.20
15	650	0.5	1860	72	38.74	6.40	6.80
	650	0.3	2409	87	36.11	3.20	5.80

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HSLWC shows similarity with the values found by the researchers Kayali et al. (2003), Hossain (2004) and Lu (2023) in terms of efficiency as well as unit weight. The efficiency of high-strength lightweight concrete produced by these researchers ranged from 28 to 34 MPa* dm^3/kg. The efficiency values obtained in this study ranged from 32 to 40 MPa* dm^3/kg . These values were 14% higher on average than the other studies' results. It is thought that this is due to the structure of RVA.

4.3.2. Water Absorption

Most good concretes have water absorption below 10% by mass (Peck 2006; Lu et al. 2021; Chandra and Berntsson 2002; Zhang et al. 1991; Newman and Owens 2003). The durability of concretes varies inversely with their water absorption rate. The high water absorption of the aggregates used in the production of lightweight concrete creates a durability problem for these concretes (Bao et al. 2023; Lu et al. 2021; Chandra and Berntsson 2002; Wilson and Malhotra 1988; Smadi and Migdady 1991; Newman and Owens 2003). It is recommended that for lightweight concrete with high durability, the maximum water absorption rate is up to 10%. The most effective factors on the water absorption rate of concrete are the void structure of the aggregate, the amount of the void, w/c ratio, and binder amount. As seen in Table 5, the water absorption rate of HSLWC varied between 4.4 % and 8.15 %. As seen in Table 5 and Fig. 7, the water absorption rate of HSLWC varied depending on the w/c ratio, cement amount, type of curing and unit weight of concrete.

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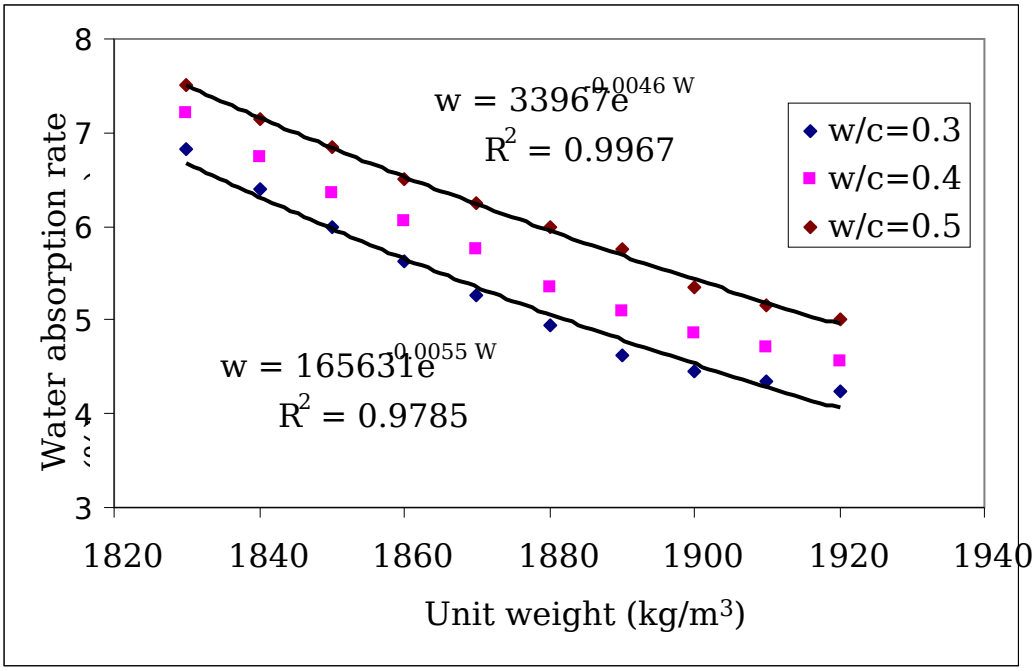


Fig. 7 Water absorption rate of HSLWC

Figure 7 shows the water absorption rate of HSLWC, which depends on the unit weight of the concrete and the w/c ratio. As seen in Fig. 7, the water absorption rate decreased with the increase in unit weight and decreased with decreasing w/c, but increased in the opposite case. The water absorption rate is also below the limit value specified by Bao et al. (2023), Aitcin (1998) and Neville (1998). Therefore, there will be no durability problem in these concretes. The water absorption rate (w) of the produced high-strength lightweight concretes can be determined by equation 1 depending on the unit volume weight (W).

$$w = 33967(e)^{-0.0046W} \quad (1)$$

4.3.3. Drying Shrinkage

Drying shrinkage, which is time-dependent deformation independent of load, must be taken into account in high-strength lightweight concrete applications. Drying shrinkage is also the volumetric shrinkage that occurs as a result of the evaporation of some of the water in the hardened concrete. This shrinkage varies depending on many factors such as the w/c ratio of the mixture, the structure of the

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aggregate and the humidity of the environment. The porous structure of the aggregate is very important in terms of drying shrinkage, as it determines its porosity and water loss capacity. Drying shrinkage is essentially limited to the volume change caused by water loss in the transition pores and gel pores. Water loss in the capillary pores causes shrinkage stress (Hong et al. 2023).

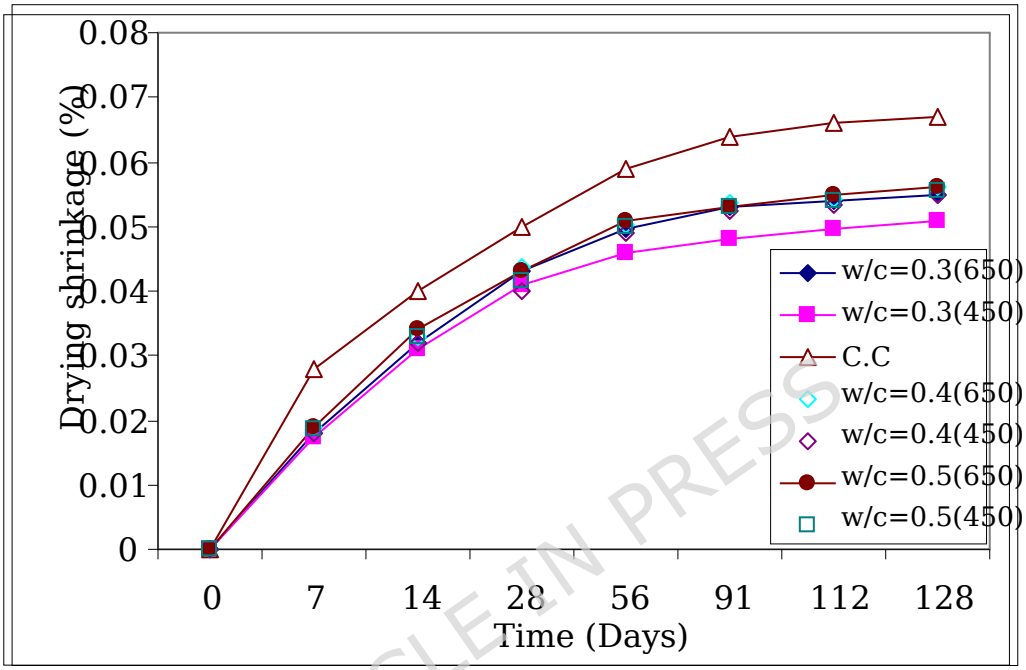


Fig. 8. Drying shrinkage

As seen in Fig. 8, the drying shrinkage of HSLWC varied between 0.047% and 0.056%. This value is quite low for lightweight aggregate concretes. The obtained values were 20% lower on average than the shrinkage value of the control concrete.

It has been determined that the modulus of elasticity of lightweight concretes with the same compressive strength produced using RVA is 40% lower than the modulus of elasticity of concretes produced with normal aggregates. This is because the modulus of elasticity of RVA is lower than the modulus of elasticity of normal aggregates. Despite this, the reason why the drying shrinkage of these concretes is 20% lower than the shrinkage value of normal aggregate concretes is that the aggregates are wetted before mixing and the drying shrinkage is slower

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and lower by giving the water they absorb at the time of mixing to the environment. Hossain (2004) and Hong et al. (2023) determined the drying shrinkage value of the lightweight concrete produced with volcanic pumice as 0.061% and the drying shrinkage value of the control concrete as 0.046%. At the same time, Anwar Hossain (2004) states that even if all other conditions are met for high performance lightweight concrete, the drying shrinkage value must not exceed 30% more than the shrinkage value of normal weight concrete. When the drying shrinkage value of the concrete is higher than these specified limit values, the drying shrinkage causes great reductions in the tensile strength and durability of the concrete by forming cracks in the internal structure (Hossain 2005; Lu et al. 2021; Chandra and Berntsson 2002). According to the shrinkage results obtained, there is no obstacle for HSLWC to be classified as high-performance lightweight concrete when other conditions are met. It is further known that cracks in the internal structure have a significant effect on the tensile strength and ultrasound transmission rate of concrete. The fact that the tensile strength and ultrasound values of HSLWC are higher than those of other high-strength lightweight aggregate concretes is a sign that the maximum drying shrinkage in perlite aggregate concrete does not have a negative effect on the durability and mechanical properties of the concrete.

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4.4. Mechanical Properties of Hardened Concrete

In order to investigate the producibility of HSLWC, mixtures of five different cement content and three different w/c ratios were prepared. The reasons for preparing samples with different cement content and w/c ratios were to determine the changes that would occur in the mechanical and physical properties of the concrete with the change of dosage and w/c ratio, and in which dosage sufficient strength could be obtained. The results obtained from the compressive strength tests performed on the samples according to w/c ratio, and to ASTM C39 and C 617, are given in Tables 6, 7 and 8. Six samples were used to

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determine the mechanical and physical properties of the hardened concrete. The average of these samples was then taken as the result. The standard deviation of the results was found to be 1.05. This result stems from the strong adherence between the aggregate and the cement matrix and the homogeneous behavior of the concrete. To determine the size effect, cube samples of 100x100x100 mm^3 and 150x150x150 mm^3, with 150 mm diameter and 300 mm height were prepared from the same mixture. Empirical conversion formulas were obtained by using the compressive strength test results on these samples. The formula for conversion of a cube of 100 mm into a cube of 150 mm is given in equation 2 and the conversion formula of a cube of 150 mm into a cylinder is given in equation 3.

$$fcu = 0.8301 * fc + 3.2 \text{ Mpa} \quad (2)$$

$$fcy = 1.0153 * fcu - 2.2 \text{ Mpa} \quad (3)$$

These empirical formulas gave very similar results with the empirical transformation formula proposed by Hossain (2004) and Neville (1997) who found that the size effect of lightweight concrete and normal concrete is very different, and the size effect is lower in lightweight concrete than normal concrete. The conversion coefficient of the cube to cylinder varies between 0.95 and 0.98 depending on the structure of the lightweight aggregate used, but varies between 0.8 and 0.9 for normal concretes. As the compressive strength of concrete increases, this ratio approaches 0.9 and, as it decreases, it approaches 0.8 (Neville 1997; Erdoğan 2003). Despite the use of different lightweight aggregates, the transformation coefficient found in this study remained within the same limits as the transformation coefficients suggested by Hossain (2004) and Neville (1997). The size effect is lower in lightweight concrete than in normal concrete because of the homogeneous distribution of the stresses occurring in the concrete due to the similar rigidity of the lightweight aggregate and the cement

matrix. In other words, lightweight aggregate concrete behaves more monolithic than normal aggregate concrete.

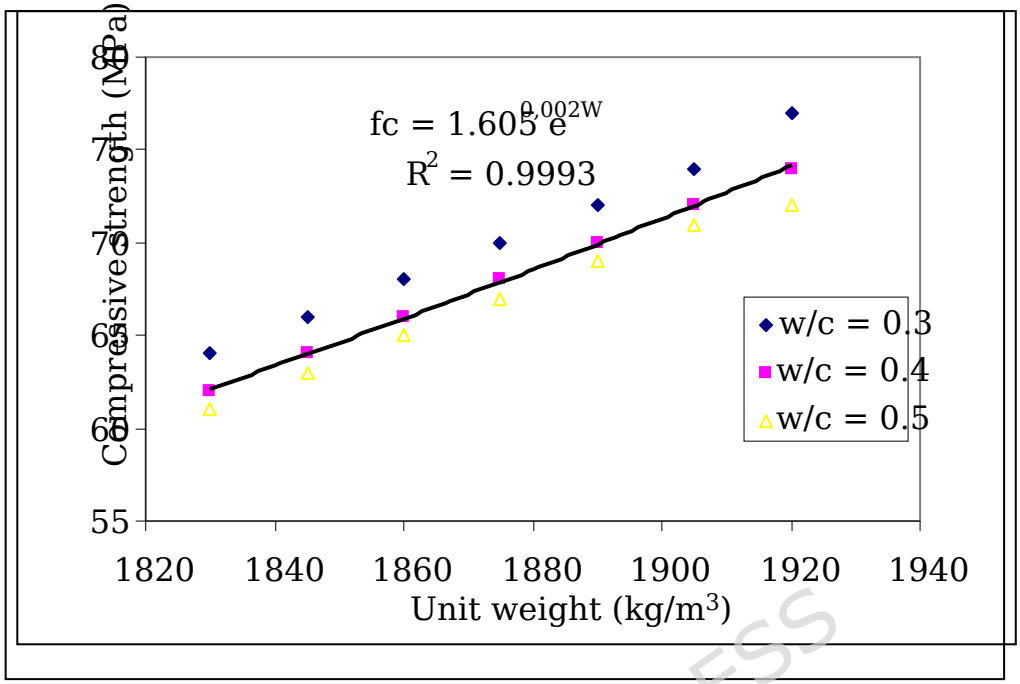


Fig. 9. Relationship between compressive strength and unit weight

The compressive strength of HSLWC varied depending on the unit weight as seen in Fig. 9. As the unit weight increased, the compressive strength of the concrete also increased. By making use of the relationship between compressive strength and unit weight, an empirical relation is obtained, as given in equation 4, which will be used to determine the compressive strength (f_c) depending on unit weight (W).

$$fc = 1.605 * (e)^{0.002*W} \quad (4)$$

This empirical relation gives similar results with the empirical relation proposed by Zhang et al. (2001) and Rossignola et al. (2003) which states that the mechanical properties of lightweight concretes increase with increasing unit weight. Kayali et al. (2003) studied the sintered fly ash aggregate with similar results and determined that the mechanical properties of lightweight concrete increase to a large extent with the increase of the unit weight of the concrete. As seen in Fig. 10, the

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compressive strength increased with increasing cement content and decreased as it decreased. At the same time, the compressive strength showed a slight variation depending on the cure type.

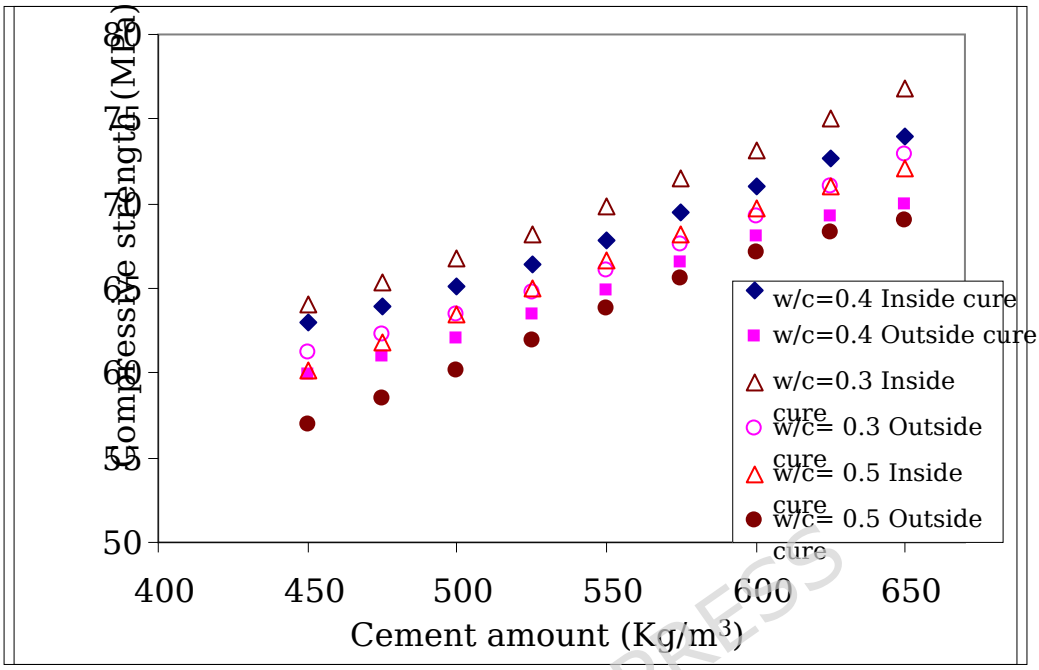


Fig. 10 The relationship between cement content and compressive strength in different curing

Dhir et al. (1984) produced lightweight concrete by using Aglite lightweight aggregate, plasticizer and 600 kg/m^3 cement. They stated that the compressive strength of lightweight concrete cured in water varies between 43 and 60 MPa, and when cured in air varies between 29 and 53 MPa. Li et al.(2025) It is stated that the compressive strength of lightweight concretes increases with curing time. The samples were cured in two ways: internally and externally. In internal curing, the samples were kept in a curing tank filled with lime-saturated water at 23 ±1°C for 24 hours after casting until the day of the experiment. For outdoor curing, samples were removed from molds 24 hours after casting and placed outdoors in a shaded area. The samples were immersed in a container of water for 5 minutes each day. The average outdoor temperature was measured at 30-35°C and the average humidity at 50-55%. Here, it is stated that curing is highly effective on

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the compressive strength of lightweight concretes. However, Bentur (2002) stated that different curing creates a maximum of 3% difference on the mechanical and physical properties of lightweight concretes and that this difference is not very important. Although this may seem like a contradiction, the curing effect can be quite different in lightweight concretes produced using different lightweight aggregates. As a result of this study, it has been seen that different curing has an effect on both the mechanical and physical properties of HSLWC and is similar in all properties, varying between 1% and 3%. The reason for the low rate of curing, as stated by Bentur (2002), is that coarse and light aggregates help the curing process by giving the water which they absorb back to the environment with the effect of capillarity both before and during mixing. All the mixtures obtained 75–80% of their 28-day strength at day seven. Similarly, Rossignolo et al. (2003) stated that high-strength lightweight concretes complete most of their compressive strength in the first seven days noting that the cement used in the concrete production is Portland cement, which gains early strength, and the plasticizers used for workability have a strength-accelerating effect up to a certain dosage. The results of the compression test showed that fracture occurred due to the breakage of the coarse aggregate as shown in Fig. 11.

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Fig. 11 Fracture surface of concrete

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Table 6. Compressive strength of the mixture at 0.3 w/c

Mixture No	Amount of cement kg/m^3	w/c	Compressive strength (MPa) 100x100x100 mm^3 (Cube)					
			Type of cure	Time (No. of Days)				
				7	14	28	60	90
1	450	0.3	Inside cure	46	53	58	62	64
			Outside cure	44	49	55	58	61
2	500	0.3	Inside cure	50	55	61	65	67
			Outside cure	47	51	56	61	64
3	550	0.3	Inside cure	54	58	63	67	70
			Outside cure	51	55	59	63	66
4	600	0.3	Inside cure	55	59	65	69	73
			Outside cure	52	57	61	66	69
5	650	0.3	Inside cure	57	63	69	75	77
			Outside cure	52	58	65	70	73
C.C	650	0.3	Inside cure	75	84	86	87	87

Table 7. Compressive strength of the mixture at 0.4 w/c

Mixture No	Amount of cement kg/m^3	w/c	Compressive strength (MPa) 100x100x100 mm^3 (Cube)					
			Type of cure	Time (No. of Days)				
				7	14	28	60	90
6	450	0,.4	Inside cure	46	51	56	60	63
			Outside cure	44	47	53	57	60
7	500	0.4	Inside cure	48	53	59	63	65
			Outside cure	46	50	56	60	62
8	550	0.4	Inside cure	52	56	61	65	68
			Outside cure	49	53	57	63	65
9	600	0.4	Inside cure	53	58	64	67	71
			Outside cure	51	55	59	64	68
10	650	0.4	Inside cure	56	62	68	72	74
			Outside cure	53	59	63	68	70

Table 8. Compressive strength of the mixture at 0.5 w/c

Mixture No	Amount of cement kg/m^3	w/c	Compressive strength (MPa) 100x100x100 mm^3 (Cube)					
			Type of cure	Time (No. of Days)				
				7	14	28	60	90
11	450	0.5	Inside cure	43	49	54	58	60
			Outside cure	41	46	51	54	57

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12	500	0.5	Inside cure	44	51	58	61	64
			Outside cure	42	47	54	58	60
13	550	0.5	Inside cure	44	53	59	63	66
			Outside cure	43	51	55	60	64
14	600	0.5	Inside cure	51	56	62	64	70
			Outside cure	48	54	60	63	67
15	650	0.5	Inside cure	52	59	64	69	72
			Outside cure	48	56	61	65	69

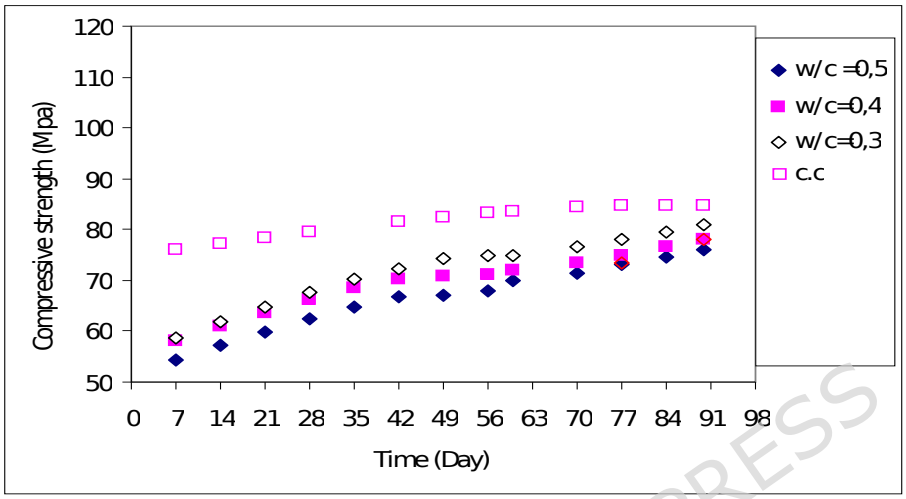


Fig. 12 Development of compressive strength with time and w/c ratio

As seen in Fig. 12, while there was no increase in strength after 28 days in the control concrete (C.C), the increase continued in HSLWC. The reason for this is that RVA has pozzolanic activity. It was clearly seen that the RVA showed pozzolanic activity in the mechanical properties of the produced concrete.

The elastic modulus of concrete is an important property especially for designing structural members. It is used in computing the strain at a known stress value. Physically, elastic modulus can be defined as the resistance of a material to elastic deformation. Mathematically, it is the slope of the linear portion (elastic region) in a stress-strain diagram of a material. In this study, the elastic moduli of the cylindrical concrete specimens were determined in accordance with ASTM C469. This method assumes, up to 40% of ultimate stress level, that the slope of a stress-strain diagram of a concrete specimen is linear. The static modulus of elasticity and Poisson ratio of HSLWC were determined with ELE ADR 200-300 EN

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digital display and speed-controlled test device and data-logger instrument which measures and records the lateral and vertical deformation. A general view of the test apparatus is shown in Fig. 13. Vertical and lateral deformations under this load value were recorded. Then, the longitudinal deformation was converted to longitudinal strain and the stress-strain curve was drawn. The static elasticity modulus of HSLWC as shown in Table 8 varied between 16.50 and 25.00 GPa. In the same study, the static elasticity modulus of the control concrete with similar strength produced using normal aggregate was determined as 32.8 GPa. In this study, since the aggregate and its ratio are the same in all mixtures, the reason for the change in the elastic modulus of the concrete is the change in the w/c ratio and the amount of binder. Since the elasticity modulus of concrete depends on many variables such as aggregate stiffness, matrix strength, adherence between aggregate and matrix, aggregate geometry and surface texture, it is normal to have differences between experimental results and theoretical results. The elastic modulus of lightweight aggregates limits the elastic modulus of lightweight aggregate concrete (Hong et al. (2022)).

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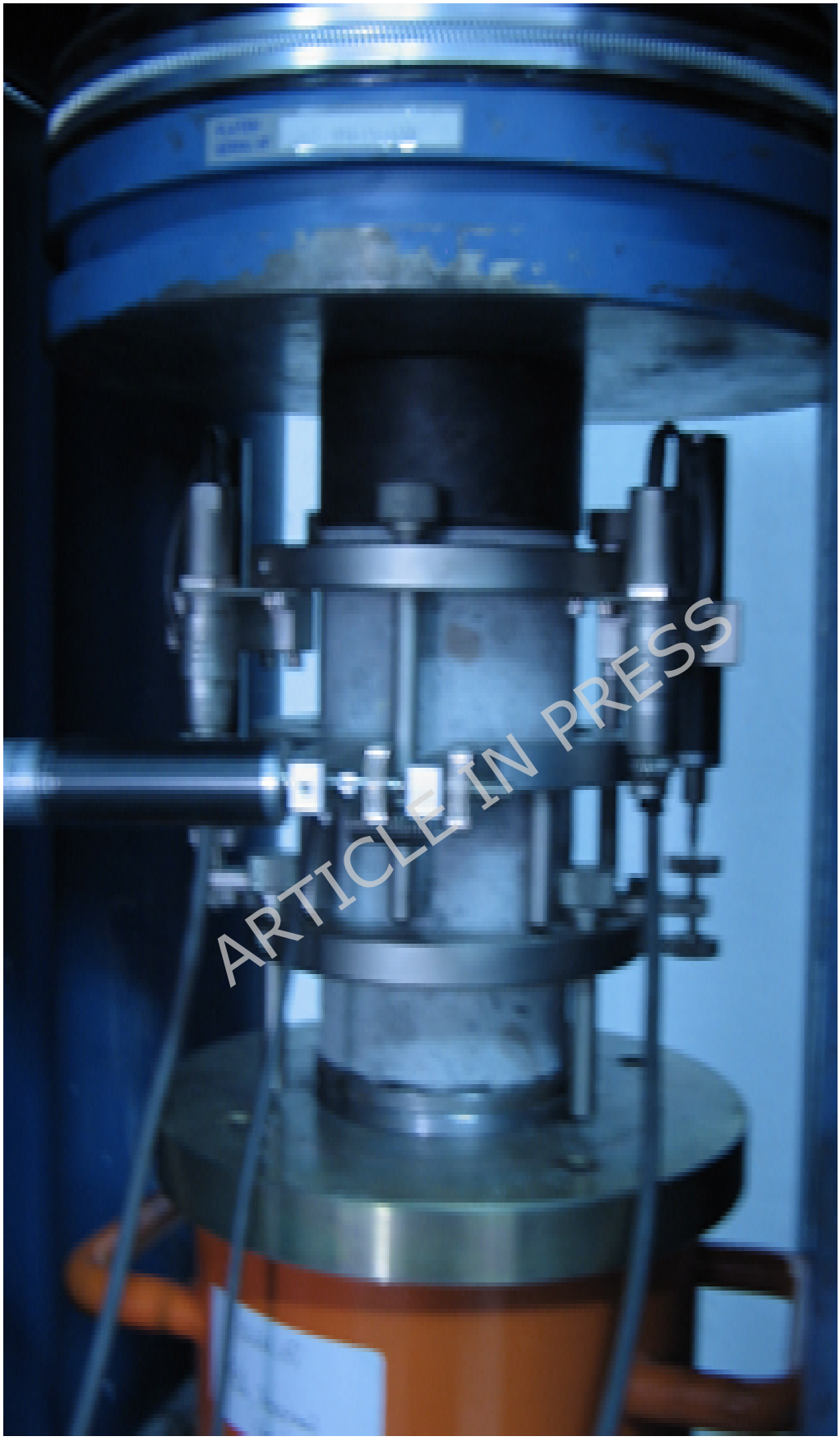


Fig. 13 General view of the elastic modulus test apparatus

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Table 8. Elastic modulus of HSLWC

Mixture No	Cement content	W/C	Modulus of elasticity		Poisson ratio
1	450	0.3	18.80	23.00	0.297
2	500	0.3	18.75	23.70	0.270
3	550	0.3	19.90	25.20	0.278
4	600	0.3	24.50	30.90	0.260
5	650	0.3	25.00	31.51	0.258
6	450	0.4	17.25	21.80	0.310
7	500	0.4	18.85	23.50	0.304
8	550	0.4	19.30	24.40	0.295
9	600	0.4	20.50	25.90	0.278
10	650	0.4	23.65	29.80	0.269
11	450	0.5	16.50	20.90	0.320
12	500	0.5	17.30	21.60	0.310
13	550	0.5	18.00	23.10	0.302
14	600	0.5	19.50	24.60	0.299
15	650	0.5	20.18	25.50	0.285
C.C	650	0,3	32.80	39.8	0.180

The important thing is that this difference remains within acceptable limits. As a result of our studies, it is possible to determine the theoretical modulus of elasticity of HSLWC by equation 5, depending on the compressive strength of the concrete (f_c).

$$Ec = 3.3183 * (e)^{0.029*fc} \quad (GPa) \tag{5}$$

The static elastic modulus of concrete was found by putting obtained compressive strength values in the formulas proposed by various researchers such as Kayali (2005), Neville (1994), Tamasawa et.al (1990) and Nasif et al. (2005). After that, the graphs showing the relationship between the static elastic modulus and the compressive strength were drawn (see Fig. 14). As shown in Fig. 14, these results are quite compatible with the experimental results which were found in this study. From the definition of ΔL= P*L/(E*A), the low elasticity modulus of concrete will result in greater creep under axial load. This means that reinforced concrete structures built using this concrete will be more ductile during an earthquake, thereby sustaining less damage. In the 1992 Erzincan

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earthquake, with a magnitude of 6.6, the vast majority of reinforced concrete structures built using concrete produced with Fırat aggregate suffered severe damage or collapsed, while a very small number of reinforced concrete structures built using RVA aggregate survived the earthquake with minor damage. Therefore, it can be said that the seismic behavior of concrete produced using RVA aggregate is better than that of concrete produced using Fırat aggregate.

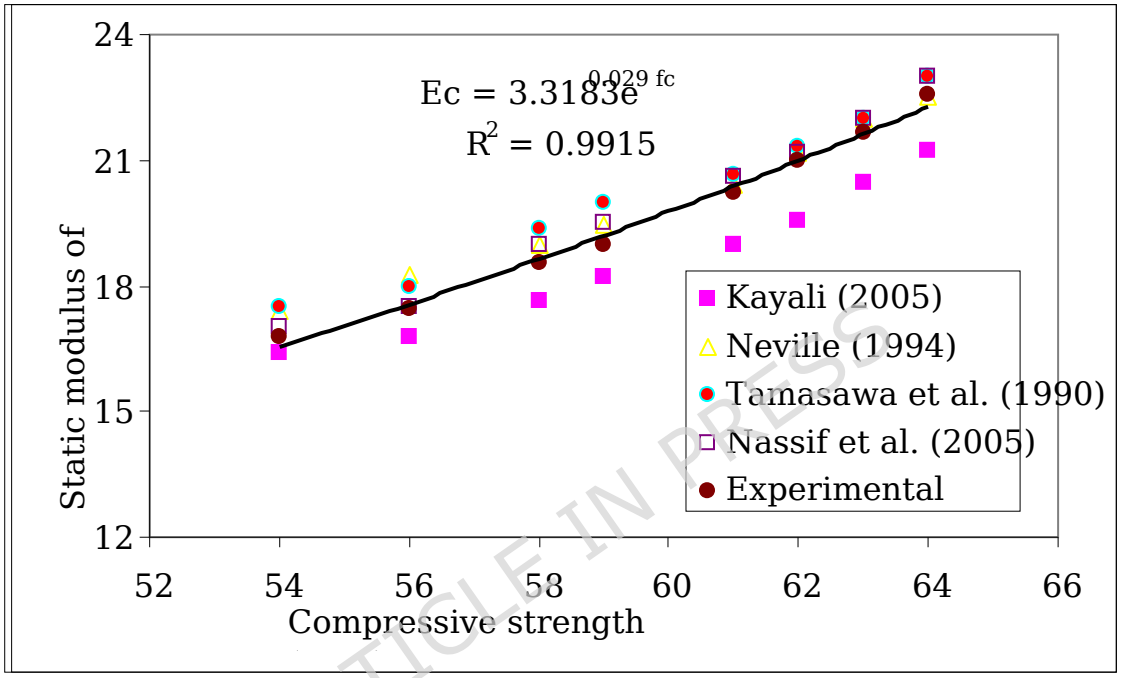


Fig. 14 Relationship between static elastic modulus and compressive strength

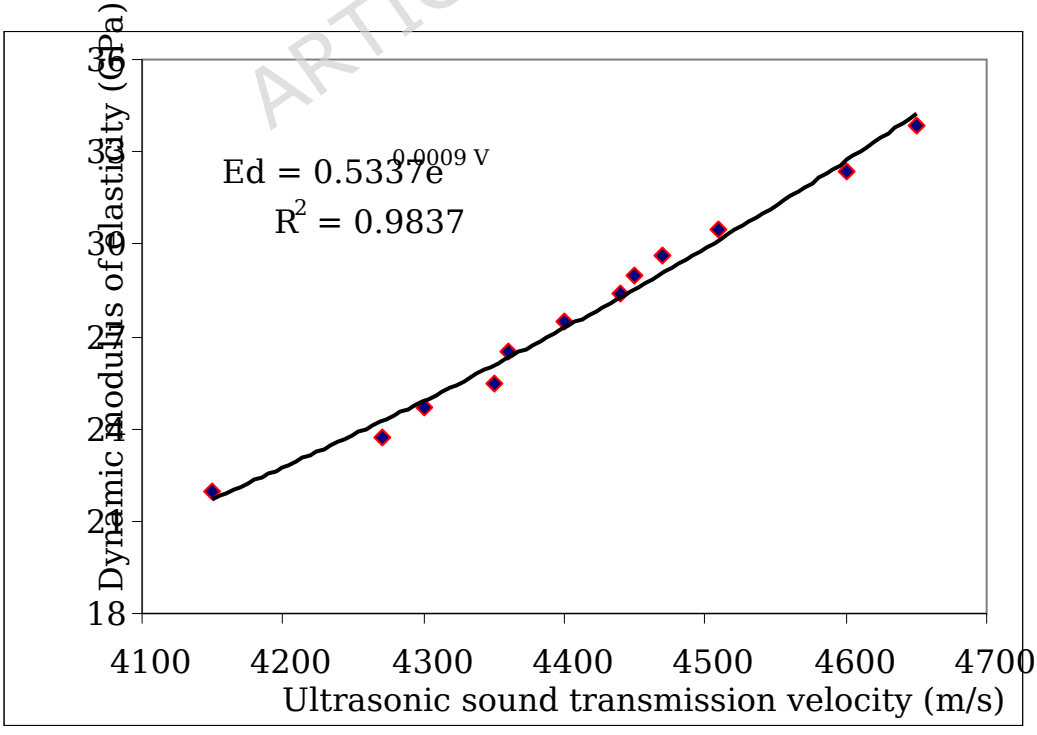
On the dynamic modulus of elasticity, which is another modulus of elasticity of concrete, pure elasticity always has an effect and creep has no effect. The dynamic modulus of elasticity is usually an approximation to the initial tangent modulus obtained in the static modulus of elasticity test. This value is always greater than the static modulus of elasticity (Neville 1994). Neville (1994) and Aïtcin (1998) state that the difference between these two moduli is due to the heterogeneity in the concrete and this difference can vary between 20% and 40%. The dynamic modulus of elasticity of HSLWC was determined by using the ultrasonic sound transmission rate and Poisson ratio of these concretes in the empirical formula proposed by Neville (1994). The relationship between the static and dynamic modulus of elasticity of HSLWC is given in equation 6.

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$$Ed = 1.250 * Ec + 0.51 \text{ (GPa)} \quad (6)$$

It has been observed that there is a difference of between 20% and 35% in the modulus obtained and an increase in this ratio with an increase in compressive strength. Chang et al. (2006) determined in their study that the dynamic modulus of elasticity of concrete is 41% higher than the static modulus of elasticity. It can be seen that there can be big differences between the elastic modulus of high-strength lightweight concretes produced by using different aggregates, and this difference becomes more evident especially in the dynamic modulus of elasticity. The relationship between the dynamic modulus of elasticity and ultrasonic sound transmission rate of HSLWC is shown in Fig. 14. As seen in Fig. 15, an increase in the dynamic elastic modulus of concrete occurred with the increase of ultrasonic sound transmission rate. The dynamic modulus of elasticity can be determined by equation 7 depending on the ultrasonic transmission velocity V(m/s).

$$Ed = 0.5337(e)^{0.0009V} \quad (7)$$



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Figure 15. Relationship between ultrasonic sound transmission velocity and dynamic modulus of elasticity

In this study, the split tensile strengths of the concrete obtained varied between 3.2 and 6.82 MPa, while the bending tensile strengths varied between 4.03 and 7.33 MPa. The splitting tensile strengths of HSLWC varied between 8% and 11% of their compressive strength and their tensile strength in bending ranged between 8% and 12% of their compressive strength. Similar results have been found by other researchers such as Gao et al. (1997) who produced high-strength lightweight concrete with a compressive strength of 85.4 MPa. They found that the split tensile strength of this concrete was 5.7% of its compressive strength and the tensile strength in bending was 7.3% of its compressive strength. While there is an increase in the ratio of tensile strength to compressive strength with the increase of compressive strength in HSLCWRLA, Malhotra (1990), Novokshchenov and Whitcomb (1990), Blanco et al. (2000) and Haque et al. (2004), found that with an increase of compressive strength, there was a decrease in the ratio of tensile strength to compressive strength. Wei et al. (2020) stated that larger LWA reduces the splitting tensile strength of LC, with the difference varying up to 36% depending on the aggregate size. They attributed this to the limitation of the tensile strength of coarse light weight aggregate, but the opposite occurred in high-strength lightweight concrete with RLA. The reason for this is that the increase in tensile stress paralleled the increase in compressive strength due to the cement matrix which was injected through the pores into the RLA during mixing which caused the tensile strength of the RLA to increase. According to these results, high-strength lightweight concrete with RLA showed a similarity with other lightweight concretes in terms of tensile strength, but gave higher tensile strength values. There was an increase in the tensile strength of the HSLCWRLA with decreasing w/c ratio and increasing the amount of cement in the mixture. The rate of increase in tensile strength was higher than normal-weight concrete and other lightweight concrete. This is due to the fact that RLA has pozzolanic

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activity. It has been observed that there is a relationship between the obtained experimental tensile stress results and the compressive strength. In order to determine the relationship between compressive strength and tensile strength, the graph in Fig. 16 was drawn using the experimental results obtained. It has been observed that there is a relationship between the obtained experimental tensile stress results and the compressive strength.

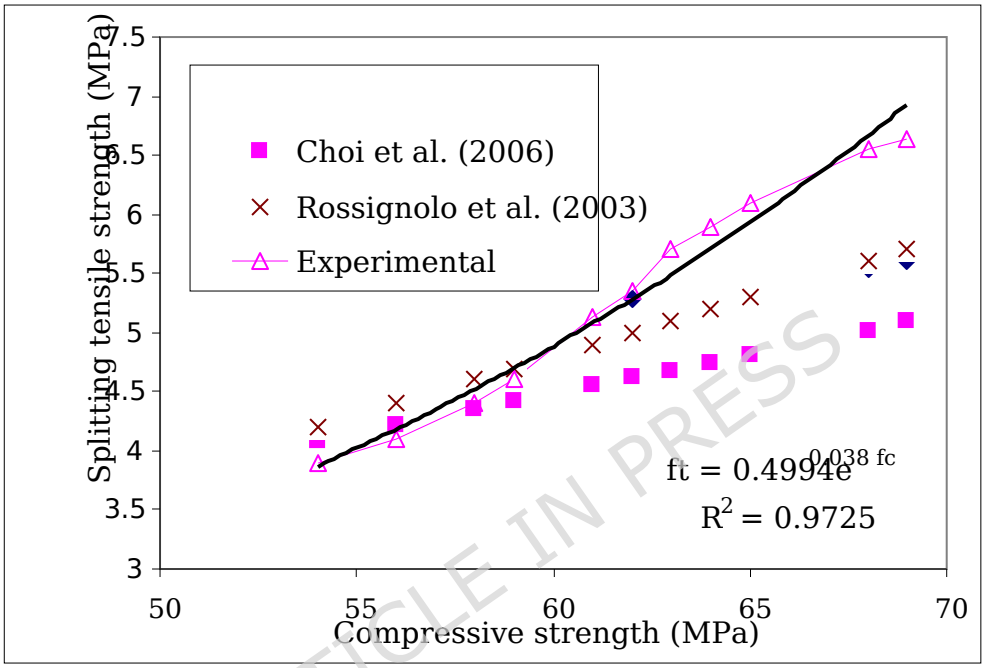


Fig. 16. Relationship between compressive strength and splitting tensile strength

Different empirical formulas have been proposed by many researchers to theoretically determine the tensile strength of normal and high-strength lightweight concretes produced using different lightweight aggregates depending on the compressive strength. In this study, tensile strength values were determined theoretically by substituting compressive strength values in the empirical formula suggested by the researchers Rossignolo et al. (2003) and Choi et al. (2024). A graph was drawn between compressive strength and tensile strength in order to compare experimental results with theoretical results, and between HSLWC and other lightweight concretes. At low compressive strength, the lowest tensile strength value was obtained in HSLWC. As the

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compressive strength increased, the tensile strength of HSLWC also increased as seen in Figure 16. The tensile strength of HSLWC reached its maximum value and exceeded the values found by Rossignolo et al. (2003), Huan (2005) and Choi et al. (2024). While the ratio of the increase in tensile strength to the increase in compressive strength remained constant in the studies of Rossignolo et al. (2003) and Choi et al. (2024), this ratio did not remain constant in HSLWC. With the increase in compressive strength, higher tensile strength values were obtained by increasing this ratio. In lightweight concretes, tensile strength increases with the increase in compressive strength up to a certain value. However, even if the compressive strength increases after a certain value, there is no increase in tensile strength because the tensile strength of lightweight concrete is limited by the tensile strength of the coarse lightweight aggregate (Aïtcin 1998). The reason why the ratio of tensile strength to compressive strength increases with the increase of the compressive strength in HSLWC may be the pozzolanic activity of the RVA. Alternatively, the strength of the matrix in contact with the aggregate surface may be higher than the matrix strength in the other regions and the voids on the aggregate surface are filled with the cement matrix, which may cause the tensile strength of the aggregate to increase. The relationship between splitting tensile strength and compressive strength is given in Fig. 17 and the relationship is defined in equation 8.

$$ft = 0.4994(e)^{0.038*fc} \quad (MPa) \tag{8}$$

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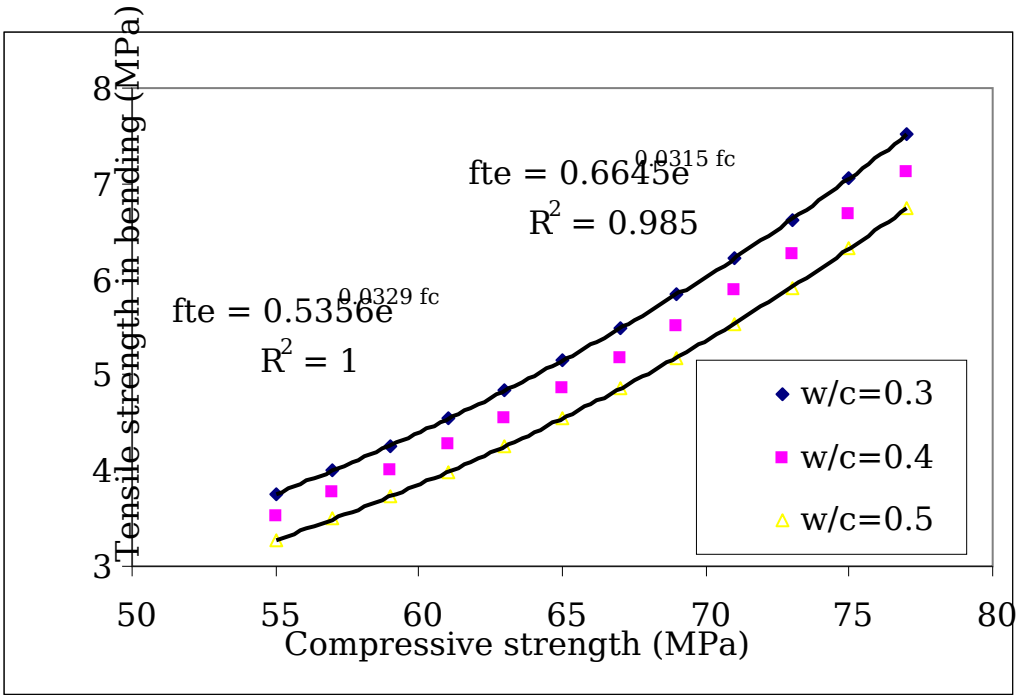


Figure 17. Relationship between compressive strength and tensile strength in bending

5. Conclusion

The findings obtained as a result of tests and experiments on the concretes produced with RLWA using different w/c ratios and binder amount are given below.

- In order to produce HSLWC with RVA, 450 kg of cement at a rate of 0.3 w/c, or at least 500 kg of cement at a higher rate of w/c and a high rate of superplasticizer (1.5%) are required to ensure workability.
- Slump values of 140 to 200 mm were found to be sufficient for the workability of concrete.
- The water/cement ratio affected the mechanical properties of the produced concrete. An increase in this ratio was observed to decrease mechanical properties, while a decrease resulted in an increase.
- Concrete lost its overall strength with the loss of the strength of the coarse aggregate. This was observed at fracture surfaces in both compressive and tensile conditions.

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- Bending and tensile strengths were higher than normal concrete.
- It was observed that ductility decreased with increasing strength and increased with decreasing strength. It showed two times more unit deformation than normal aggregate concretes with the same strength. It was observed that the obtained deformation values are up to 50% higher than the values of high-strength lightweight concrete obtained by other researchers using different lightweight aggregates.
- HSLWC produced with RVA is 20-25% lighter than normal concrete with similar strength.
- Drying shrinkage values varied between 0.047% and 0.055%. These values are quite low compared to normal aggregate and other lightweight concretes.
- Ultrasonic sound transmission velocities were measured between 4310 and 5100 m/s. This is quite high even for a concrete with normal aggregate. These results indicate that there are no voids or cracks in the internal structure.
- It was observed that different types of curing did not have much effect on either the mechanical or physical properties of concrete. The reason is that the need for curing is reduced by giving the water, which coarse and light aggregates absorb before and during mixing, back to the environment over time.
- The cube compressive strengths of the produced concretes ranged from 54 to 87 MPa and their tensile strengths ranged from 4 to 11 MPa. The tensile-compressive strength ratio was higher than normal concrete.
- The static modulus of elasticity of the concretes varied between 17 and 25 GPa and the dynamic modulus of elasticity ranged between 22 and 35 GPa. The results were similar to the results of high-strength lightweight concretes produced by other researchers using different aggregates.
- It is thought that reinforced concrete structures produced with HSLWC may have better seismic behaviour due to HSLWC having

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high adherence, and low elasticity modulus and unit volume weight. This explains why all reinforced concrete structures in Erzincan using concrete produced with RLWA prior to 1992 survived the 1992 Erzincan earthquake without damage.

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Declarations

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