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Compressive Strength and Capillary Water Absorption of Concrete Containing Recycled Aggregate

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Abstract**—**This paper presents results of compressive strength, capillary water absorption, and density tests conducted on concrete containing recycled aggregate (RCA) which is obtained from structural waste generated by the construction industry in Turkey. In the experiments, 0%, 15%, 30%, 45% and 60% of the normal (natural) coarse aggregate was replaced by the recycled aggregate. Maximum aggregate particle sizes were selected as 16 mm, 22,4 mm and 31,5 mm; and 0,06%, 0,13% and 0,20% of air-entraining agent (AEA) were used in mixtures. Fly ash and superplasticizer were used as a mineral and chemical admixture, respectively. The same type (CEM I 42.5) and constant dosage of cement were used in the study. Water/cement ratio was kept constant as 0.53 for all mixture. It was concluded that capillary water absorption, compressive strength, and density of concrete decreased with increasing RCA ratio. Increasing in maximum aggregate particle size and amount of AEA also affect the properties of concrete significantly.

Keywords**—**Capillary water absorption, compressive strength, density, recycled concrete aggregates.

I. Introduction

CONSTRUCTION sector is a sector consuming natural resources rapidly, and which may generate billions of tons of waste and may impact sustainable development negatively [1]. Accordingly, evaluating building wastes generated as a result of construction processes or demolition of the buildings by a conscious waste management planning is required. Waste management is a method of management including reducing wastes in their source, separating according to their properties, collecting, temporary storing, recovering, carrying, disposing, controlling after disposing process and similar processes [2]. By waste management, considering building wastes as a source to be evaluated instead of a pollution to be eliminated shall be an approach providing economic and environmental benefit.

Natural aggregate which is the most important raw material of construction sector having a wide area is consumed approximately 8-12 billion tons every year in the World [3]. This situation has brought out the need for alternative aggregate resources. For example, by breaking old concrete obtained from demolition of a building, concrete aggregate may either be reused as materials for pavement subbases in road construction. Heavy matrix of concrete makes it a recyclable material which can be used as the same or with a slight strength and performance loss. However, a sufficient awareness could not be created yet. Recycled aggregate usage is quite limited and is generally preferred for non-structural components [4]. In this study, some physical and mechanical properties of concretes produced by using recycled aggregate (RCA) were examined.

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II. Materials and Methods

Normal Portland Cement (CEM I 42,5R), river sand as fine aggregate, limestone based crushed stone as normal (natural) coarse aggregate, and 0-0.125 mm size limestone powder as filler material were used in the experiments. As mineral admixture Class F fly ash, as chemical admixture modified synthetic carboxylate polymer based new generation superplasticizer concrete admixture (specific gravity 1,085 g/cm^3) and air-entraining agent (AEA, specific gravity 1,010 g/cm^3) were used. As RCA, 4-31.5 mm size aggregates supplied from the recycling facility of Istanbul Environmental Management in Industry and Trade Inc. (ISTAÇ) were used. Some physical properties of aggregates determined according to the relevant Turkish Standards were given in Table I, and specific gravities of the aggregates were given in Table II.

TABLE I
SOME PHYSICAL PROPERTIES OF AGGREGATES

	Water Absorption (%)	Abrasion Ratio (%)	Mass loss in Freeze –Thaw Tests (%)
Crushed stone (NA)	0,96	15,4	0,95
RCA	6,94	38,04	13,75
Fine Aggregate	4,99	-	-

A. Parameters, Levels and Coding

In mixtures; water/cement ratio as 0.53, binding dosage as 350 kg/m^3, fly ash ratio as 15% (by substituting with cement) and superplasticizer ratio as 1.5% were kept fixed. On the other hand, RCA ratio in five (0%, 15%, 30%, 45% and 60%), maximum aggregate particle size (d_{max}) in three (16mm, 22.4 mm and 31.5 mm), and AEA ratio in three (0.06%, 0.13% and 0.20%) different levels were examined. 45 mixtures were produced in accordance with these parameters and their levels.

In the study, the following way was followed in relation with coding: the first three characters indicate maximum particle size; the following three (two in control samples) characters indicate RCA ratio (as percent), and the last two or three characters indicate AEA ratio (as in ten thousandths). Accordingly, 31D60G20A shows concrete including 31.5 mm maximum aggregate particle size, 60% RCA ratio, and 0.20% AEA ratio.

B. Mixing Proportions

In the study, being fixed for all mixtures, it was taken cement as 297.5 kg/m^3, fly ash as 52.5 kg/m^3, water as 185.5 kg/m^3 and superplasticizer as 5.3 kg/m^3. AEA was taken as; 0.2 kg/m^3 for the ratio of 0.06%, 0.5 kg/m^3 for the ratio of 0.13%, and 0.7 kg/m^3 for the ratio of 0.20%.

Aggregate ratios were determined as:

i. Filler material in ratio of 5% of the total aggregate volume was taken fixed as 93.4 kg/m^3 for all mixtures.
ii. The remaining aggregate volume was distributed equally (i.e., in the ratio of 25%) for each aggregate fractions (i.e., 0/2, 2/4, 4/8 and 8/d_{max}).
iii. Fine aggregate ratio was taken constant. Accordingly, aggregate fraction 0/2 as 392 kg/m^3, aggregate fraction 2/4 as 408 kg/m^3 were taken fixed for all mixtures.
iv. Coarse aggregates were added to mixtures differently according to aggregate fractions. Accordingly; for series d_{max} =16 mm, two aggregate fractions (4/8 and 8/16), for series d_{max} =22.4 mm, three aggregate fraction (4/8, 8/16 and 16/22.4), and for series d_{max}=31.5 mm, four aggregate fraction (4/8, 8/16, 16/22.4 and 22.4/31.5) were determined. In all mixtures, for aggregate fraction 4/8, NA+RCA ratio was 25%. For 8/d_{max}, for two (8/16 and 16/22.4), and three (8/16, 16/22.4 and 22.4/31.5) aggregate fractions, total of NA+RCA ratio was 25%. In the study, only normal coarse aggregate was replaced with the same particle size of RCA in the ratio of 0%, 15%, 30%, 45% and 60%.

By following the method explained above, mix design made for 31D60G20A coded sample was given in Table II.

TABLE II
MIX PROPORTION FOR 31D60G20A CODED CONCRETE

Ingredient (Ratio)		Specific gravity	Weight (kg)	Volume (dm^3)
Cement		3,13	297,5	95,0
Water		1,00	185,5	185,5
Fly Ash (%15)		2,33	52,5	22,5
Superplasticizer (%1,5)		1,09	5,3	4,8
Air Content (%1)		-	0,0	10,0
Air-entraining agent (%0,20)		1,01	0,7	0,7
Filler (%5)		2,74	93,3	34,1
Aggregate (647.35 dm^3):				
	0/2 (25%)	2.42	391.6	161.8
	2/4 (25%)	2.52	407.8	161.8
Normal Aggregate (NA)	4/8 (10%)	2.63	170.2	64.7
	8/16 (3.33%)	2.68	57.8	21.6
	16/22.4 (3.33%)	2.68	57.8	21.6
	22.4/31.5 (3.33%)	2.71	58.4	21.6
RCA	4/8 (15%)	2.25	218.5	97.1
	8/16 (5%)	2.30	74.4	32.4
	16/22.4 (5%)	2.37	76.7	32.4
	22.4/31.5 (5%)	2.35	76.1	32.4
TOTAL			2071.5	1000.0

C. Experimental Details

In the study, capillary water absorption test, compressive strength test and density test were performed on hardened concrete samples. All three tests were performed on 15cmx15cmx15cm sized cube samples and details of each test were given below.

Capillary water absorption tests were performed according to TS EN 13057 [5] and ASTM 1585 [6]. In this test, samples were left in water (leaving 5mm part in water) and amount of water absorption in the 1, 4, 9, 16, 25, 36, 49 and 64th minutes (t, min) were determined by weighing on digital balance with 0.1 gr sensitivity (Q, cm^3). Surface area dimensions of the samples contacting water (F, cm^2) were measured by a caliper. Capillary water absorption coefficient (K, cm^2/sn) was determined by the help of (1). In this study, results of the calculations were obtained from the mass increase in the end of 64 minute period.

$$K = Q^2 / (F^2 \times t) \tag{1}$$

Samples taken out of water curing after the 27th day were kept in laboratory for a day and their compressive strengths were determined. The compressive strength tests were performed according to TS EN 12390-3 [7] and 3000 kN capacity press was used in the tests. While the tests were performed, loading rate was taken as 0.4 MPa/s.

In hardened concrete samples, density tests were performed according to TS 12390-7 [8]. Mass (m, g) and volume (V, cm^3) of the samples were determined after the samples were saturated and dried, and then, densities of concrete (D, g/cm^3) were found by proportioning these two values.

III. EXPERIMENTAL RESULTS AND EVALUATION

Results of the hardened concrete tests performed on concrete series produced within the scope of the study were given in Table III. Evaluations of the experimental results were made separately for each property below.

A. Evaluation of the Results of Capillary Water Absorption Test

On the basis of the experimental results given in Table III, effects of the parameters on water absorption coefficients of concretes were given in Fig. 1.

As it may be seen in Fig. 1, as maximum aggregate particle size increases, capillarity coefficients of hardened concretes have significantly reduced. A similar situation was seen when amount of AEA was increased. However, decrease in capillarity coefficient as AEA was increased has been less when compared to that of maximum aggregate particle size. It is evaluated that as maximum aggregate particle size is increased, diameters of capillary voids in concrete have grown large and accordingly, capillary absorption has reduced (Jurin's Law). As pores formed by air entraining are free from each other and have spherical shapes [9], it may be stated that these pores block capillary voids and prevent water transport or slow down water progress and accordingly reduce capillary absorption of concretes. On the other hand, as it is seen in Fig. 1, although we cannot make a definite judgement for the effect of increase in RCA ratio in the mixture on capillary absorption of concretes, it can be said that these aggregates affect capillary absorption rate in a reducing way even if it is quite little.

TABLE III
HARDENED CONCRETE TEST RESULTS

CODE	Water Abs. Coef., Kx10^{-7} (cm^2/sn)	Comp. Strength (MPa)	Density (G/CM^3)	CODE	Water Abs. Coef., Kx10^{-7} (cm^2/sn)	Comp. Strength (MPa)	Density (g/cm^3)
16D0G6A	18.67	34.7	2.24	22D30G20A	7.11	14.1	2.01
16D0G13A	12.00	29.4	2.19	22D45G6A	16.44	25.7	2.08
16D0G20A	15.78	27.4	2.13	22D45G13A	12.22	16.0	1.96
16D15G6A	22.67	32.2	2.18	22D45G20A	9.78	16.8	1.98
16D15G13A	21.78	20.7	2.02	22D60G6A	15.11	25.6	2.08
16D15G20A	22.89	23.5	2.08	22D60G13A	10.44	16.6	1.98
16D30G6A	17.78	28.2	2.13	22D60G20A	12.22	18.9	1.99
16D30G13A	16.89	23.0	2.04	31D0G6A	12.67	25.4	2.21
16D30G20A	15.56	12.9	1.88	31D0G13A	10.89	13.7	1.96
16D45G6A	24.00	21.2	1.97	31D0G20A	9.11	14.0	1.98
16D45G13A	23.78	15.9	1.92	31D15G6A	7.33	20.4	2.05
16D45G20A	10.44	15.1	1.90	31D15G13A	5.56	15.7	1.98
16D60G6A	16.44	20.4	2.04	31D15G20A	6.89	12.3	1.92
16D60G13A	14.89	13.4	1.89	31D30G6A	7.33	16.0	1.97
16D60G20A	16.00	17.1	1.95	31D30G13A	6.44	10.6	1.89
22D0G6A	14.67	27.9	2.20	31D30G20A	12.89	17.6	1.98
22D0G13A	16.89	19.0	1.99	31D45G6A	7.33	17.3	2.08
22D0G20A	15.78	21.8	2.05	31D45G13A	5.78	18.3	2.04
22D15G6A	17.33	28.2	2.15	31D45G20A	5.78	14.7	2.01
22D15G13A	12.00	18.2	1.99	31D60G6A	8.00	21.1	2.04
22D15G20A	13.33	15.3	1.99	31D60G13A	6.89	19.7	2.05
22D30G6A	10.89	21.4	2.12	31D60G20A	7.33	19.6	2.05
22D30G13A	11.33	17.9	2.04				

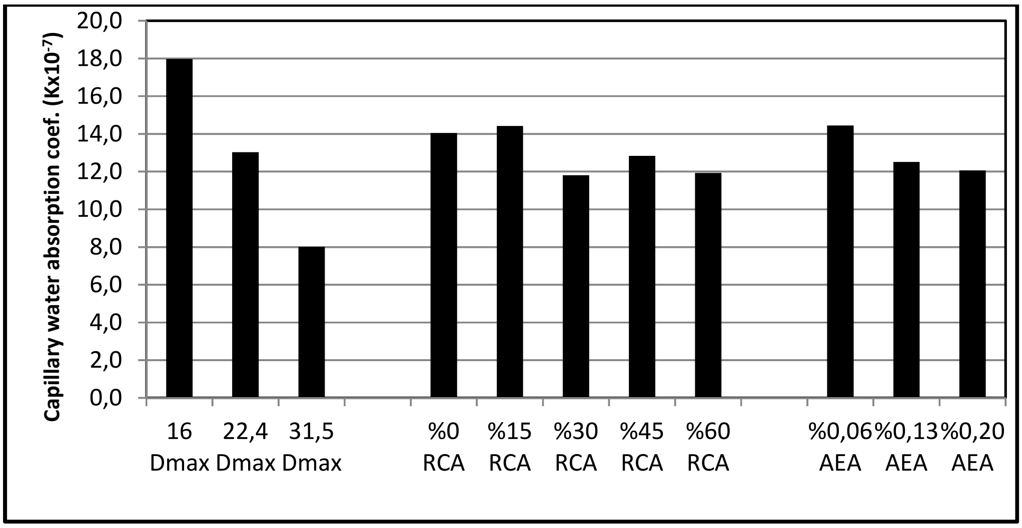

Fig. 1 Changes in average capillary water absorption coefficients according to parameters

As the amount of pores open outside are quite much, RCA's having high volumetric water absorptions enlarge pore structure of concrete, it may be said that they reduce a little the capillary absorption ratio of concrete.

B. Evaluation of the Results of Comp. Strength Test

Effects of parameters selected within the scope of the study on compressive strength of concrete were shown in Fig. 2.

As it is seen in Fig. 2, compressive strengths of concretes change according to RCA ratio, maximum aggregate particle size and amount of AEA. Increase in maximum aggregate particle size and amount of AEA reduce compressive strength of concretes. Decrease in compressive strength of concrete as air-entraining substances increase is an expected result in concrete technology. However, decreases seen in compressive strength as maximum aggregate particle size increases were found interesting. It is thought that increase in the pore volume in concretes induced from increasing maximum particle sizes of RCA was the reason of this decrease.

Decrease in compressive strength of concretes as RCA ratio in the mixtures increases were also seen in Fig. 2. This decrease is observed more clearly specifically up to the ratio of 30%. RCA ratio in concrete going over 30% has not caused significant changes in compressive strength of the samples, only compressive strength of mixtures including 60% RCA has shown a slight increase compared to those including 30% and 45% RCA. While many studies (e.g. [10]-[13]) in the literature say that compressive strength decreases as the quantity of RCA increases, there are also some studies (e.g. [14] and [15]) saying that it has no considerable effect.

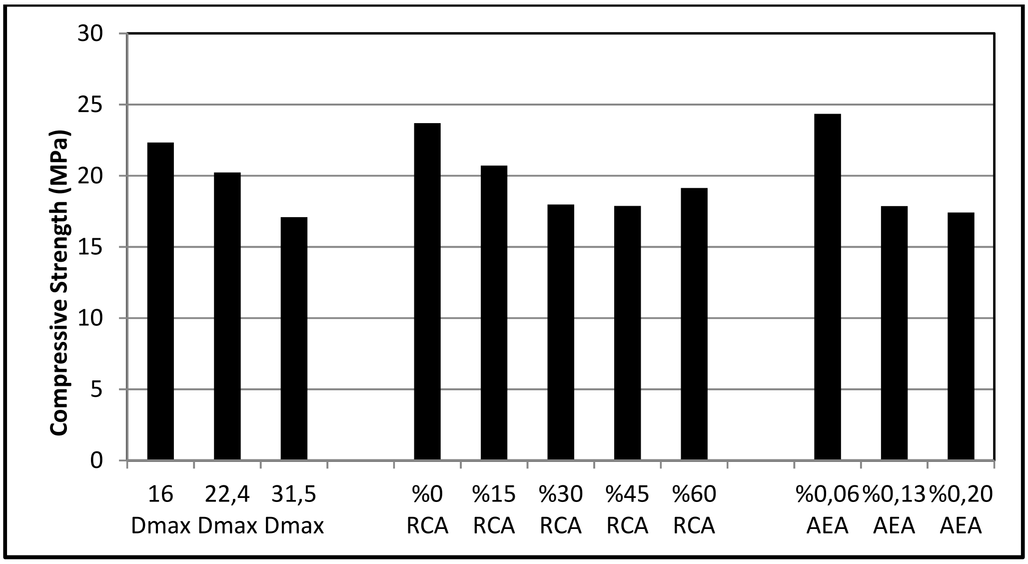

Fig. 2 Effects of parameters on average compressive strength

In the study, the highest compressive strength (34.7 MPa) in all series was obtained in the mixture not containing RCA and having the lowest maximum aggregate particle size (16 mm) and the least AEA ratio (0.06%) (16D0G6A coded sample). In groups which RCA was used, the highest compressive strength with 32.2 MPa value was obtained in 16D15G6A coded samples, and the lowest compressive strength with 10.6 MPa value was obtained in 31D30G13A coded samples.

C. Evaluation of the Results of Density Test

As seen in Table III, densities of hardened concretes have changed between 1.88-2.24 g/cm^3. In all series, the highest density value with 2.24 g/cm^3 was obtained from 16D0G6A coded sample and following that, with 2.21g/cm^3, was obtained from 31D0G6A coded sample. In mixtures which RCA was added, the highest density value was obtained from 16D15G6A coded mixture with 2.18 g/cm^3. The lowest density value was obtained from 16D30G20A, 16D60G13A and 31D30G13A coded sample with 1.88-1.89 g/cm^3.

On the basis of the averages of experimental results, effects of parameters selected on densities of hardened concretes were given in Fig. 3.

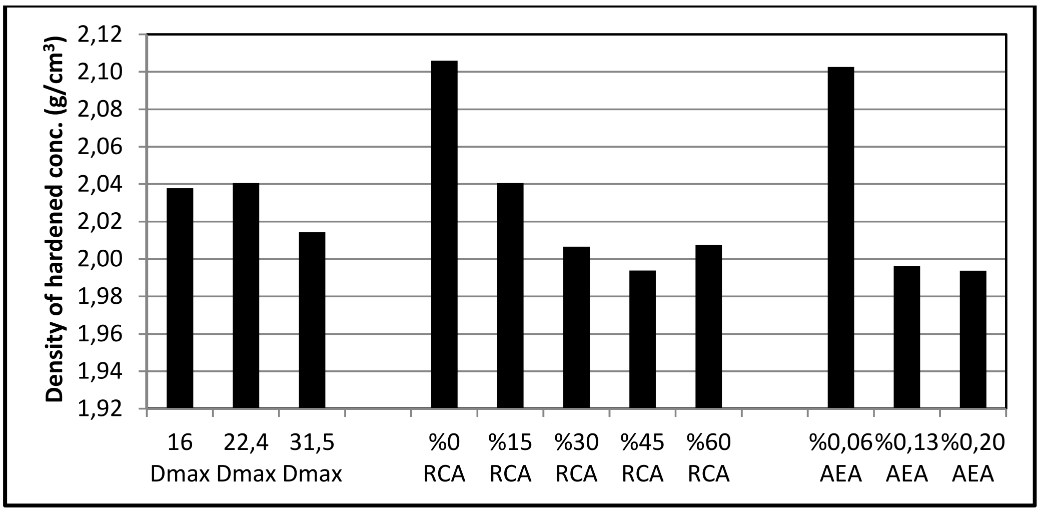

Fig. 3 Change in average density values according to parameters

As seen in Fig. 3, while densities of concretes having 16 mm and 22.4 mm maximum aggregate particle size were almost the same, as maximum aggregate particle size was increased to 31.5 mm, there has been a slight decrease in the densities of concretes.

As RCA ratio and AEA used were increased, densities of hardened concretes were reduced. Decreases seen in densities of concretes as maximum particle size, RCA ratio and AEA amount increase may be explained by these parameters increasing the amount of pores in concrete.

On the other hand, decrease in density of concrete as RCA ratio increases is related also to particle densities of these aggregates. Thus, it is seen in Table II that normal aggregates have densities changing between 2.44-2.71 g/cm^3 while RCA densities are between 2.22-2.43 g/cm^3. In literature, (e.g. [16]-[18]) there are results similar to results obtained in this study. On the other hand, it should be stated that a very slight increase was seen in density as RCA ratio was increased from 45% to 60%, and that 0.20% AEA ratio have almost the same effect on density of concrete when compared that of 0.13% AEA ratio.

IV. Conclusions

Obtained results within this study are summarized as:

a. Particularly for mortar residue on their surface, water absorption, abrasion ratio and mass loss under the effect of freezing and thawing of recycled coarse aggregates are higher than normal coarse aggregate. Additionally, due to high heterogeneity risks of RCA, the experimental studies conducted with the aggregates are more difficult than that of normal aggregates.
b. As increasing RCA ratio increases pore volume in concrete and causes pore diameters to get greater, it has reduced capillary absorption coefficient. Accordingly, it may be suggested to use this type of concretes in areas where capillary absorption problem may be experienced.
c. As increase of RCA ratio, maximum aggregate particle size and AEA amount increase pore volume in concrete, it has reduced compressive strength and density of concrete. For this reason, using RCA in important structural elements is not suggested. In decrease of density of concrete, RCA's having lower specific gravities compared to normal aggregates have an effect.

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