Dicle University
Journal of Engineering

https://dergipark.org.tr/tr/pub/**dumf**
duje.dicle.edu.tr

Research Article

Comparison of lightweight and normal-weight aggregate concrete

Hatice ÇİÇEK[1], İsmail Ağa GÖNÜL[2*]

[1] Dicle University, Department of Architecture, hatice@dicle.edu.tr, Orcid No: 0000-0003-3271-1854
[2] Dicle University, Department of Architecture, ismail@dicle.edu.tr, Orcid No 0000-0002-9833-7140

ARTICLE INFO

Article history:

Received 7 July 2022
Received in revised form 2 August 2022
Accepted 13 August 2022
Available online 30 September 2022

Keywords:

Lightweight aggregate concrete, normal-weight aggregate concrete, interfacial transition zone, calcium hydroxide crystals, compressive strength, oven-dry density

Doi: 10.24012/dumf.1142146

* Corresponding author

ABSTRACT

In this experimental study, lightweight aggregate concrete (LWAC) and normal-weight aggregate concrete (NWAC) were compared within the contexts of the size of calcium hydroxide (CH) crystals in interfacial transition zone (ITZ), compressive strength, and oven-dry density. Six LWAC and NWAC mixtures were prepared for this study. Thirty-six images obtained from Scanning Electron Microscope (SEM) were used to determine the size of CH crystals in ITZ of LWAC and NWAC. Eighteen test specimens (three for each of the six LWAC and NWAC mixtures) were prepared in 150x300 mm sizes and in the form of cylinders for the compressive strength tests and also eighteen test specimens in 100x100x100 mm sizes and in the form of cubes for the oven-dry density tests. It was determined that the size of CH crystals in ITZ of LWAC is 8.43% less than (on average), compressive strength of LWAC is 39.09% more than (on average), and oven-dry density of LWAC is 10.97% less than (on average) the NWAC's that has the same volumetric proportions of ingredients. The findings of this study show that lightweight aggregate that has high particle density, angular shape, rough surface texture, and a structure that enables chemical reaction with CH crystals will be beneficial for the ITZ microstructure and properties of concrete. It is considered that these properties should be taken into consideration in the selection of lightweight aggregate for structural concrete production.

Introduction

The components of the hydrated cement paste are some unhydrated clinker grains, pores, and hydration products. Calcium hydroxide (CH), calcium sulfoaluminates hydrates, and calcium silicate hydrate (C-S-H) are the main hydration products [1].

In the hydrated cement paste, CH constitutes up to 25% of the volume of solids [1]. Microcrystalline or amorphous CH can be formed in C–S–H. They are usually in the form of micrometer-sized crystals. The vast majority of CH are formed as isolated hexagonal crystals and/or as massive clusters [2]. The studies related with CH are given in References [3-17].

CH is the most soluble hydration product. When the cement paste is exposed to water, CH dissolves and increases the porosity of cement paste. This makes the cement paste more vulnerable to further leaching and chemical attack. In this respect, CH is one of the weak links for the durability of concrete. Furthermore, CH isn't important as much as C-S-H for contributing strength to cement paste [18]. CH also has a preferential direction of fracture, so that with its larger crystal dimensions favorable conditions for crack propagation are formed, and thus a possible reduction of strength may occur [19].

The concrete has three phases according to microstructural observations. One of them is named as bulk cement paste. The other is known as aggregate phase. The third phase is referred as interfacial transition zone (ITZ) and links the other two phases. ITZ is located typically 10 to 50 μm thick around the aggregate particles [20]. Larger crystal dimensions (particularly of CH) and pores differentiate ITZ from bulk cement paste. Primary cause of this difference is water accumulation around coarse aggregate particles in fresh concrete, which is called "bleeding". Bleeding increases water/cement (W/C) ratio in ITZ. Increased W/C ratio causes crystals to be larger in this zone.

In order to decrease the size and content of CH crystals in ITZ, various studies have been done. Most of these studies focused on the mineral admixtures that have a decreasing effect on CH size and content in ITZ. Some aggregates may also offer a similar effect in ITZ. However, the quantitative studies on the size of CH crystals in ITZ of concrete produced with various aggregate types have been very limited.

Lightweight aggregate (LWA) recently has found extensive use in structural concrete applications. It has different characteristics according to normal-weight aggregate (NWA). Thus, the size of crystals in ITZ and as well as the mechanical and physical properties of lightweight aggregate concrete (LWAC) and normal-weight aggregate concrete (NWAC) vary. In this experimental study, LWAC and NWAC were compared within the contexts of the size of CH crystals in ITZ, compressive strength, and oven-dry density. In LWAC scoria aggregate, in NWAC gravel aggregate were used as coarse aggregate. Scoria is a natural lightweight aggregate. It was determined that there are few studies [21-29] in literature concerned with scoria aggregate. None of them examines the size of CH crystals in ITZ of concrete produced with scoria aggregate.

Material and methods

Preparation of LWAC and NWAC mixtures

Six LWAC and NWAC mixtures that were prepared and ratios and proportions of their ingredients are given in Table 1. Properties of cement, physical properties of aggregates and chemical content of scoria aggregate used in mixtures were given respectively in Table 2, Table 3, and Table 4.

Table 1. Mixture design of LWAC and NWAC.

Mixture Code	Coarse Aggregate / Total Aggregate (Ac/At) Ratio by Volume (%)	Water / Cement (W/C) Ratio by Weight (%)	Cement Weight (kg/m^3)	Coarse Aggregate (scoria or gravel) Weight (kg/m^3)	Fine Aggregate (river sand) Weight (kg/m^3)	Water Weight (kg/m^3)
LWAC 1	40	37.5	500	474.8	994	187.5
LWAC 2	50	37.5	500	593.5	828.4	187.5
LWAC 3	60	37.5	500	712.3	662.7	187.5
NWAC 1	40	37.5	500	673.1	994	187.5
NWAC 2	50	37.5	500	841.4	828.4	187.5
NWAC 3	60	37.5	500	1009.7	662.7	187.5

Table 2. Properties of cement used in LWAC and NWAC mixtures.

Strength Properties		Physical Properties		Chemical Properties	
Compressive strength at 28 days	46.5 MPa	Specific weight (g/cm^3)	3.12	Insoluble residue (%)	0.55
Compressive strength at 7 days	39.5 MPa	Volume constancy (mm)	1.2	SO_3 (%)	2.38
Compressive strength at 2 days	31.0 MPa	Specific surface area (cm^2/g)	3395	Cl (%)	0.0085
		Initial setting time (hr)	2.15	Loss on ignition (%)	2.65
		Final setting time (hr)	3.35		

Table 3. Physical properties of aggregates used in LWAC and NWAC mixtures.

Aggregates Used in Mixtures	Physical Properties					
	Maximum Particle Size (mm)	Particle Density (Mg/m^3)	Bulk Density (Mg/m^3)	Shape Index	Water Absorption (24 h) (%)	Moisture Content (%)
Scoria (coarse aggregate)	16	1.82	0.86	10	10.88	0.89
Gravel (coarse aggregate)	16	2.58	1.66	11	1.39	1.54
River sand (fine aggregate)	4	2.54	1.71	-	2.54	1.96

Table 4. Chemical content of scoria aggregate used in LWAC mixtures.

Contents	Ratios (%)
SiO_2 (total)	45.06
Insoluble residue	59.53
Al_2O_3	13.34
Fe_2O_3	12.80
CaO	12.05
MgO	7.41
SO_3	0.36
Loss on ignition	1.01
Na_2O	2.88
K_2O	1.32

Absolute volume method was used for proportioning the ingredients of LWAC and NWAC mixtures. Each LWAC and NWAC mixture was targeted to have high strength. River sand and gravel aggregate were entirely dried in the oven before used in concrete mixtures. It is suggested to keep lightweight aggregates in water during ten minutes before using them in concrete mixtures. However, it was thought that this period of time wouldn’t be sufficient due to high cement content used in LWAC mixtures and ambient temperature of 30-35 °C at the time of LWAC production. Therefore, before used in LWAC mixtures, scoria aggregate was kept in water during thirty minutes after entirely dried in the oven. Saturation water of aggregates was added to LWAC and NWAC mixtures subsequently.

Preparation of test specimens and determination of the compressive strength and oven-dry density

In order to determine the compressive strength and oven-dry density of prepared LWAC and NWAC mixtures in the hardened state, test specimens were prepared. In this regard, moulds for test specimens were prepared, moulds were filled with LWAC and NWAC mixtures that were prepared and then compacted (by vibrating table), surfaces of them were leveled and finally test specimens were cured. These operations carried out according to procedures given in TS EN 12390-1 [30] and TS EN 12390-2 [31].

In this study, 18 test specimens (three for each of the six LWAC and NWAC mixtures) were prepared in 150x300 mm sizes and in the form of cylinders for the compressive strength tests and also 18 test specimens in 100x100x100 mm sizes and in the form of cubes for the oven-dry density tests.

It was seen that there is no consensus in literature on the curing time and testing age of LWAC test specimens. In this study, LWAC test specimens were cured in lime-saturated water during 56 days. Later on, they were kept in the laboratory under environmental conditions at the end of 90th day.

The compressive strength of these test specimens was determined according to instructions given in TS EN 12390-3 [32] and TS EN 12390-4 [33], and the oven-dry density of test specimens was determined according to instructions given in TS EN 12390-7 [34].

Preparation of SEM specimens and determination of the size of CH crystals in ITZ

In this study, images obtained from Scanning Electron Microscope (SEM) were used to determine the size of CH crystals in ITZ. For this, 100x100x500 mm sized beam specimens were prepared at first. Considering the fact that ITZ and scoria aggregate may interact within time, the prepared beam specimens were kept in the laboratory under environmental conditions for one year. The 10x25x50 mm sized SEM specimens were obtained from these beam specimens (Figure 1). SEM specimens were polished, wiped with methyl alcohol to obstruct further hydration, coated with gold for conductivity, and dried in an oven.

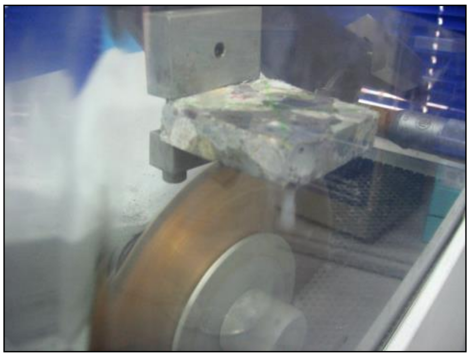


Figure 1. Preparation of SEM specimens.

In able to determine the size of CH crystals in ITZ, 6 SEIs were taken from each SEM specimen. Thus, 36 SEIs at 10000x magnification ratio were taken in total. Quantitative data related with the size of CH crystals was obtained from SEIs by direct measurement. The size of each CH crystal was measured in two perpendicular directions and was determined by taking average of these two sizes. The size of CH crystals in ITZ of each SEM specimen was determined by taking the average of the measured sizes of the largest three CH crystals in ITZ.

Results and discussion

Comparison of LWAC and NWAC within the context of the size of CH crystals in ITZ

The sizes of CH crystals in ITZ of LWAC and NWAC that have three different Ac/At ratios and the same volumetric proportions of ingredients are given in Figure 2 and the images of CH crystals in Figure 3. The size of CH crystals in ITZ of LWAC that has Ac/At ratio of 40% is 6.52%, LWAC's that has Ac/At ratio of 50% is 9.51%, and LWAC's that has Ac/At ratio of 60% is 9.27% less than the sizes of CH crystals in ITZ of NWAC specimens that have the same Ac/At ratios.

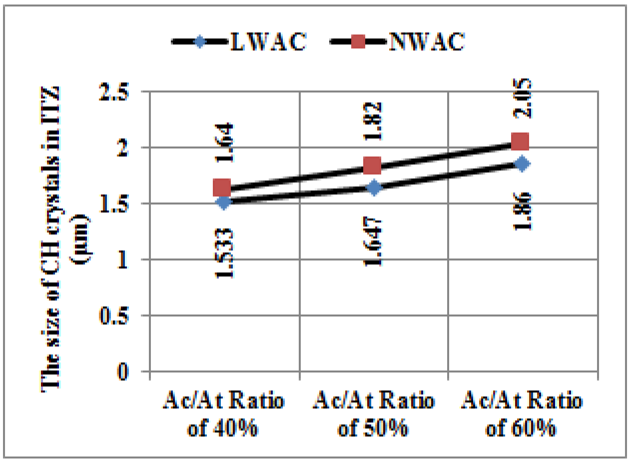
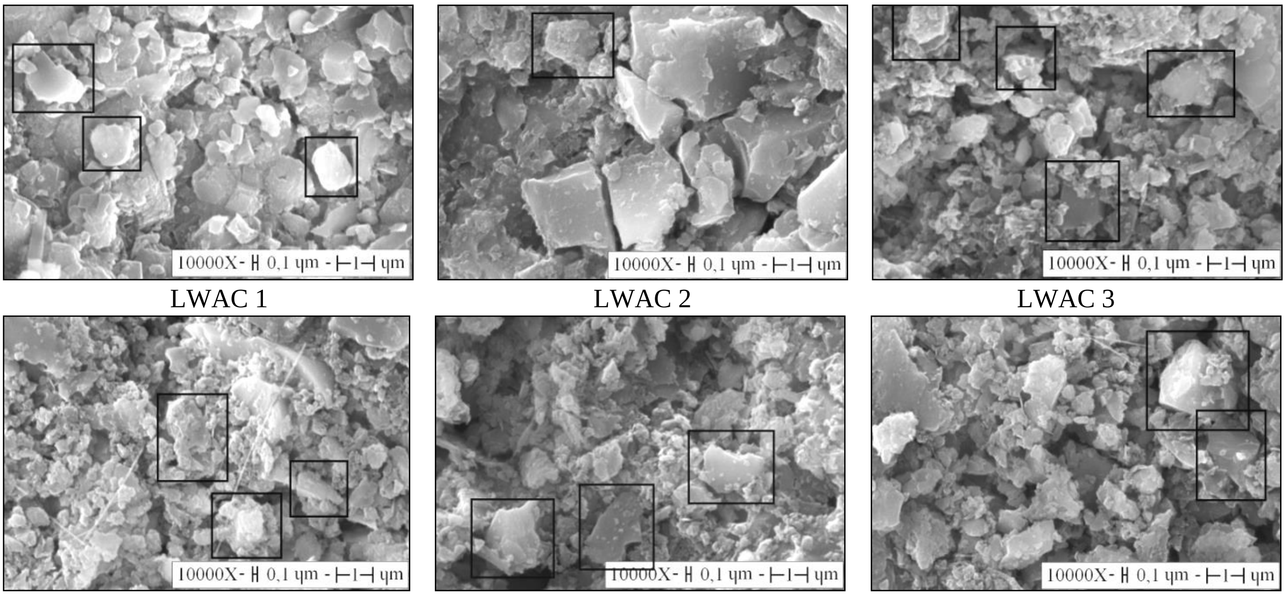


Figure 2. The sizes of CH crystals in ITZ of LWAC and NWAC.



LWAC 1
LWAC 2
LWAC 3
NWAC 1
NWAC 2
NWAC 3

Figure 3. The images of CH crystals in ITZ of LWAC and NWAC.

The differences in the sizes of CH crystals in ITZ of LWAC and NWAC are considered to arise from the differences in the chemical content of the aggregates used for the production of them. In order to explain this situation, ITZ's hydration development must be followed: When cement is dispersed in water, water gets rapidly saturated with various ions. Then, some ions combine to form CH and ettringite in ITZ, as in the bulk cement paste. These crystalline products in ITZ consist of relatively larger crystals. In the next stage of hydration, C-S-H and smaller crystals of CH and ettringite are formed and the space between the large CH and ettringite crystals starts filling by them. In later process of hydration, chemical reactions between the aggregate (siliceous aggregate or limestone) and the cement paste may form new hydration products (C-S-H or carboaluminate hydrates) in the pores of ITZ. Such chemical reactions reduce the concentration of CH in ITZ [1].

Scoria aggregate particles that were used in LWAC have a rich silica and alumina content. In this study, considering the fact that ITZ and scoria aggregate may interact within time, the prepared beam specimens that SEM specimens removed from were kept in the laboratory under environmental conditions for one year. In this long term, scoria aggregate particles must have reacted with portlandite crystals to form so-called secondary hydration products. In this case, small portlandite crystals dissolve entirely, and large portlandite crystals become smaller.

On the other hand, when the Ac/At ratio of both LWAC and NWAC gets increased, the size of CH crystals in ITZ is found to be increased. The change in aggregate grading when W/C ratio and the maximum size of coarse aggregate held constant, effects the bleeding in concrete mixture. When the Ac/At ratio of concrete gets increased, the bleeding around the coarse aggregate particles is increased. In this situation, the W/C ratio of ITZ is increased. CH forms as crystals with a wide range of shapes and sizes, depending primarily on the amount of space available for growth [18]. According to Richardson, there is a lot of space when the W/C is high. Thus, hydration products can grow unhindered and large crystals are formed [35].

Comparison of LWAC and NWAC within the context of compressive strength

Compressive strengths of LWAC and NWAC that have three different Ac/At ratios and the same volumetric proportions of ingredients are given in Figure 4. Compressive strength of LWAC that has Ac/At ratio of 40% is 24.7%, LWAC's that has Ac/At ratio of 50% is 40.09%, and LWAC's that has Ac/At ratio of 60% is 52.47% more than the compressive strengths of NWAC specimens that have the same Ac/At ratios.

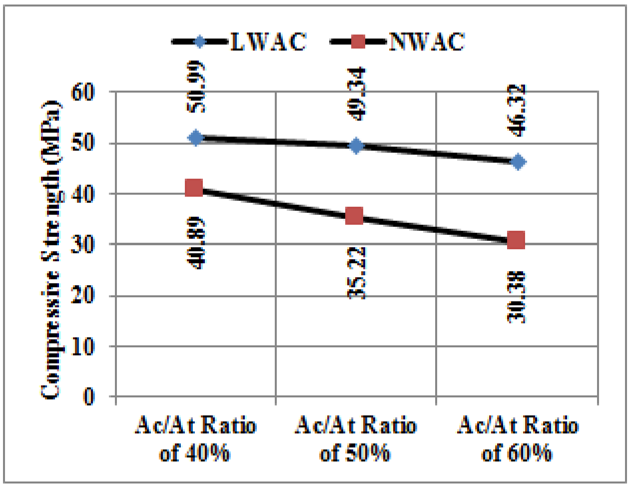


Figure 4. Compressive strengths of LWAC and NWAC.

Since the strength of the scoria aggregate is less than the strength of the gravel aggregate, it can be expected that the compressive strength of LWAC that is produced with scoria aggregate would be less than the compressive strength of NWAC that is produced with gravel aggregate. However, the values obtained from the tests that were made for this study demonstrate that the compressive strength of LWAC is much more than the compressive strength of NWAC.

Concrete is a composite material that consists of three phases named bulk cement paste, aggregate and ITZ, as mentioned before. It is the weakest of these three phases that determines the compressive strength of produced concrete.

In NWAC, aggregate is usually not the critical phase because it is generally stronger and stiffer than the bulk cement paste and ITZ. Aggregate strength only becomes important as target strength increases; particularly in the case of very high strength concrete [36]. In NWAC, the pores and the micro-cracks in ITZ are more than in the bulk cement paste because of the bleeding that occurs around the coarse aggregates in fresh concrete. Therefore, strength limiting phase in NWAC is generally ITZ.

The conditions can be different in LWAC. In TS 1114 EN 13055-1 [37], aggregate with a particle density not exceeding 2 Mg/m^3 is qualified as lightweight aggregate. Lightweight aggregate has less particle density and therefore strength compared to normal-weight aggregate. Lightweight aggregate with very low particle density can be the strength limiting phase in LWAC. However, the particle density (1.82 Mg/m^3) of the scoria aggregate used in this study is close to the maximum particle density limit determined for lightweight aggregates. In this context, it is considered that the strength limiting phase is ITZ for both LWAC and NWAC produced in this study.

ITZ causes concrete to collapse at levels below the stress level that the other two phases can withstand. ITZ strength of LWAC is considered to be much more than the ITZ strength of NWAC. There are several reasons for this consideration.

In the first instance, the adhesion between hydration products in ITZ depends on the van der Waals force of attraction as in cement paste. Therefore, the strength of ITZ is affected by the volume and size of pores present. Larger hydration products of ITZ have lower surface area and weaker van der Waals forces of attraction accordingly. Thus, they possess less adhesion capacity. Besides, larger hydration products of ITZ form a more porous framework [1]. In this manner, the size of CH crystals can be regarded as one of the indicators of the ITZ strength. Since the size of CH crystals in ITZ of LWAC is less than NWAC's, ITZ strength of LWAC is considered to be more than NWAC's.

Further, in fresh NWAC, the water accumulated around the normal-weight aggregates evaporates during the drying process, leaving behind a porous ITZ. Lightweight aggregates, on the other hand, can absorb the water in ITZ due to their porous structure, leading to a stiffer ITZ microstructure. This situation increases the ITZ strength of LWAC.

Furthermore, in the concrete's strength gaining process, the water absorbed by the lightweight aggregates moves towards ITZ and bulk cement paste, so increases the hydration degree of the cement. This process, which is defined as 'internal curing' in the literature, contributes to the hydration development of cement more than the 'external curing'. Internal curing is particularly useful for concrete with low water/cement ratio and high cement content, as in this study, because the cement paste is denser in this situation and it is more difficult for water to reach the inner parts of the concrete by external curing. Increasing hydration degree by internal curing decreases the capillary porosity and consequently increases the ITZ strength of LWAC.

In addition to ITZ strength, the physical bond between ITZ and the aggregate particles also affects the compressive strength of the concrete. When the physical bond between ITZ and aggregate particles gets stronger, the compressive strength of the concrete increases, and can resist the stresses as a whole. When the porosity of ITZ gets increased, physical bond weakens because the contact surface between ITZ and aggregate particles decreases. Since the ITZ of NWAC is more porous, the bond between ITZ and aggregate particles is weaker. In addition, according to Neville, Gündüz, Uğur, Çelik and Gürdal, as the indentations and protrusions on the surface of the aggregate particle increase, the contact surface and the cohesive force between ITZ and the aggregate particle also increase and physical locking occurs [38]. Therefore, it is considered that angular shaped and rough surface textured scoria aggregate particles (Figure 5) provides a much stronger bond with ITZ than the round shaped and smooth surface textured gravel aggregate particles.

Figure 5. Scoria aggregate particles that were used in the study.

LWAC and NWAC were produced with three different Ac/At ratios. Increase in the ratio of coarse aggregate to total aggregate increases the weak ITZ phase. For this reason, with higher Ac/At ratios, it was possible to produce LWAC and NWAC that have lower compressive strength values. However, the decrease in the compressive strength value of LWAC remained limited due to the positive contribution of the scoria aggregate to ITZ strength and its stronger bond with this zone. Thus, the difference between the compressive strength values of LWAC and NWAC is found to be increased when the Ac/At ratios of them get increased.

Comparison of LWAC and NWAC within the context of oven-dry density

Oven-dry densities of LWAC and NWAC that have three different Ac/At ratios and the same volumetric proportions of ingredients are given in Figure 6. Oven-dry density of LWAC that has Ac/At ratio of 40% is 8.97%, LWAC's that has Ac/At ratio of 50% is 10.71%, and LWAC's that has Ac/At ratio of 60% is 13.22% less than the oven-dry densities of NWAC specimens that have the same Ac/At ratios.

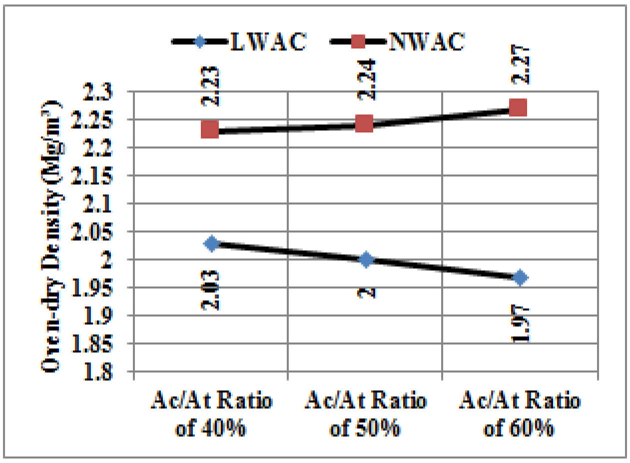


Figure 6. Oven-dry densities of LWAC and NWAC.

The density of the concrete increases when the bulk cement paste and ITZ get stiffer. The density of the concrete also increases when the particle density of aggregate used in concrete gets higher. The particle density of normal-weight aggregates is very high. In this context, lightweight aggregates are advantageous for reducing the density of concrete. The particle density of the scoria aggregate used in this study is 1.82 Mg/m^3 and the gravel aggregate's particle density is 2.58 Mg/m^3. Thus, oven-dry density of LWAC is less than the oven-dry density of NWAC.

Since the particle density of the scoria aggregate used as coarse aggregate is also less than the particle density (2.54 Mg/m^3) of the river sand used as fine aggregate, with a higher Ac/At ratio it was possible to produce LWAC that has a lower oven-dry density value. Since the particle density of the gravel aggregate is more than the particle density of the river sand, with a higher Ac/At ratio it was possible to produce NWAC that has a higher oven-dry density value. Thus, the difference between the oven-dry density values of LWAC and NWAC is found to be increased when the Ac/At ratios of them get increased.

Conclusions

In this experimental study, the size of CH crystals in ITZ of LWAC was found to be 8.43% less than (on average) the size of CH crystals in ITZ of NWAC. The differences in the sizes of CH crystals in ITZ of LWAC and NWAC are considered to arise from the differences in the chemical contents of the aggregates used for the production of them. Scoria aggregate particles that were used in LWAC have a rich silica and alumina content. The large CH crystals formed in ITZ at the beginning of the hydration process are considered to become smaller by slow chemical reactions between scoria aggregate particles and CH crystals. Smaller CH crystals mean stiffer ITZ microstructure, and are beneficial from mechanical, physical and durability points of view.

Compressive strength of LWAC was found to be 39.09% more than (on average) the compressive strength of NWAC. The differences in compressive strength values of LWAC and NWAC are considered to arise from the differences in strengths of ITZs and strengths of physical bonds between ITZ and aggregate particles. Scoria aggregate particles that were used in LWAC are considered to make more contribution to ITZ strength. Besides, angular shaped and rough surface textured scoria aggregate particles provides a much stronger bond with ITZ than the round shaped and smooth surface textured gravel aggregate particles.

Oven-dry density of LWAC was found to be 10.97% less than (on average) the oven-dry density of NWAC. The differences in oven-dry density values of LWAC and NWAC are considered to arise from the differences in particle densities of aggregates used for the production of them. The particle density of the scoria aggregate that was used in LWAC is less than the particle density of gravel aggregate that was used in NWAC. In this context, scoria aggregate particles are considered to make an important contribution in reducing the density of concrete.

The findings of this study show that lightweight aggregate that has high particle density, angular shape, rough surface texture, and a structure that enables chemical reaction with CH crystals will be beneficial for the ITZ microstructure and properties of concrete. It is considered that these properties should be taken into consideration in the selection of lightweight aggregate for structural concrete production.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for this article prepared.

There is no conflict of interest with any person in this article prepared. All authors declare that they have no conflict of interest.

Authors’ Contributions

All authors contributed equally.

References

[1] P. K. Mehta and P. J. M. Monteiro, *Concrete - Microstructure, Properties, and Materials*. Third ed., New York, NY, USA: McGraw-Hill, 2006.

[2] E. Gallucci and K. Scrivener, “Crystallisation of calcium hydroxide in early age model and ordinary cementitious systems,” *Cem. Concr. Res.*, vol. 37, pp. 492-501, 2007.

[3] H. Gönül, “Bazalt skoriasının taşıyıcı yarı hafif beton üretiminde kullanımı / Use of basaltic scoria for produce of semi lightweight concrete,” Ph.D. dissertation, Dept. of Architecture, Gazi Univ., Ankara, 2008.

[4] M. Ayhan, H. Gönül, İ. A. Gönül, and A. Karakuş, “Effect of basic pumice on morphologic properties of interfacial transition zone in load-bearing lightweight / semi-lightweight concretes,” *Constr. Build. Mater.*, vol. 25, pp. 2507-2518, 2011.

[5] V. Nežerka, P. Bílý, V. Hrbek, and J. Fládr, “Impact of silica fume, fly ash, and metakaolin on the thickness and strength of the ITZ in concrete,” *Cem. Concr. Compos.*, vol. 103, pp. 252-262, 2019.

[6] J. Skalny, J. Gebauer, and I. Odler, eds., *Materials Science of Concrete: Calcium Hydroxide in Concrete*. Westerville, USA: The American Ceramic Society, 2001.

[7] C. Carde and R. François, “Effect of the leaching of calcium hydroxide from cement paste on the mechanical and physical properties,” *Cem. Concr. Res.*, vol. 27, pp. 539-550, 1997.

[8] N. Hernandez, J. Lizarazo-Marriaga, and M. A. Rivas, “Petrographic characterization of Portlandite crystal sizes in cement pastes affected by different hydration environments,” *Constr. Build. Mater.*, vol. 182, pp. 541-549, 2018.

[9] T. Sacki and P. J. M. Monteiro, “A model to predict the amount of calcium hydroxide in concrete containing mineral admixtures,” *Cem. Concr. Res.*, vol. 35, pp. 1914-1921, 2005.

[10] J. Marchand, D. P. Bentz, E. Samson, and Y. Maltais, “Influence of calcium hydroxide dissolution on the transport properties of hydrated cement systems,” in *Materials Science of Concrete: Calcium Hydroxide in Concrete*, J. Skalny, J. Gebauer, and I. Odler, eds., Westerville, USA: The American Ceramic Society, 2001, pp. 113-129.

[11] Z. Yan-Rong, K. Xiang-Ming, L. Zi-Chen, L. Zhen-Bao, Z. Qing, D. Bi-Qin, and X. Feng, “Influence of triethanolamine on the hydration product of portlandite in cement paste and the mechanism,” *Cem. Concr. Res.*, vol. 87, pp. 64-76, 2016.

[12] T. Müller, C. Krämer, C. Pritzel, R. Bornemann, T. L. Kowald, R. H. F. Trettin, and P. H. Bolívar, “Influence of cocamidopropyl betaine on the formation and carbonation of portlandite – A microscopy study,” *Constr. Build. Mater.*, vol. 163, pp. 793-797, 2018.

[13] W. Kunther, S. Ferreiro, and J. Skibsted, “Influence of the Ca/Si ratio on the compressive strength of cementitious calcium–silicate–hydrate binders,” *J. Mater. Chem. A*, vol. 5, pp. 17401-17412, 2017.

[14] S. Diamond, “The microstructure of cement paste and concrete––a visual primer,” *Cem. Concr. Compos.*, vol. 26, pp. 919-933, 2004.

[15] K. Wu, H. Shi, L. Xu, G. Ye, and D. G. Schutter, “Microstructural characterization of ITZ in blended cement concretes and its relation to transport properties,” *Cem. Concr. Res.*, vol. 79, pp. 243-256, 2016.

[16] J. S. Belkowitz and D. Armentrout, “An investigation of nano silica in the cement hydration process,” presented at the *Concrete Sustainability Conference*, USA, 2010.

[17] Q. Ye, Z. Zhang, D. Kong, and R. Chen, “Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume,” *Constr. Build. Mater.*, vol. 21, pp. 539-545, 2007.

[18] J. J. Thomas and H. Jennings, “Materials of cement science primer: The science of concrete,” Northwestern University Infrastructure Technology Institute, USA, Rep. Project A474, 2009.

[19] T. Slamečka and F. Škvára, “The effect of water ratio on microstructure and composition of the hydration products of Portland cement pastes,” *Ceram. Silik.*, vol. 46, no. 4, pp. 152-158, 2002.

[20] M. Alexander and S. Mindess, *Aggregates in concrete*. New York, NY, USA: Taylor & Francis, 2005.

[21] A. A. SamsonDuna, “Utilization of scoria as aggregate in lightweight concrete,” *Int. J. Eng. Res.*, vol. 6, no. 1, pp. 34-37, 2017.

[22] T. J. Gomes, “Structural lightweight concrete produced with volcanic scoria from São Miguel Island,” Instituto Superior Técnico, 2015.

[23] I. Lau, S. Setunge, and N. Gamage, “Properties of concrete using scoria lightweight aggregate concrete,” in *23rd Australasian Conference on the Mechanics of Structures and Materials*, Lismore, Australia, 9-12 December 2014, pp. 95-100.

[24] A. Kılıç, C. D. Ati, A. Teymen, O. Karahan, and K. Arı, “The effects of scoria and pumice aggregates on the strengths and unit weights of lightweight concrete,” *Sci. Res. Essays*, vol. 4, no.10, pp. 961-965, 2009.

[25] K. M. A. Hossain, “Blended cement and lightweight concrete using scoria: mix design, strength, durability and heat insulation characteristics,” *Int. J. Phys. Sci.*, vol. 1, no. 1, pp. 5-16, 2006.

[26] A. Kılıç, C. D. Atiş, E. Yaşar, and F. Özcan, “High-strength lightweight concrete made with scoria aggregate containing mineral admixtures,” *Cem. Concr. Res.*, vol. 33, pp. 1595-1599, 2003.

[27] E. Yaşar, C. D. Atiş, A. Kılıç, and H. Gülsen, “Strength properties of lightweight concrete made with basaltic pumice and fly ash,” *Mater. Lett.*, vol. 57, pp. 2267-2270, 2003.

[28] M. R. Moufti, A. A. Sabtan, O. R. El-Mahdy, and W. M. Shehata, “Assessment of the industrial utilization of scoria materials in Central Harrat Rahat, Saudi Arabia,” *Eng. Geol.*, vol. 57, pp. 155-162, 2000.

[29] The European Union, “Properties of LWAC made with natural lightweight aggregates,” Eurolightcon BE96-3942/R17, pp. 8-35, 2000.

[30] Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds, TS EN 12390-1, 2002.

[31] Testing hardened concrete - Part 2: Making and curing specimens for strength tests, TS EN 12390-2, 2002.

[32] Testing hardened concrete - Part 3: Compressive strength of test specimens, TS EN 12390-3, 2003.

[33] Testing hardened concrete - Part 4: Compressive strength - Specification for testing machines, TS EN 12390-4, 2002.

[34] Testing hardened concrete - Part 7: Density of hardened concrete, TS EN 12390-7, 2002.

[35] P. C. Aitcin, “Portland cement,” in *Science and Technology of Concrete Admixtures*, P. C. Aitcin and R. J. Flatt, eds., UK: Woodhead Publishing, 2016, pp. 27-53.

[36] M. A. Caldarone, *High-strength concrete: A Practical Guide*. New York, NY, USA: Taylor & Francis, 2009.

[37] Lightweight aggregates - Part 1: Lightweight aggregates for concrete, mortar and grout, TS 1114 EN 13055-1, 2004.

[38] L. Gündüz and İ. Uğur, “The effects of different fine and coarse pumice aggregate / cement ratios on the structural concrete properties without using any admixtures,” *Cem. Concr. Res.*, vol. 35, pp. 1859-1864, 2005.