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Some mechanical properties of normal and recycled aggregate concretes

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Concrete strength;
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Abstract. This paper describes an experimental study conducted to investigate the properties of concretes produced with recycled aggregates and normal aggregates for two different concrete classes (C20/25, C30/37). Tests of compressive strength, splitting tensile strength, ultrasonic pulse velocity, rebound hammer, wet and dry density, and freeze-thaw resistance were conducted on specimens of the concretes. Moreover, slump test was conducted on fresh concrete. The results showed that the slump of Recycled Aggregate Concrete (RAC) was less than that of Normal Aggregate Concrete (NAC). For class C20/25, the average compressive strength, rebound hammer, and density of the RAC were 26%, 17%, and 16.6% less, respectively, than those of NAC. The splitting tensile strength of RAC was 3.5% greater than that of NAC. Moreover, for C30/37 the average compressive strength, splitting tensile strength, rebound hammer, and density of the RAC were 32.5%, 12%, 21% and 30% less, respectively, than those of NAC. For classes C20/25 and C30/37, the ultrasonic pulse velocities of RAC were 17% and 18%, respectively, smaller than those of NAC, RAC for C20/25 lost 2.5% more weight than NAC in freeze-thaw resistance tests and RAC for C30/37 lost 29% more weight than NAC in this test.

1. Introduction

Natural resource protection is one of the most important issues in environmental management. Recycling, reuse, combustion, and landfilling reduce construction and demolition waste.

Landfilling is known to be a cheaper and easier way than recycling to reduce construction waste. The amount of construction and demolition waste in north Cyprus was estimated to be 129,100 tons in 2007 [1]. Cyprus is an island with limited space for landfills; therefore, construction waste recycling is the best method for reducing construction and demolition waste.

The purpose of this research was to examine the mechanical properties of recycled concrete used as aggregate for structural concrete in North Cyprus.

Recycling plants for many demolished materials have existed for several years. Recycling materials offer benefits such as financial savings, and reduce use of natural materials such as wood products, stone ores, water, and energy. Literature shows a growing interest in concrete recycling among academicians and practitioners in various parts of the world, such as the UK, the USA, Canada, Japan, India, Nigeria, and New Zealand.

Movasagh [2] used concrete from back-fill or road sub-base materials in pavements as recycled aggregates. The maximum size of coarse aggregate was 16 mm. He

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Table 1. Chemical composition and physical properties of the cement.

SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Cl (%)	Specific gravity (g/cm^3)	Specific surface area (cm^2/g)
16.12	3.13	6.97	56.52	2.09	2.16	0.02	2.95	4355

compared reinforced concrete with natural aggregates and recycled aggregates. His results showed that compressive strength of concrete with natural aggregates was 35% higher than compressive strength of concrete with recycled aggregates.

Dosho [3] in Japan replaced 30% and 50% of recycled coarse aggregates from a building with 30 years of age. He obtained 32.6-35.8 MPa compressive strength after 28 days with standard curing conditions.

Butler et al. [4] focused on characterizing two recycled concrete aggregate sources in Ontario and produced a novel concrete containing recycled concrete aggregate as the coarse aggregate. They found that "the recycled aggregates had lower densities and higher absorption capacities than the natural aggregates. "In the 30-MPa direct-replacement mixtures that they studied, both types of recycled aggregate concretes had higher compressive strength values than the natural aggregate concrete.

Limbachiya et al. [5] used samples of four diverse sources. Recycled concrete aggregate samples were made of aggregate sizes between 5 mm and 20 mm, and the maximum size of natural aggregates used was 20 mm. Their results showed that the density of recycled concrete aggregate was 3% to 10% less than that of natural aggregate and the water absorption of recycled concrete aggregate was 3 to 5 times more than that of natural aggregate in the saturated surface dry state, due to the porosity of mortar around the recycled concrete aggregate.

Arum [6] found that the workability of virgin aggregate concrete is better than that of recycled aggregate concrete at the same water/cement (w/c) ratio. The compressive strength of recycled aggregate concrete tends to be lower than that of virgin aggregate concrete at low w/c ratios. At higher w/c ratios, the compressive strength of recycled aggregate concrete is similar to that of virgin aggregate concrete.

Jeong [7] used concrete structures at Chicago's O'Hare Airport to study recycled coarse aggregate. He found that a Two-Stage Mixing Approach (TSMA) is an effective technique for increasing the strength of an RAC mixture. TSMA consists of the following steps. First, coarse and fine aggregates are mixed for 60 seconds and half of the water to be used for the specimen is then added and mixed for another 60 seconds. Second, cementitious material is added and mixed for 30 seconds. Third, the rest of the water is added and mixed for 120 seconds. TSMA produces a thin layer of cement slurry on the surface of recycled aggregates, which is expected to permeate the porous old mortar and fill the old cracks and voids.

2. Experimental details

2.1. Materials

2.1.1. Cement

ASTM Type I Portland cement was used in this study. Properties of the cement are shown in Table 1.

2.1.2. Recycled Aggregates (RA)

Three different nominal sizes of recycled aggregates were chosen: 5 mm, 13 mm, and 23 mm. Concrete from a laboratory waste yard was taken to an aggregate crusher plant and crushed to predetermined sizes using a jaw crusher. Based on the particle size requirements of BS 812-112 [8], two sizes of recycled coarse aggregates (13 mm and 23 mm) were used.

The properties of recycled aggregates were also tested according to BS 812-112 [8] methods. Figure 1 shows the grading curve for recycled aggregates.

Natural fine and coarse aggregates were obtained from the Beşparmak Mountains for use as crushed limestone in this study. Based on the particle size requirements of BS 812:1990, four different nominal sizes of natural aggregates were selected: 5 mm, 10 mm, 14 mm, and 20 mm.

The properties of aggregates are given in Table 2.

2.2. Concrete mixes

This study compared concretes made with recycled aggregates and natural aggregates in two classes (C20/25, C30/37). Concrete mixes were designed using the BRE method [9]. A variety of mix designs were developed

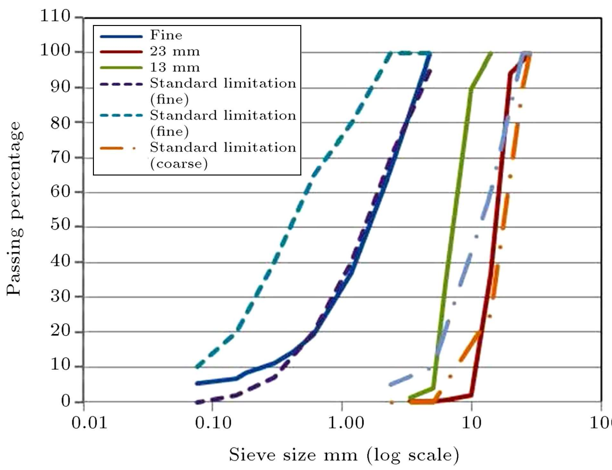

Figure 1. Grading curve for recycled aggregates.

Table 2. Properties of the recycled and normal aggregates.

Aggregate type (size)	Properties			
	Water absorption (%)	Specific gravity (SSD)	Crushing value (%)	Aggregate impact value (%)
RA (5 mm)	5.49	2.48	27.13	31.60
RA (13 mm)	5.22	2.47	27.13	31.60
RA (23 mm)	5.18	2.47	27.13	31.60
NA (5 mm)	2.06	2.74	23.42	16.52
NA (10 mm)	0.47	2.70	23.42	16.52
NA (14 mm)	0.76	2.68	23.42	16.52
NA (20 mm)	1.50	2.65	23.42	16.52

Table 3. Concrete mix proportions.

Mix type	Cement (kg/m^3)	Water (kg/m^3)	w/c	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)				
				D5	D10	D13	D14	D20	D23
Mix A (NC)	350	225	0.65	876	237	—	380	332	—
Mix B (NC)	450	225	0.46	828	224	—	359	314	—
Mix C (RC)	350	316	0.90	876	—	474	—	—	474
Mix D (RC)	450	311	0.69	828	—	448	—	—	448

by varying the cement contents and w/c ratios. The proportions of concrete mixes are shown in Table 3.

Four types of concrete mixes were prepared with w/c ratios of 0.65 and 0.9 for concrete class C20/25 and 0.46 and 0.68 for concrete class C30/37. The cement contents were 350 kg/m^3 and 450 kg/m^3 for the C20/25 and C30/37 classes, respectively.

Recycled aggregate concrete was made with 100% fine and coarse recycled aggregates. The mix proportions of the concrete mixes are shown in Table 3.

2.3. Specimen casting and curing

For each concrete mix, 150-mm cubes and cylinders of 100 mm diameter and 200 mm height were cast. The cubes were used to determine the compressive strength of concrete mixes by crushing and using a rebound hammer. Ultrasonic Pulse Velocity (UPV) and freeze-thaw resistance tests were also conducted on the cubic samples. The cylinders were used to evaluate the splitting tensile strength of concrete mixes. The cubes and cylinders specimens were cast in plastic and steel molds, respectively. After casting and compacting the concrete samples, the samples were placed in a curing room at a relative humidity of more than 90% and a temperature of 21°C for 24 hours. The samples were then placed in a curing tank and kept at a temperature of 27±2°C until testing at the 7th, 14th, and 28th days.

2.4. Tests

2.4.1. Workability

Slump test was the only one type of test performed on the fresh concrete mixes. This test was performed according to BS EN 12350-2 [10].

2.4.2. Hardened density of concrete

Concrete cube specimens were used to determine the Saturated-Surface-Dry (SSD) density of concretes in accordance with BS EN 12390-7 [11].

2.4.3. Compressive strength and splitting tensile strength

BS EN 12390-3:2009 was considered for evaluation of the compressive strength of cubes. Loading speed was adapted to be 0.6 ± 0.2 MPa/s (BS EN 12390-3:2009). These tests were performed on samples at the ages of 7, 14, and 28 days.

Splitting tensile strength tests were performed on cylinder samples at the ages of 7, 14, and 28 days.

2.4.4. Ultrasonic Pulse Velocity (UPV)

Ultrasonic pulse velocity tests, which are nondestructive tests for measuring porosity, were performed on cubic samples at 28 days. Waves were propagated by direct transmission. For each cube, one measurement was conducted (BS 1881: Part 201) [12].

2.4.5. Rebound hammer

Rebound hammer tests, which are nondestructive tests for measuring surface hardness and thereby estimating compressive strength, were performed on cubic samples. During the process of compressive strength test, 10 times were exerted on one side of the sample in horizontal direction (BS 1881: Part 201) [12].

2.4.6. Accelerated freeze-thaw resistance testing

Accelerated freeze-thaw testing was conducted according to TS 699 [13] using a sodium sulfate solution to measure the freeze-thaw resistance of concretes.

Table 4. Slump test results.

Mix design	Slump (cm)
A	15
B	14
C	14
D	13

3. Results and discussion

3.1. Workability

Slump test was conducted for each mix design. Table 4 shows the results of the slump test.

According to the obtained results, slump was decreased by increasing amount of water.

The main reason for mix design A having high slump was low water/cement ratio (0.65). Three types of coarse aggregates were used in mix design A.

In mix design C, the water/cement ratio was increased to 0.9 because of using two types of coarse aggregates.

The slump test results indicated that slump decreased with increasing water content. The main reason for mix designs A and B having high slump values was their lower w/c ratio than the w/c ratio of mix designs C and D. It means that in C20/25, w/c ratio changed from 0.65 to 0.9, and in C30/37, w/c ratio changed from 0.46 to 0.68.

3.2. Hardened density of concrete

Based on BS EN 12390-7 [11], hardened concrete density was determined for each mix design. The curing condition for specimens used in this test was water curing.

Density increased with increasing w/c ratios for all of the mix designs. Increasing the amount of water increases the mass of concrete, so the hardened density of mix design B was a little lower than the density of mix design A, and the density of mix design D was lower than that of mix design C.

3.3. Compressive strength and splitting tensile strength

Compressive tests were performed on cubic samples at the 7th, 14th, and 28th days. The results of compressive strength tests of concrete are given in Table 5. In this table, every strength value is an average of five test

Table 5. Compressive strength of concrete mixes (MPa).

Age (days)	Mix design A	Mix design B	Mix design C	Mix design D
7	17.30	25.22	11.57	15.34
14	24.58	30.90	16.08	22.70
28	28.60	38.74	21.22	26.24

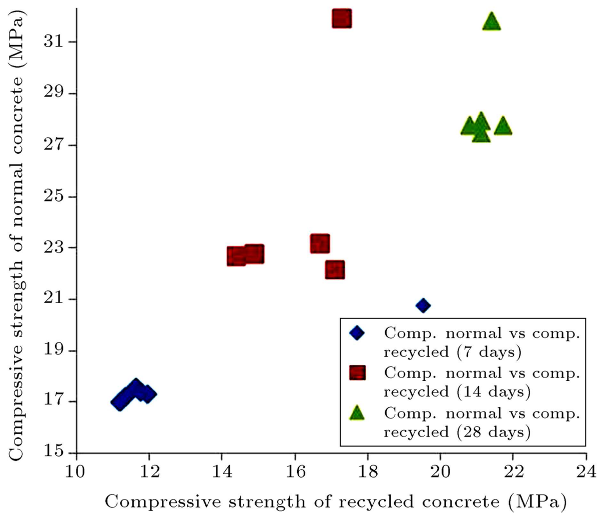

Figure 2. Compressive strength of normal concrete versus compressive strength of recycled aggregate concrete in 7, 14, and 28 days (mix designs A and C).

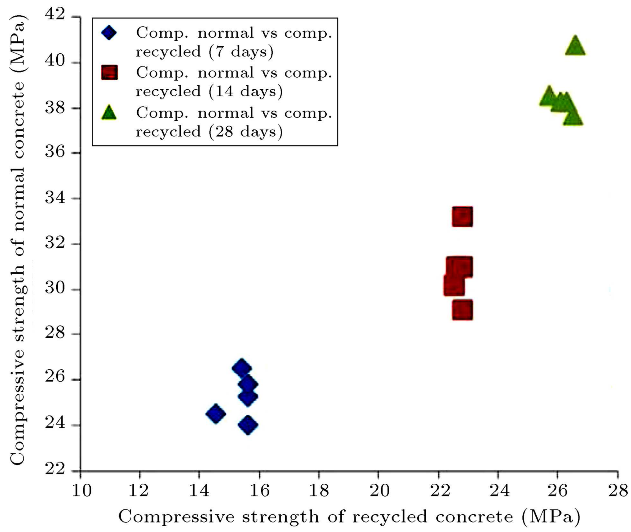

Figure 3. Compressive strength of normal concrete versus compressive strength of recycled aggregate concrete in 7, 14, and 28 days (mix designs B and D).

results. Figures 2 and 3 show comparisons between the compressive strengths of recycled aggregate concretes and those of normal concretes. Because of 100% recycled coarse aggregate replacement and the increased w/c ratio used for the recycled aggregate concrete mixes, and because the recycled aggregates were not washed, the compressive strengths of both types of recycled aggregate concretes (C20/25 and C30/37) were approximately 30% lower than the compressive strengths of corresponding normal concretes. Similarly, Lin [14] found that the compressive strength of recycled concrete with 100% recycled coarse aggregate is approximately 30% less than the compressive strength of normal concrete. Yamato et al. [15] found that with replacement of 30%, 50%, and 100% coarse aggregates,

Table 6. Average splitting tensile strength, ultrasonic pulse velocity, and rebound hammer results for cylinder samples in 28 days.

Tests	Mix design A	Mix design B	Mix design C	Mix design D
Splitting tensile strength (MPa)	2.92	3.38	3.02	2.98
Ultrasonic pulse velocity (km/s)	3.74	3.78	3.17	3.24
Rebound hammer (MPa)	26.90	30.72	22.42	24.24

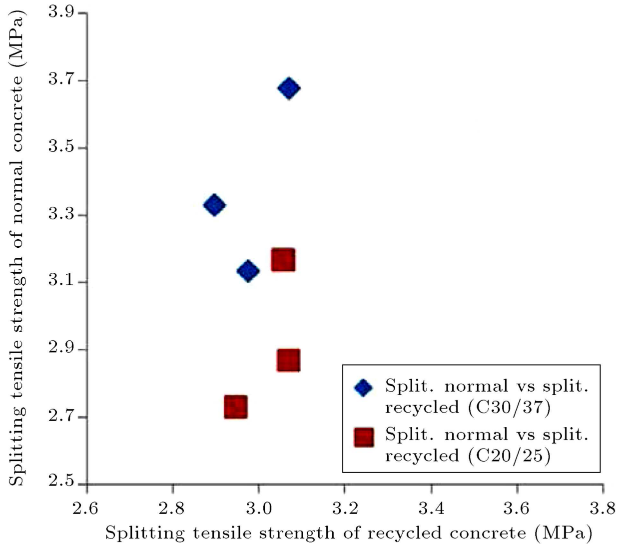

Figure 4. Splitting tensile strength of normal concrete versus splitting tensile strength of recycled aggregate concrete in 28 days.

compressive strengths decreased by 20%, 30%, and 45%, respectively.

Splitting tensile strength testing was conducted on cylinder samples (100×200 mm) in 28 days. The averages of results of this test are shown in Table 6.

Figure 4 presents a comparison of splitting tensile strengths of normal concrete and recycled aggregate concrete.

Increasing the w/c ratio, for C20/25, from 0.64 to 0.9 decreased the splitting tensile strength by 3.4%, and increasing the w/c ratio, for C30/37, from 0.5 to 0.69 decreased the splitting tensile strength by 12%.

According to Figure 4, there is a linear relation between the splitting tensile strengths of normal concretes tested and the splitting tensile strengths of recycled concretes tested.

Figures 5 and 6 provide comparisons between compressive strength and splitting tensile strength in 28 days.

As shown in Figures 5 and 6, the compressive strengths for both types of concretes (normal and

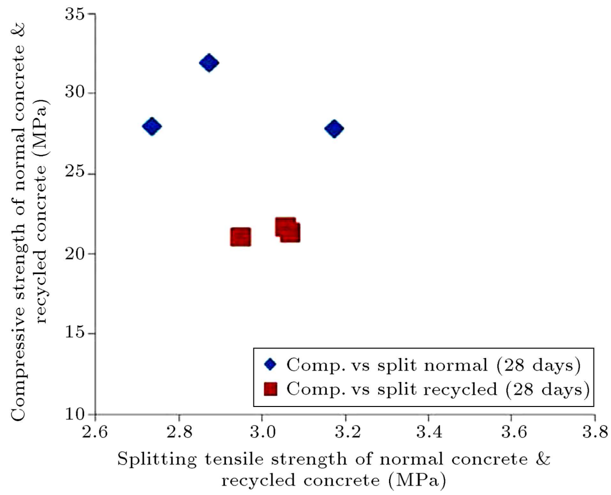

Figure 5. Compressive strength versus splitting tensile strength in 28 days (mix designs A and C).

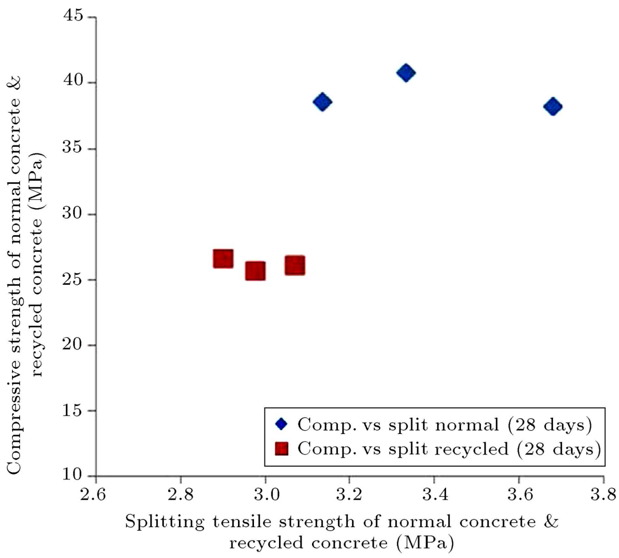

Figure 6. Compressive strength versus splitting tensile strength in 28 days (mix designs B and D).

recycled) were linearly related to the splitting tensile strength. The splitting tensile strength and compressive strength both increased with increasing cement content. Similar findings were reported by Sagoe-Crentsile et al. [16].

3.4. Ultrasonic Pulse Velocity (UPV)

UPV was measured to have an idea about the quality of concrete which may be indirectly considered as strength or density. A higher value of UPV means that concrete is denser so that sound wave travels faster. Moreover, the modules of elasticity are related to the strength of concrete.

Table 6 shows the average results from ultrasonic pulse velocity tests, and Figures 7 and 8 show comparisons between the compressive strength results and the ultrasonic pulse velocity results in 28 days.

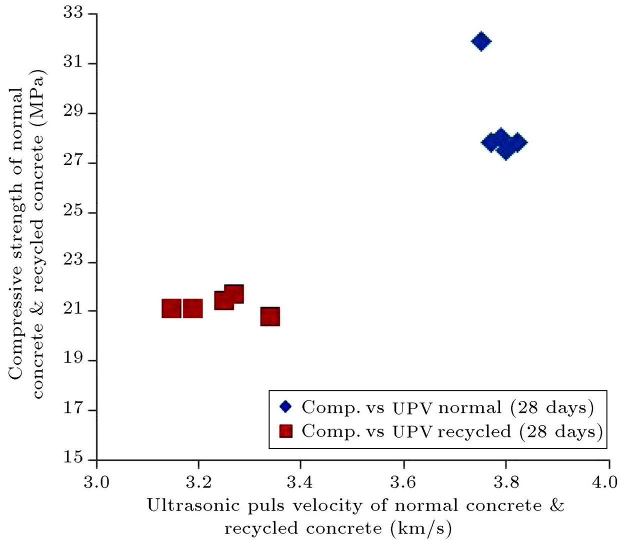

Figure 7. Compressive strength versus ultrasonic pulse velocity in 28 days (mix designs A and C).

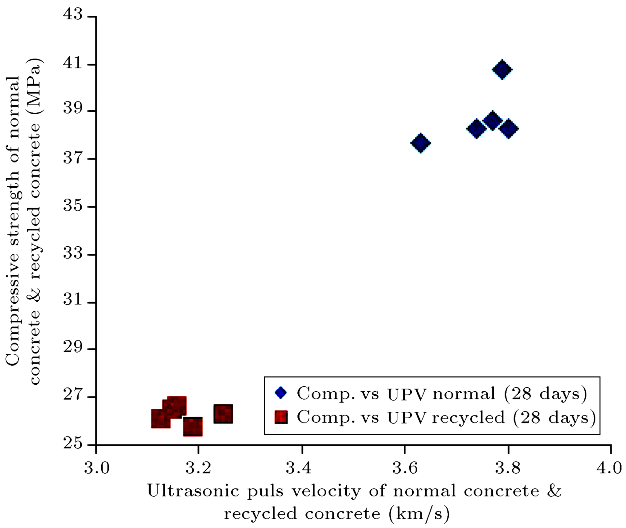

Figure 8. Compressive strength versus ultrasonic pulse velocity in 28 days (mix designs B and D).

Angulo and Muller [17] stated that reducing the compressive strength by approximately 65% increases porosity by 0% to 40%. In this research, when the compressive strengths were decreased by 25.8% and 32.26%, the UPVs were decreased by 15.24% and 14.28% for C20/25 and C30/37, respectively. Trtnik et al. [18] studied the influence of aggregate on the compressive strength of concrete based on UPV. They found that the amount of aggregate in concrete does not affect the UPV and compressive strength to the same degree. Moreover, in some cases, a higher aggregate content can cause an increase in the UPV and a decrease in compressive strength. Madandoust et al. [19] achieved a higher UPV for a fine aggregate/coarse aggregate ratio of 0.8 to 1.0 by increasing the compressive strength. Curing conditions seem to be less important than the amount of cement used. They found that in 3 days, for a fine aggregate/coarse aggregate ratio of 0.9, the effect of compressive strength on the UPV is less significant than the effect of w/c ratio. The influence of w/c ratio on the UPV-compressive strength relationship was not very significant during the first 7 days, but at later ages, the w/c ratio had a greater effect on the results, and this is more pronounced for higher values of UPV. The effect of w/c ratio can be explained by the fact that an increase in w/c ratio increases the volume of capillary pores, which results in a reduction in the ultrasonic pulse velocity. This phenomenon will also lead to a reduction in the concrete compressive strength. The compressive strength also increases with age, especially between 14 and 42 days. There is an inverse relationship between the volume of pores and the compressive strength as well as between the volume of pores and the ultrasonic pulse velocity. The volume of capillary pores in hydraulic cement paste decreases with time, because the degree of hydration of cement depends on the duration of hydration as well as the curing conditions. The UPV-compressive strength relationship has a steeper slope for concretes with low w/c ratios. This is most probably due to an increase in the rate of hydration for the corresponding ratio. Trtnik et al. [18] found that increasing the amount of water increased the ultrasonic pulse velocity and decreased the compressive strength.

3.5. Rebound hammer

The results of rebound hammer tests and compressive strengths are shown in Table 7; also, Figures 9 and 10 show comparisons between the splitting tensile strength results and the rebound hammer results in 28 days.

The rebound hammer test result value increases with increasing compressive strength.

Table 7. Results of compressive strength and rebound hammer tests in 28 days.

Tests	Samples	Mix design A	Mix design B	Mix design C	Mix design D
Compressive strength (MPa)	No. 1	31.90	38.60	21.40	25.70
	No. 2	27.80	40.80	21.70	26.60
	No. 3	28.00	38.30	21.10	26.10
	No. 4	27.50	38.30	21.10	26.30
	No. 5	27.80	37.70	20.80	26.50
Rebound hammer (MPa)	No. 1	29.00	30.70	24.00	24.40
	No. 2	25.40	34.70	21.70	23.30
	No. 3	27.00	29.70	23.30	25.00
	No. 4	26.50	26.40	20.60	24.40
	No. 5	26.60	32.10	22.50	24.10

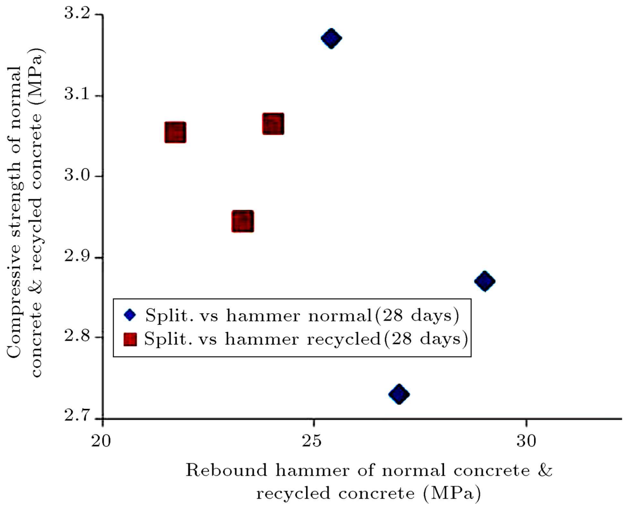

Figure 9. Splitting tensile strength versus rebound hammer in 28 days (mix designs A and C).

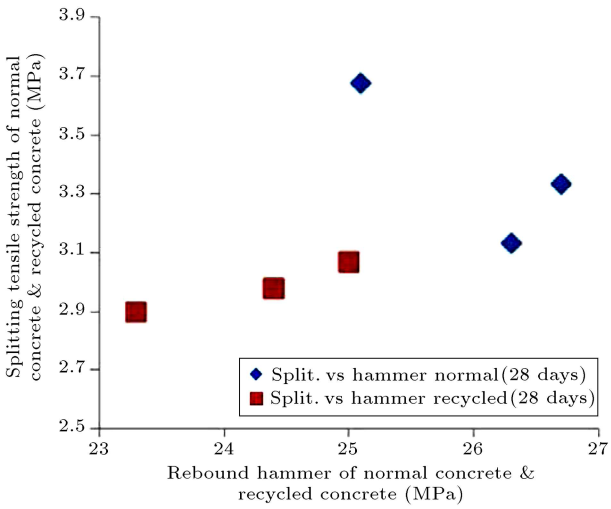

Figure 10. Splitting tensile strength versus rebound hammer in 28 days (mix designs B and D).

The rebound hammer results can be related to the surface hardness of aggregates. In accordance with BS 1881: Part 201 [12], the rebound hammer test results are related to the concrete density of surface. Sagoe-Crentsil et al. [16] found that recycled concrete aggregates are lower in density than natural aggregates because of the porous and less dense residual mortar lumps that adhere to the surfaces of recycled concrete aggregate particles. The residual mortar percent by volume increases with increasing particle size. By increasing the maximum size of coarse aggregates in both concrete classes, C20/25 and C30/37, and for both normal and recycled aggregates 20 to 23 mm in size, the amount of adhered mortar volume increases. As a result, density decreases for each concrete class (16.6% density decrease in C20/25 and 21% density decrease in C30/37).

Based on the rebound hammer test results, when surface hardness values decreased for recycled and normal concretes, the ultrasonic pulse velocity test decreased.

3.6. Freeze-thaw resistance

The results of the freeze-thaw resistance tests are shown in Table 8 and Figure 11.

The bar chart shows that mix design B, which had a higher cement content, lost more weight than the other mix designs. The weight loss percentage for mix design B was approximately 80%.

Accelerated freeze-thaw resistance of concrete was calculated by Eq. (1):

$$K_d = \frac{G_0 - G_1}{G_0} \times 100, \tag{1}$$

where:

$K_d =$ Accelerated freeze-thaw resistance of concrete (%);

$G_0 =$ Initial mass of test sample (gr);

$G_1 =$ Mass of the retained sample on the sieve after test (gr).

Eq. (1) was used for each group and total freeze-thaw resistance was calculated by Eq. (2):

$$K_{dt} = 0.5 \times K_{d1} + 0.3 \times K_{d2} + 0.2 \times K_{d3}, \tag{2}$$

where:

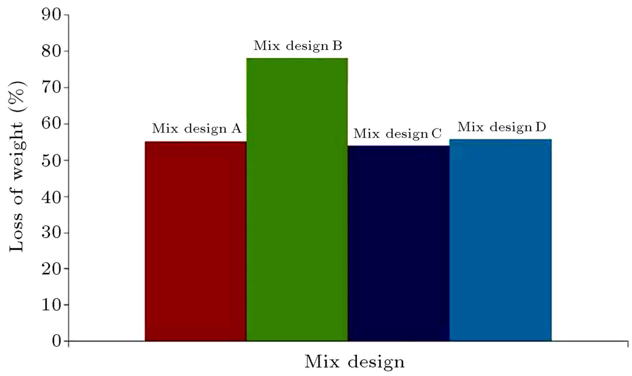

Figure 11. Weight loss after freeze-thaw tests for various concrete types.

Table 8. Results of freeze-thaw resistance tests.

Accelerated freeze-thaw resistance	Mix design A	Mix design B	Mix design C	Mix design D
K_{d1} (%)	64.75	86.55	56.65	61.05
K_{d2} (%)	52.40	71.20	50.40	49.60
K_{d3} (%)	35.00	67.00	52.00	52.00
K_{dt} (%)	55.09	78.03	53.84	55.80

K_{dt} = Total accelerated freeze-thaw resistance of concrete (%);

K_{d1} = Accelerated freeze-thaw resistance of sample between 37.5 mm-20 mm sieve (%);

K_{d2} = Accelerated freeze-thaw resistance of sample between 20 mm-10 mm sieve (%);

K_{d3} = Accelerated freeze-thaw resistance of sample between 10 mm-5 mm sieve (%).

4. Conclusions

The general conclusions of this study are as following:

1. The slump of RAC was less than that of NAC due to higher water absorption;
2. The compressive strength of recycled aggregate concrete was 35% less than that of normal aggregate concrete for the same amount of cement;
3. The splitting tensile strength of recycled aggregate concrete was 15% less than that of normal aggregate concrete for the same amount of cement;
4. The rebound hammer test values for recycled aggregate concrete were 18% lower than those of normal aggregate concrete;
5. The ultrasonic pulse velocity results for RAC were 15% smaller than those for NAC;
6. The density of recycled aggregate concrete was 8% lower than that of normal aggregate concrete;
7. The loss in weight due to accelerated freeze-thaw testing of recycled aggregate concrete was 20% greater than that of normal aggregate concrete.

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Biographies

Kani Akhavan Kazemi received the BEng degree in Civil Engineering from the University of Applied

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Özgür Eren received all of his degrees in Civil Engineering as BEng degree from Eastern Mediterranean University, MSc degree from the University of Leeds, and PhD degree from Eastern Mediterranean University. He has been teaching courses on Civil Engineering materials, material sciences, and concrete repair and maintenance at the undergraduate and graduate levels since February 2000. Professor Eren has more than 50 research articles published. His research interests are fiber reinforced concrete, natural building stones, recycling of concrete, assessment of buildings, high strength of concrete, and use of pozzolans in cement. He supervised many MSc and PhD theses. Currently, he is the chair of Civil Engineering Department, Eastern Mediterranean University.

Alireza Rezaei received his BEng degree in Civil Engineering from Tabriz University, Tabriz, Iran, in 1997, and his MSc degree in Civil Engineering, Structure of Mechanics from Mazandaran University of Science and Technology, Babol, Iran, in 2000. He graduated from Eastern Mediterranean University, North Cyprus, in 2011 with the PhD degree in Civil Engineering, Construction Technology and Management. His research interests are mainly concentrated on construction industry by special focus on quality management, value management, occupational safety management, waste management, and risk management.