Magazine of Civil Engineering. 2024. 17(4). Article No. 12804

Magazine of Civil Engineering

journal homepage: http://engstroy.spbstu.ru/

ISSN
2712-8172

Research article

UDC 622

DOI: 10.34910/MCE.128.4

Lightweight concrete containing recycled aggregates

A.A. Alani ✉

University of Anbar, Ramadi, Iraq

✉ *ahmed.anees@uoanbar.edu.iq*

Keywords: construction waste, recycled aggregate, green composites, lightweight concrete

Abstract. This study investigated the replacement of fine concrete aggregates with recycled aggregate. The results showed that the effect of recycled aggregate, so that, replacing 25, 50, 75 and 100 % of natural aggregate led to an 8, 23, 15 and 11 %, respectively, increase in the compressive strength of lightweight concrete samples. Based on these results, a microstructural analysis of the contact zone of the concrete using various types of aggregate was conducted. The shrinkage and expansion development of samples containing recycled aggregate formed from demolished waste differed from that of ordinary concrete, and the findings over 90 days indicated the impact of the substitution percentage in the recycled aggregates contained in the mixture. When 100 % fine natural aggregate was replaced with recycled aggregate, expansion increased by 15 % at 14 days and shrinkage increased by 45 % at 90 days as compared to references. Cement hydration in concrete mixes using different types of aggregates has been investigated by using an X-ray diffraction. The results showed that the sample without recycled aggregate from demolition waste LW-1 contained the maximum amount of C_3S and C_2S compared to the sample with recycled aggregate from demolition waste LW-5, which can harden when interacting with water. The concrete samples used to evaluate the abrasion resistance were first cured for 28 days. The results revealed that the abrasion Δh values for samples containing recycled aggregate were lower than that for the reference samples.

Funding: The research was financially supported by Shukhov Belgorod State Technological University (BSTU).

Acknowledgements: The author wishes to thank the College of Engineering, University of Anbar, for supplying materials to conduct the research work.

Citation: Alani, A. A. Lightweight concrete containing recycled aggregates. Magazine of Civil Engineering. 2024. 17(4). Article no. 12804. DOI: 10.34910/MCE.128.4

1. *Introduction*

Natural disasters and armed conflicts unfortunately can cause significant destruction to cities and infrastructure. In addition to the environmental effect and costs associated with obtaining and processing natural resources for the creation of new building materials, handling the waste from such disasters and reconstructing destroyed cities is undoubtedly a critical task. The traditional approach of using raw materials for construction can indeed have negative implications for sustainability and the principles of Green Building.

The high efficiency of using scrap concrete as a secondary concrete filler has been confirmed by numerous studies conducted in this direction. As reported in [1], the aggregates account for more than half of the material composition and up to 60–75 % of the total volume of concrete mix. Because of the increasing consumption for construction, which results in up to 48 billion tons of aggregates being used yearly for concrete production [2], the notion of using recycled concrete aggregate (RA) in the making of concrete was proposed. As compared to natural aggregate (NA), RA has 30 % lower embodied energy and

60 % lower CO_2 emissions, which makes it more environmentally friendly and promotes sustainable construction [3]. European nations have been striving to employ RA in brand-new concrete structures since the early 1980s. Several studies have been conducted that looked at recycled aggregate concrete (RC) and came to the conclusion that using RA is practical and widely acceptable [4]. Since up to 50 % of the materials used in the concrete for their contemporary constructions are recycled, Zurich, Switzerland, has been a leader in RC for more than 15 years. The percentage of non-concrete mineral components added to the concrete has been capped at 10 % in certain other nations, such as Finland and Germany [5]. In order to enhance RC's qualities and broaden its use as a respectable concrete in the building industry, numerous studies have been undertaken on the material. It is conceivable that the RC-built structures may be torn down once more at some point or for other causes, such as ongoing conflicts and natural disasters in specific regions [6–11].

According to [12], raising the strength from 30 to 40 MPa may decrease abrasion losses by approximately 17 %, while employing steel fibers with volumetric contents of 0.75 and 1.0 % can enhance abrasion resistance by over 23 %. As a multi-recycled aggregate (MRA), which is RA made from RC, will be employed in this instance, the created debris will be utilized. Concrete will be multi-recycled as a result of the application of MRA in its manufacture (MRC). There have not been many studies that have looked at the mechanical and other characteristics of MRC with various replacement amounts. By using MRA as an aggregate replacement for NA up to 100 % when studying the mechanical behavior of MRC [13, 14], it was discovered that the compressive strength was slightly decreased and that the third generation of MRC could outperform the necessary strength by at least 25 % replacement, demonstrating the beneficial influence of MRA.

Large amounts of concrete trash are created through the planned destruction of old buildings and structures, technical and natural disasters, and armed conflicts in different nations [15]. To address the seepage problem of recycled concrete, the effects of altering parent concrete strengths, the ratio of recycled aggregate, fly ash concentration, and water gel ratio were investigated using a design orthogonal experiment. Water gel ratio, matrix concrete strength, recycled aggregate replacement rate, and fly ash percentage were shown to have a significant to modest influence on the impermeability of recycled concrete [16]. According to [17–18], these wastes should primarily be used for new construction as well as repair and restoration work in their occurrence places. It is important to employ raw resources in this case, from demolished buildings and structures, to produce construction materials, including "green composites". Several papers, as is shown in [19], investigate the usefulness of recycling trash from destroyed buildings. Future research opportunities identified in [20] include:

1) detecting pollutant sources in construction and demolition waste generated by industrial structures;
2) creating complete pollution control strategies for construction waste;
3) improving construction and demolition waste recyclability;
4) creating enhanced assessment standards for debris and repurposed materials;
5) broadening the scope of demolition waste flows study;
6) establishing a demolition waste management fee scheme;
7) developing improved approaches for evaluating construction waste management performance;
8) investigating a better application of technology in demolition waste management;
9) minimizing construction waste from the beginning of the project;
10) minimizing waste from construction during the building process.

The results of this study are important not just for a better understanding of demolition waste research, but they may also help operators improve their waste management efficiency and reduce related pollutants.

The search for a more ecologically responsible strategy that has both economic and social benefits is aided, as described in [21], by the examination and use of foreign experiences in the processing of municipal solid waste and its secondary use. The rule of affinity of microstructures, which directs the selection of raw materials for composites with comparable physical and mechanical properties, is one part of this field. Composite binders with low water requirements have been developed. Their strength is roughly double that of the original cement, with 50–70 % of the crushed slag or quartz sand in its composition giving the same strength as Portland cement. It was proven that quartzite sand screening can be employed as filler in the production of fine-grained concretes [22, 23]. Based on the aforementioned, it can be concluded that the use of recycled materials from demolition waste aims to reduce costs associated with construction by making efficient use of resources and accounting for the complex influence of environmental and energy-saving factors, as well as the value of territories in urban planning [24].

The scientific innovation is that the nature of the processes of construction of samples based on recycled aggregate from fragments of demolished buildings has been conceptually established and empirically validated as a complicated polyfunctional system.

2. Materials and Methods

2.1. Materials

The binder utilized was Ordinary Portland cement (OPC) CEM I/42.5N (Belgorod cement, Russian Federation). Tables 1–2 show the chemical and mineralogical compositions, as well as the physical and mechanical properties of Portland cement. Portland cement has a specific surface area of 230–250 m^2/kg. NA from a nearby area in the Anbar governorate (Iraq) and an expanded clay fraction of 5–10 mm were used as raw materials (Fig. 1). Tables 3–5 show the characteristics of sand, gravel, and expanded clay.

Table 1. Mineralogical and chemical composition of Portland cement type CEM I/42.5N.

Chemical composition, % wt.							**Mineralogical composition, % wt.**			
SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	SO_3	Alkalis	C_3S	C_2S	C_3A	C_4AF
4.19	84.73	0.57	1.37	3.30	1.11	0.70	59.3	17.8	6.6	14.2

Table 2. Physical and mechanical properties of Portland cement type CEM I/42.5N.

Setting time, h:min		**Flexural strength, MPa**		**Compressive strength, MPa**	
start	end	3 d	start	end	3 d
2:25	3:28	6.2	2:25	3:28	6.2

Table 3. Characteristics of the sand used.

Characteristics	**Value**
Specific gravity, kg/m^3	2400
Fineness modulus	1.85
Content of dusty, clay and silt particles, % wt.	0.75
Bulk density, kg/m^3	1450
Absorption capacity, %	9.85

Table 4. Characteristics of expanded clay.

Characteristics	**Value**
Compressive strength, MPa	0.3–3.5
Water absorption, %	25
Freeze-thaw resistance, cycles	17
Bulk density, kg/m^3	350
Porosity, %	49

Figure 1. View of expanded clay.

The composition of the demolition and construction waste of buildings and structures in Iraq is shown in Table 5. According to the table, debris and cement concrete make up 99.88 % of the trash generated during building and demolition projects in Iraqi cities due to hostilities. In Fig. 2, the view of the crushed demolition waste is depicted.

Table 5. Demolition waste compositionю

Material	OPC	Crushed stone	Fiber	Wood	Metal	Plastic	Gypsum
Content, %	38.60	61.30	0.02	0.01	0.03	0.03	0.01

Table 6. Characteristics of the buildings and structures demolition and construction waste.

Density, kg/m^3	Bulk density, kg/m^3	Porosity, %	Water absorption, %
2560	1233	52	20

Figure 2. View of the crushed demolition waste.

After being crushed by a jaw crusher, the crushed stone from concrete waste reveals intermittent mortar component interlayers that are firmly clinging to the grains of the rock. Surfaces of crushed stone can have thin layers of hydrated phases when there is not a layer of cement-sand mortar. There is every reason to expect that this will increase the cement matrix's adherence in concrete. This notion is supported by the discovery that cement paste adheres to a wide range of materials, including quartz, granite, limestone, and clinker, with increasing consistency with time. These assumptions are supported by previous studies [22, 23].

2.2. Methods

Construction waste was processed with a jaw crusher laboratory (ECO building materials, Russian Federation) to produce aggregate (Fig. 3). Utilizing an average particle size of not greater than 5 mm. This material was utilized as a fine aggregate in compliance with the sieve analysis criteria.

Figure 3. Laboratory jaw crusher.

The microstructure features and properties of raw materials and the samples were investigated using both theoretical and empirical approaches. A scanning electron microscope with an accelerating voltage of 8.0 kV was used to analyze the morphology of raw materials and miniature concrete samples measuring 15 × 15 × 4 mm. The microstructure of materials was studied using a Tescan MIRA 3 LMU scanning electron microscope. The model is designed to operate under varying vacuum conditions (up to 150 Pa) in the sample chamber (Fig. 4). Working in a low vacuum, while maintaining all the advantages of a high vacuum, provides the opportunity to study non-conducting materials without first applying a layer of heat-conducting material. Scanning electron microscope allows the use of a raster method for imaging, which consists of sequential point-by-point scanning of the surface under study with a thin electron beam. In this case, the detector registers secondary electrons generated by the electron probe.

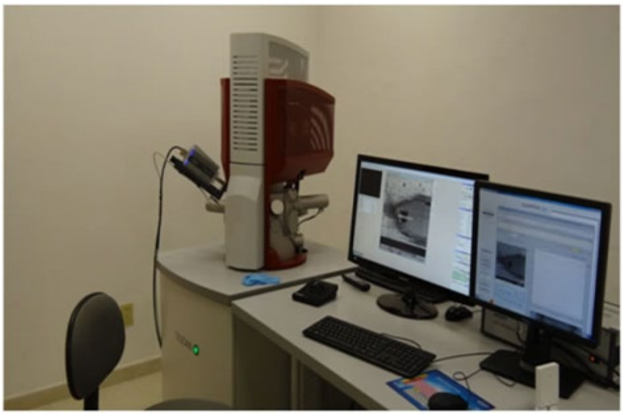


Figure 4. Electron microscope “Tescan MIRA 3 LMU”.

The results showed that the use of recycled aggregate has an effect on abrasion resistance. LKI-3 abrasion circles were used on cube samples measuring 70 × 70 × 70 mm to determine abrasion. Abrasion tests were performed on samples that had been dried to a consistent weight before assessment. Following drying, the samples were measured and weighed to an accuracy of 1 mm and 0.1 g. The sample was clamped with an applied pressure element and subjected to an axial load of 300 ± 1 N. The sample was rotated at 30 ± 1 rpm after applying 20 g of typical corundum powder to a steel disk. After each cycle, the disk and specimen's front surface were cleaned and rotated 90°. Between each test cycle, the specimen was weighed to within 0.1 g accuracy (Fig. 5).

Figure 5. LKI-3 abrasion device.

The chemical components of raw materials and microscopic concrete samples were evaluated using an X-ray spectrometer with an integrated diffraction system. The study of the mineralogical composition of raw materials and fragments of destroyed buildings and structures was carried out by X-ray phase analysis using an X-ray diffractometer model “ARL X’TRA. Thermo Fisher Scientific” with the use of which it is possible to determine the crystallographic, quantitative and qualitative parameters of materials, their phase composition, structural features and surface quality (Fig. 6).

Figure 6. X-ray diffractometer model "ARL X'TRA. Thermo Fisher Scientific".

The determination of the chemical and mineral composition of samples was carried out using an ARL 9900 WorkStation series spectrometer with a built-in diffraction system using the X-ray fluorescence (XRF) technique. The modular design and various additional options provide the ability to use this unit to solve a wide range of problems in a variety of production conditions (Fig. 7).

Figure 7. Spectrometer "ARL 9900 WorkStation".

Recognition of products of mineral composition and new formations was also carried out using differential thermal analysis and differential thermal device "NETZSCH STA 449F1" (Fig. 8).

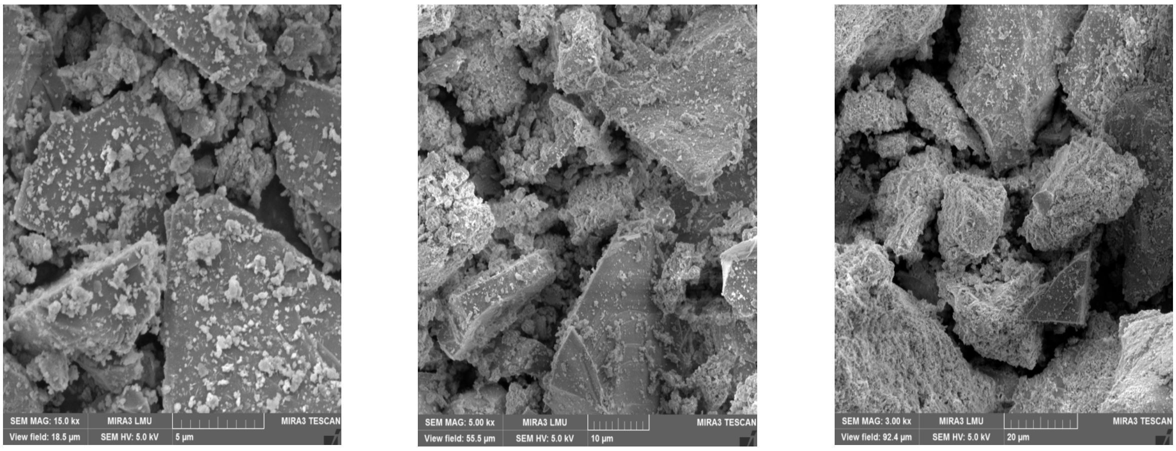
Figure 8. Differential thermal device "NETZSCH STA 449F1".

The thermo gravimetric analyzer was used to conduct thermo gravimetric and differential thermal analyses (DTA). The amount of slump is measured after the liquid has been poured into a 30 cm high cone. The mean density of the material was determined using concrete cube samples of 100 × 100 × 100 mm. Six samples were obtained in each series to ensure acceptable results. A portion of the samples were hardened for 3 and 28 days under normal conditions, while another portion was hardened for one day while steaming using the "3 h + 8 h + cooling" technique (isothermal holding temperature 80 °C). The overall computed inaccuracy is less than 4 %.

3. Results and Discussion

3.1. Scanning Electron Microscope Images of Construction Waste

Fine aggregate was produced by grinding the demolition waste. Fig. 9 shows SEM images of the obtained aggregate. Table 7 provides the mineral composition of aggregate produced from demolition waste.



a) **b)** **c)**

Figure. 9. Micrographs of aggregate obtained from demolition waste: a) 5 mkm; b) 10 mkm; c) 20 mkm.

Table 7. The mineral composition of recycled aggregate from construction waste.

Sizes of particles, mm	**Mineral content, %**					
	$Ca(OH)_2$	SiO_2	$CaCO_3$	C-S-H	C_3S	C_2S
0.0–5	10.60	58.7	5.40	5.30	7.40	8

A considerable number of sharp particles may be seen in the aggregate from concrete waste as seen in SEM pictures, and this number increases as particle size decreases from 2.5 to 0–0.16 mm. This type of aggregate is the most sensible since it strengthens the interfacial transition zone by providing adhesion between the aggregate and cement matrix.

According to studies [25–29], the comminuted shape of the particles and their high silica and clinker mineral content will also contribute to their high activity. The particle form that has been crushed leads to a significant particular surface area, which interacts with the cement clinker's hydration byproducts. The reasonable reactivity of the particles of grinded concrete debris is also a result of the high silica content and previously unhydrated clinker minerals.

3.2. Compressive Strength

The C8/10 expanded clay concrete class experimented with substituting natural sand with synthetic crushed sand. The research investigations have been carried out using 1.8 mm demolition waste in place of sand, both partially and completely. Concrete mixes were created in this instance by using natural sand (control composition) and partial replacement artificial sand (25, 50, 75 and 100 %) (Table 8). According to the results of a study, the use of demolition waste increases the compressive strength of expanded clay concrete. This can be attributed to an increase in cement paste adhesion (Fig. 10).

Table 8. Lightweight concrete compositions and properties.

Materials content, kg/m³						**Slump test, cm**	**Density, kg/m³**	**Compressive strength, MPa**
Mix ID	**Portland cement**	**Natural sand**	**Demolition waste**	**Expanded clay**	**Water**			
LW-1	475	600	–	410	240	3–4	1674	15.2
LW-2	475	450	150	410	243	4–5	1658	17.4
LW-3	475	300	300	410	249	3–4	1666	19.5
LW-4	475	150	450	410	255	3–4	1674	18.2
LW-5	475	–	600	410	270	3–4	1671	17.6

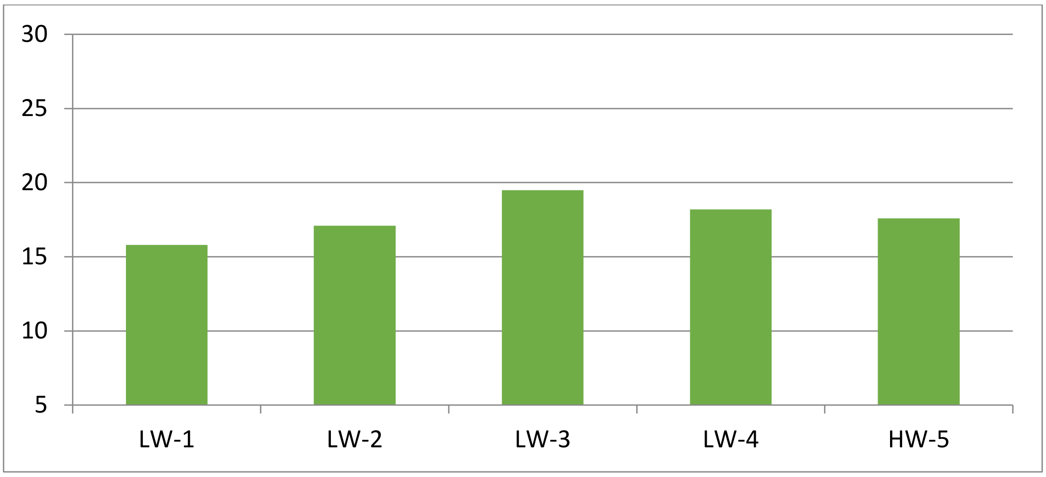


Figure 10. Compressive strength of lightweight concretes.

Experiments showed that when recycled aggregate replaces natural sand in lightweight concrete, the strength of the concrete increases rather than diminishes. Recycled aggregate was created by the classification of screening of crushed fragments of demolished waste, and it may be used as fine aggregate in concrete. The results of measured compressive strength for concrete samples surpassed those of previous authors by 12–35 % for lightweight concrete [30].

3.3. Microstructure Study

The interaction space of the paste of cement and the aggregate created from scrapped debris is shown in Fig. 11. The cement matrix's surface has a thick intergrowth and germination of concrete debris, and the two appear to be one cohesive unit.

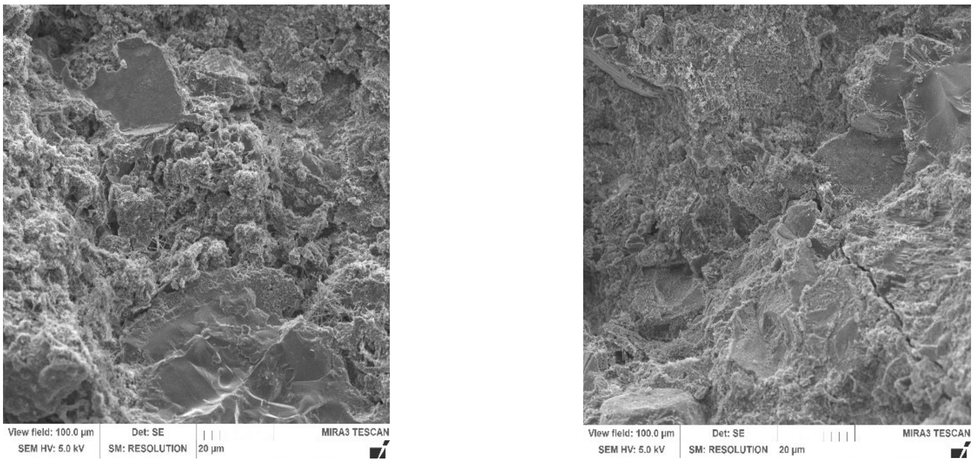


Figure 11. The zone of contact between the cement paste and the recycled aggregate.

The first phase in which the aggregate collects water from the concrete mix and the water retained in the pores, like in capsules, will offer an inflow of moisture for additional hydration of the binder, ensuring a thick contact zone. The water from the aggregate pores is drawn out by clinker minerals and new growths after the formation of a capillary-porous microstructure, increasing the rate of cement hydration without adversely influencing the workability of the concrete mix. Due to the presence of partially hydrated belite and portlandite particles, which make about up 15–25 % of fresh concrete, secondary (residual) cementitious characteristics may be present in concrete waste if it is small and has not undergone hydrothermal treatment.

The next step was to study the further hydration of concrete with the composition of cement and recycled aggregate from concrete scrap, at the age of 28 days. It can be seen that the microstructure of the samples is significantly compacted, the pores become smaller, they are gradually overgrown with cubic crystals of calcium hydro-alumoferrites, and partially or completely overgrown with calcium hydrosilicates (Fig. 11). The rough surface of semi-dissolved cubic crystals contributes to their better adhesion to calcium hydrosilicate crystals of a colloidal degree of dispersion. It is noted that the formation of the contact zone is so densely overgrown with neoplasm products that it is viewed with great difficulty.

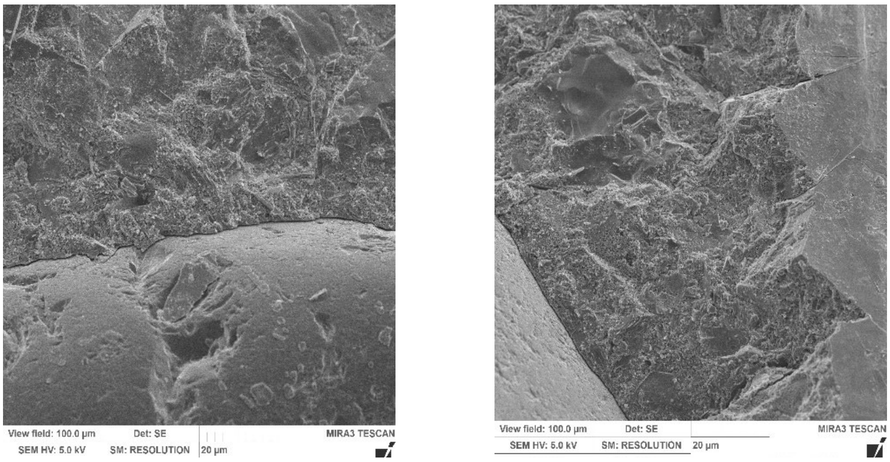


Figure 12. The zone of contact between the cement paste and natural sand.

Fig. 12 shows the contact zone of cement stone and grains of natural sand. The photo clearly shows the boundary, on the surface of which fine-grained calcium hydrosilicates form, forming a dense mesh layer of neoplasms that fills the entire space.

As a result, concretes made from waste concrete have greater cement matrix adhesion, which improves the eventual product's deformability, fracture resistance, dynamic load resistance, and other characteristics. These results have already been demonstrated in [22, 23], which are based on the rule of affinity of microstructures.

3.4. Shrinkage and Expansion Deformations

The impacts of alternating shrinkage and expansion of the material cause the development of destructive processes in concrete, which lead to permanent deformations and destruction of the material structure. Therefore, concrete shrinkage and expansion deformations are significant because they affect the basic qualities of structural elements. In this scenario, the acceptable concrete hardening regime is critical. As a result, after assessing shrinkage and expansion deformations for lightweight concrete, the samples were immediately placed in a typical hardening chamber with a relative humidity of up to 95 % and an air temperature 18–22 °C. Following two days of typical hardening, measurements were taken to assess sample deformations and moisture content changes. At the ages of 3, 7, 14, 28, 60, and 90 days, studies were conducted to detect sample deformations and changes in moisture content. Fig. 13 shows the test results.

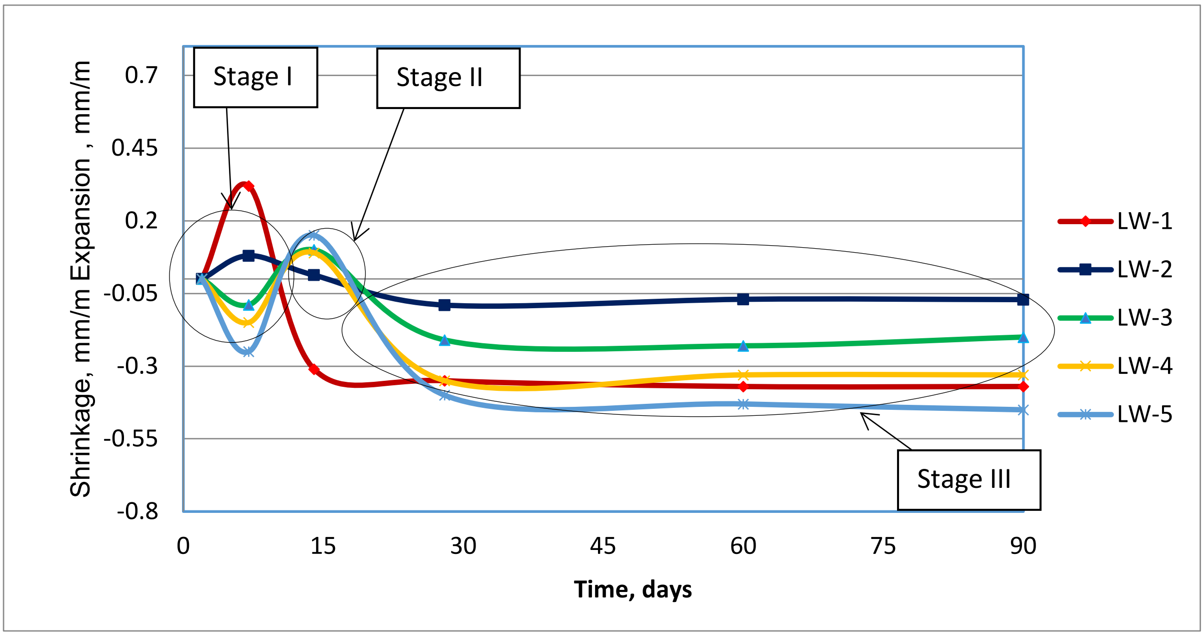


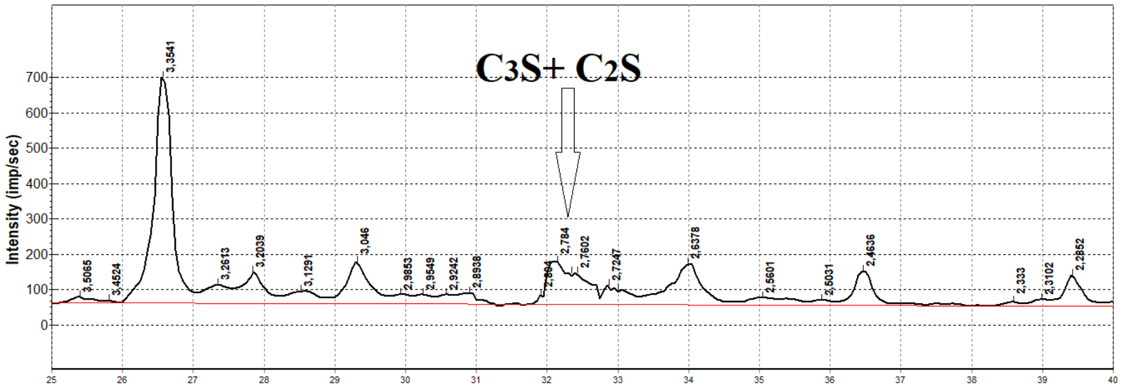
Figure 13. Shrinkage deformations of lightweight concrete.

Fig. 13 shows the evolution of autogenous shrinkage in mixtures containing various aggregates and water adsorptions. The results revealed three phases of hardened concrete growth, including fast shrinkage (Stage I), micro-expansion (Stage II), and continuous shrinkage (Stage III). Stage I lasts around 5 days after “Time zero”, whereas Stage II lasts approximately 8–7 days. The autogenous shrinkage evolution of the performance of concrete built with various particles shows a significant difference. The autogenous shrinkage of the mixes made using recycled aggregate from demolition waste is almost insignificant for the first day before entering a shrinkage stage lasting around 9 days. This remarkable evolution pattern is characterized by little deformation and expansion lasting around 8 days.

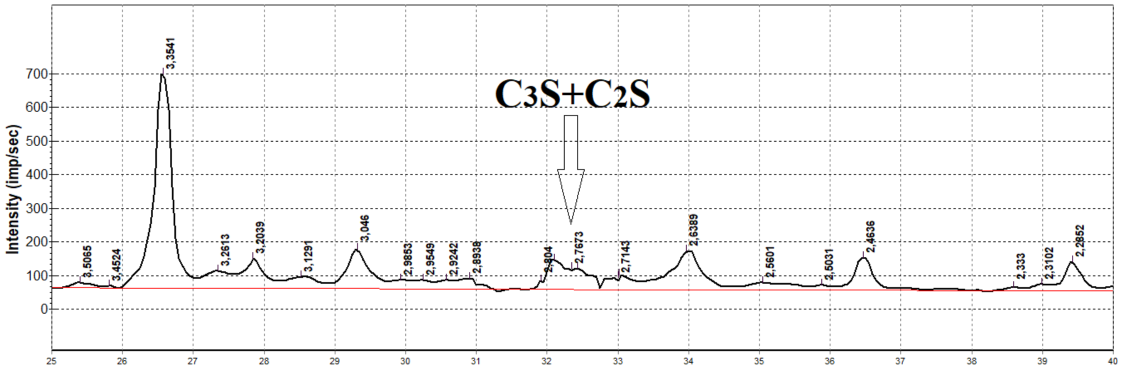
Eventually, it is discovered that the commencement time of Stage III is uniform in all mixtures, and that variances in shrinkage growth during this stage are dependent on the amount of recycled aggregate. In addition, a temperature gradient distribution will be created within the matrix by the thermal energy produced by the hydration reaction of mixes with different aggregates, and thermal deformation will be a major element in how the samples behave when they gradually shrink on their own.

3.5. Cement Hydration in Concrete Mixes using Different Types of Aggregates

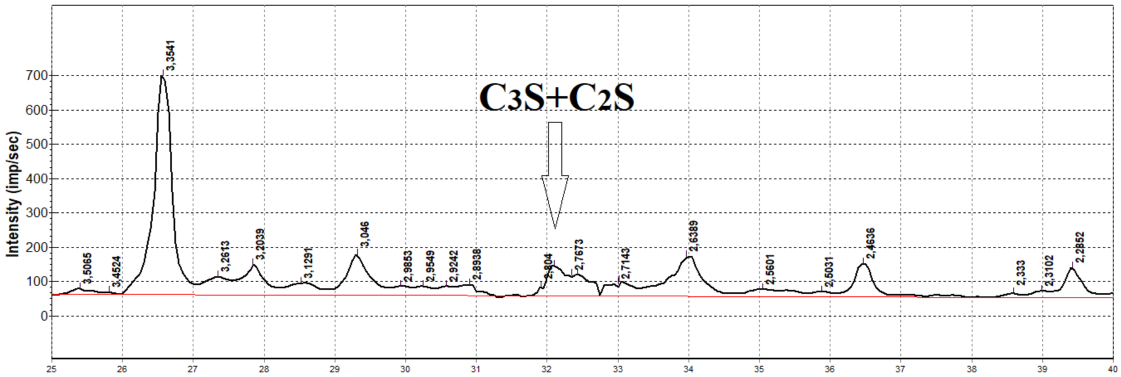
The benefits of reusing recycled aggregate from concrete scrap crushing were discovered using current X-ray phase analysis. An analysis of X-ray patterns of the samples showed that the intensity of C_3S and C_2S reflections decreases with the transition from a sample LW-1 to a sample LW-5. The sample LW-1 (without recycled aggregate from demolition waste) contains the maximum amount of C_3S and C_2S compared to sample LW-5 (with maximum amount of recycled aggregate), which can harden when interacting with water (Fig. 14).



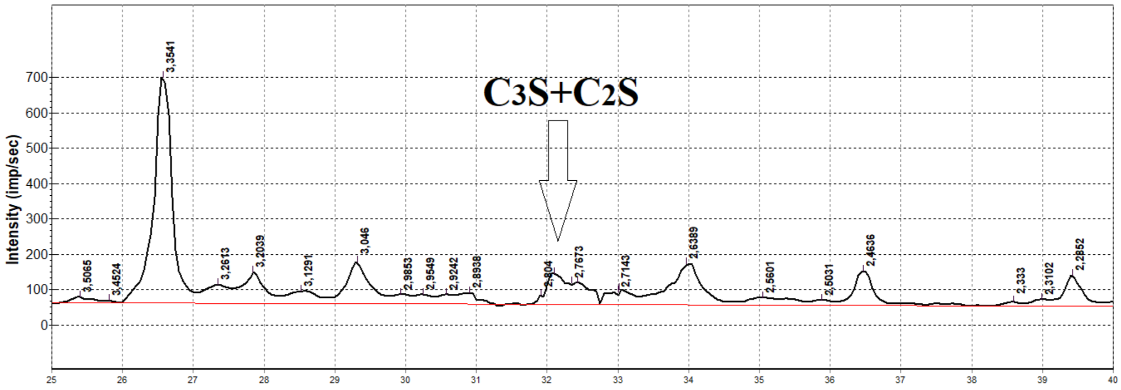
LW-1



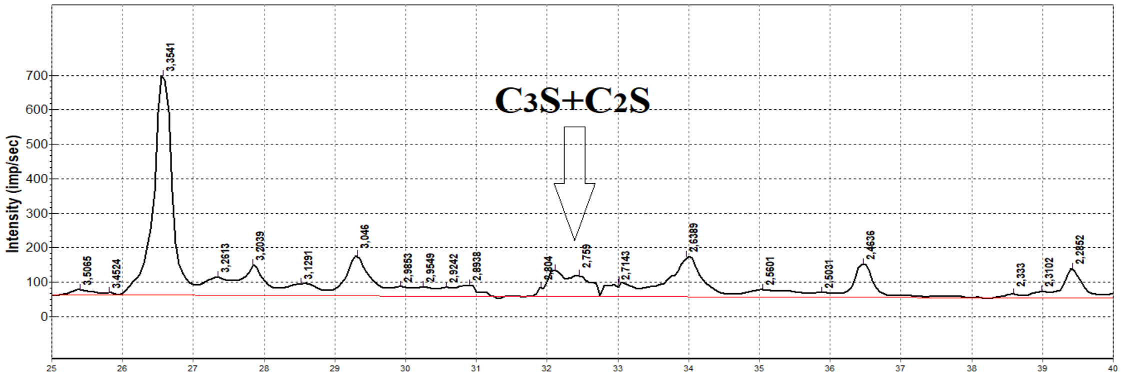
LW-2



LW-3



LW-4



LW-5

Figure 14. X-ray of cement paste, recycled aggregate and expanded clay.

It should be noted that the recycled aggregate from concrete scrap and expanded clay have certain porosity, which is clearly visible. The presence of porosity in the screening of concrete scrap crushing will certainly ensure an increase in the strength of the cement stone in the long term. Water trapped in the pores, as in capsules, will provide an influx of moisture for further hydration of the cement, which explains the increase in compressive strength.

3.6. Abrasion Resistance

In comparison to the reference samples, the abrasion testing results indicated that the samples containing recycled aggregate from demolition waste had a better resistance to abrasion. Table 9 shows results of the abrasion resistance test for lightweight concrete.

Table 9. Abrasion resistance test results for lightweight concrete.

Mix ID	Density, kg/m^3	Compressive strength, MPa	Abrasion, g/cm^2
LW-1	1674	15.2	0.8
LW-2	1658	17.4	0.7
LW-3	1666	19.5	0.6
LW-4	1674	18.2	0.6
LW-5	1671	17.6	0.7

It has been established that the samples LW-3 and LW-4 containing recycled aggregate allow for the production of lightweight concrete with up to 25 % lower abrasion than other samples. It is worth mentioning that the main reason for abrasion resistance is the presence of gravel in the recycled aggregate, which is inherently friction resistant.

4. Conclusions

This paper investigates the potential of reusing demolition waste to solve two problems: disposal of waste and concrete physic and mechanical characteristics. Its high activity is a result of its sharp shape, and high silica and clinker mineral concentration. Based on the results of the study, the following conclusions can be drawn:

1. The mechanical properties of lightweight concrete are produced in a manner similar to using natural sand when construction waste from buildings and other structures is used as a fine aggregate. These properties are the result of the dense development and sprouting of concrete debris onto the cement matrix's surface, which has given them the appearance of being a permanent fixture.
2. The additional cementitious material provides for higher compressive strength and a better contact zone of lightweight concrete when substituting recycled aggregate made from demolition waste. This is due to previously unreacted clinker mineral hydration products, which compact the microstructure of concrete waste. Because more hydration products are formed in a constant volume, the area of the matrix's interfacial transition of cement and aggregate can be compressed. Long-term strength of the cement stone would certainly increase with the existence of porosity, and water trapped in the pores, like in capsules, will give an input of moisture for further hydration of the cement, which explains the increase in compressive strength.
3. The water absorption of crushing screenings of fragments of destroyed buildings and expanded clay is 4 times higher than that of gravel. This explains the high consumption of water, which is absorbed and retained in the pores and microcracks of cement stone and aggregate grains. Lightweight concrete based on cement, recycled aggregate from demolition waste, and expanded clay (LW-2) shows the smallest shrinkage of 0.071 mm/m, which makes it possible to recommend this concrete for use in the construction of residential and civil facilities.
4. An increase in the strength of samples with demolition waste of concrete scrap is explained by the presence of aggregate porosity, which encapsulates a small fraction of water, which provides additional hydration in the absence of water in the surface layers. According to the studies carried out and the results obtained, it can be noted that in order to ensure a normal hydration process, it is necessary to create the essential moist conditions for gaining strength by covering the molded products with a film or tarpaulin with an exposure of up to 28 days.
5. Using recycled aggregate from building waste allows producing lightweight concrete with up to 25 % less abrasion than other samples. It is important to note that the primary reason for abrasion resistance is the presence of gravel in the recycled aggregate, which is naturally abrasion resistant.

In the future, research can be carried out to create completely cement-free binders, in which recycled aggregate and just grinded building waste are used as cement.

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Information about the author:

Ahmed Anees Alani,
ORCID: https://orcid.org/0000-0003-2104-6457
E-mail: ahmed.anees@uoanbar.edu.iq

Received: 02.10.2023. Approved after reviewing: 28.06.2024. Accepted: 28.06.2024.