EFFECT OF RECYCLED CONCRETE AGGREGATE, AIR ENTRAINING ADMIXTURE AND MAXIMUM AGGREGATE PARTICLE SIZE ON THE BEHAVIOR OF CONCRETE UNDER FREEZE-THAW CYCLES

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ABSTRACT

This article presents freeze-thaw (F/T) resistance of concrete containing recycled concrete aggregate (RCA). RCA percentages of 15%, 30%, 45%, and 60% were replaced by natural aggregate. Air entraining admixture (AEA) with three different ratios (0.06%, 0.13%, and 0.20%) were used and three different maximum aggregate particle sizes (d_{max} = 16 mm, 22.4 mm and 31.5 mm) were selected. F/T resistances of the concretes were determined through the measurement of scaling on the surfaces of the samples placed in 3% NaCl solution in pursuance of TS CEN/TS 12390-9. It was observed that the compressive strength of the concretes decreased by 20% on average compared to the control samples with the increase in the amount of RCA. However, it was determined from the experiments that the use of RCA increases the F/T resistances of the concretes as it provides extra voids in the concrete and decreases capillary permeability. Within the limits of this study, d_{max} = 22.4 mm, RCA = 45% and AEA = 0.13% are recommended as the optimum values for F/T resistance of the concrete. It is also recommended to use RCA in pavement applications including roadways, highways, parking facilities, and other non-structural concrete elements subjected to severe winter conditions.

KEYWORDS

recycled concrete aggregate, freeze-thaw resistance, concrete pavement, NaCl solution

1. INTRODUCTION

The construction industry takes 50% of its raw materials from nature, consumes 40% of total energy, and creates 50% of total waste [1]. Most of the wastes causing environmental pollution are structural construction wastes and 40% of these wastes are concrete. The old concrete resulting from the demolition of a building or any structure can be reused as concrete aggregate or as infrastructure material on roads by crushing. The heavy matrix of concrete causes it to be an ideal recyclable material, which can be utilized by incurring very little loss of performance. However, there is insufficient awareness of this type of waste. Some issues such as lack of appropriately located recycling facilities, absence of appropriate technology, lack of awareness, lack of

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government support, and lack of proper standards act as barriers in promoting more widespread use of recycled aggregate and concrete made with recycled aggregate [2, 3].

RCAs have lower specific gravity than crushed aggregates, but water absorption rates and abrasion percentages are higher than those of the virgin aggregates [2, 4, 5]. Although their air content is higher [4], the workability of concrete produced with RCA is lower than conventional concrete [6]. It has been observed that compressive, bending, tensile strength, and the elasticity modulus of concrete decrease according to the ratio of the addition of RCA [2, 7, 8]. However, generally, the carbonation depth of the concrete decreases as the RCA content in concrete increases [9].

There is a limited number of studies investigating the effect of recycled aggregate on the freeze-thaw (F/T) resistance of concrete. As a result of the test with 50 F/T cycles, Çelik [10] observed that the freezing and thawing resistances of concretes containing recycled aggregates were much higher than those containing normal aggregates. Richardson et al. [11] demonstrated that the use of air-entraining agent and polypropylene fibers in concrete made with recycled aggregate are equally effective for providing F/T durability when compared with concrete made with virgin aggregates with air-entraining agent and polypropylene fibers. In two different R&D studies by Petkovic et al. [12], it was noted that the freeze-thaw resistance of RCA was sufficient for the most common exposure conditions, but the freeze-thaw resistance of RCA was unacceptable for extreme exposure conditions such as when the aggregate was submerged in water in combination with deicing salts. On the other hand, Zaharieva et al. [13] recommend that saturated RCA with high w/c ratio, which causes high porosity and low mechanical properties, should not be used in structures exposed to severe climate, while Medina et al. [14] stated that concretes containing sanitary ware industry aggregate may be appropriate for use in structural concrete when they are in a specific exposure class type "with frost and without deicing salts," such as constructions in mountainous areas and winter resorts. Detailed discussions on this subject can be found in the report prepared by Verian et al. [15].

Concretes containing RCA have been proposed for use in rigid and/or flexible paved roads and slabs-on-ground concretes [2, 5, 16, 17, 18]. Although a wide variety of substances are used as the deicer; for example, NaCl, $CaCl_2$, $MgCl_2$, urea, potassium acetate, sodium acetate and calcium-magnesium acetate [19], NaCl is the most broadly used as the de-icing salt to melt the ice formed on the roads during winter seasons. The main aim of this study was to investigate the F/T resistance of concretes with RCA under the influence of NaCl solution. Another objective of this study is to contribute to the explanation of the controversial results, some of which were given in the paragraph above, obtained from the studies on the F/T resistance of concretes produced by recycled aggregates.

2. MATERIALS AND METHODS

2.1 Materials

Ordinary Portland Cement (OPC) of type CEM I 42,5R as main binder, river sand as fine aggregate, natural limestone-based crushed stone as coarse aggregate, and limestone powder with d_{max} = 0.125 mm as a filler were used in the experiments. F-Class fly ash was used as mineral additive while air entraining admixture (AEA, specific gravity = 1.010) and synthetic carboxylate polymer-based superplasticizer as chemical concrete admixture (specific gravity = 1.085) were used. The chemical and physical properties of the cement and fly ash taken from the suppliers are provided in Table 2.1.

TABLE 2.1. Physical and chemical characteristics of the cement and fly ash.

	Cement (CEM I 42,5R)				Fly Ash (F)			
Chemical composition (%)	SiO_2	18.72	SO_3	2.98	SiO_2	53.69	SO_3	0.99
	Al_2O_3	4.54	Na_2O	0.19	Al_2O_3	20.29	Na_2O	—
	Fe_2O_3	3.43	K_2O	0.68	Fe_2O_3	11.83	K_2O	2.53
	CaO	62.25	Cl	0.0098	CaO	3.40	Cl	—
	MgO	3.34	Insol. residue	0.95	MgO	4.09	Loss of ign.	2.01
Physical characteristics	Blaine (cm^2/g)		3812		4020			
	Specific Grav.		3.13		1.98			
	28-day Comp. Str. (MPa)		57.9		—			

Aggregates of 4–31.5 mm in size obtained from the recycling facility of the Istanbul Environment Management Industry and Trade Company (İSTAÇ) were used as RCA. As a result of urban renewal activities in Istanbul, a lot of construction and demolition waste occurs. This waste is recycled as infrastructure materials of different sizes by the recycling facility of the Istanbul Metropolitan Municipality, with a capacity of 200 tons/hour. In İSTAÇ, the incoming materials are loaded to the crusher as a means of excavator. Products between 0–38 mm taken from the crusher are separated into desired dimensions by means of a sieve set. Before the product passes from the crusher to the sieve set, the metal materials are separated with the help of the magnet on the crusher [20]. Some physical properties and specific gravity of natural aggregate (NA) and RCA determined according to Turkish Standards (TS 706 EN 12620+A1[21], TS EN 1097-6 [22] and TS EN 1097-2 [23]) are provided in Table 2.2.

2.2 Experimental parameters and coding

In the mixtures, the water/binder ratio was kept constant at 0.53, the binder dosage was 350 kg/m^3, and the replacement levels of cement by fly ash (FA) was 20% by weight. The quantity

TABLE 2.2. Physical properties of the aggregates.

	Particle Density	Water Absorption (%)	Abrasion Rate (%)	Freeze-Thaw Mass Loss (%)
Fine Aggregate (River Sand)	2.44	4.99	—	—
Coarse Aggregate (Crushed Limestone)	2.68	0.96	15.4	0.95
RCA	2.37	6.94	38.04	13.75

of superplasticizer was determined as 1.5% of the binder dosage by weight in all mixtures. RCA ratios were selected at five different levels as 0%, 15%, 30%, 45%, and 60% of normal aggregate by volume for all coarse aggregate classes. The maximum aggregate particle size (d_{max}) was chosen at three different levels which were 16mm, 22.4 mm and 31.5 mm. Three different levels were investigated for the amount of air-entraining admixture as 0.06%, 0.13%, and 0.20% of binder dosage by weight.

As mentioned in the paragraphs above, the parameter of recycled concrete aggregate (RCA) ratio was determined as five levels, while parameters of maximum aggregate particle size (d_{max}) and air entraining admixture (AEA) were determined as three levels in the study. According to the full-factorial experimental design method, the number of samples to be tested has been determined as $5^1 \times 3^2 = 45$ mixtures. Ninety cube samples of 15 × 15 × 15 cm for mechanical experiments and ninety samples with dimensions of 15 × 15 × 7.5 cm for F/T tests have been produced within the scope of the study.

The following method was considered for coding: the first three characters show the maximum aggregate particle sizes, the next three (two for control samples) characters following them show the RCA ratio (in percent) and the last two or three characters show the AEA ratio (per ten thousand). Accordingly, 31D60G20A denotes the concrete with a nominal maximum aggregate particle size of 31.5 mm, 60% RCA and 0.20% AEA. The character G comes from the first letter of the Turkish word "Geri Dönüşüm" for "recycling" in coding.

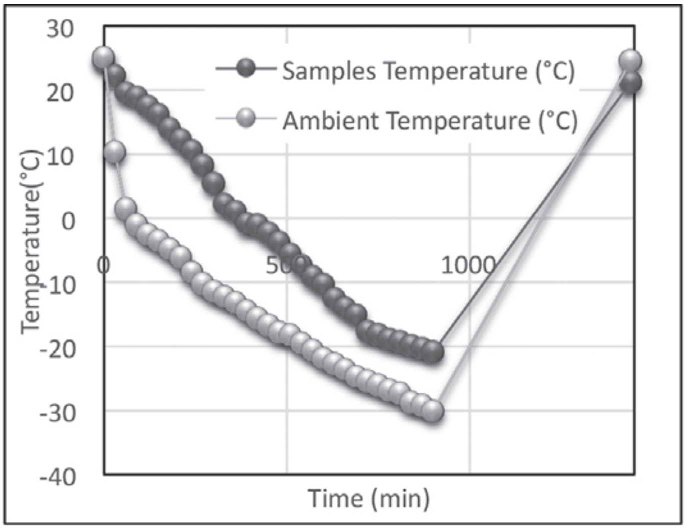
2.3 Experimental Study

During the mix design phase, the following acceptances and calculations were made for the aggregate ratios.

1. The filler, which was 5% of the total volume of aggregates, was taken as a constant for all mixtures as 93.4 kg/m^3.
2. Subsequently, the remaining aggregate volume was divided into equal volumes (25%) for each friction of aggregates (i.e., 0/2, 2/4, 4/8 and 8/d_{max}).
3. The fine aggregate ratios were taken in a fixed manner. Accordingly, the fine aggregate content for all mixtures was kept constant as 392 kg/m^3 and as 408 kg/m^3 for the 0/2 mm and the 2/4 mm fraction of fine aggregate, respectively.
4. The ratio of 8/d_{max} varied depending on the maximum aggregate particle size. In series with d_{max} = 16 mm, the volume of 8/16 aggregate class was 25%. In mixtures with d_{max} = 22.4 mm, the volume of 8/16 and 16/22.4 were 12.5%. For those with d_{max} = 31.5, the volume of 8/16, 16/22.4 and 22.4/31.5 were equal (8.3%).
5. 0/2 and 2/4 aggregate classes in all mixtures were normal (virgin) aggregates (NA). Only coarse aggregate was replaced by RCA according to the ratio of RCA in the mixture. For example, in mixtures containing 45% RCA and d_{max} = 31.5 mm, 45% of the normal aggregates in each of the 4/8, 8/16, 16/22.4, and 22.4/31.5 classes were substituted by RCA.

Concrete samples have been produced by mixing with vertical axis laboratory type mixer with 60 dm^3 capacity, with a mixing speed of 25 rpm. After long preliminary tests, a pre-mixing process has been applied first by adding coarse aggregates and powder materials (cement, fly ash and filler material) to the mixture. The mixture formed by the addition of fine aggregates was subjected to dry mixing for 1 minute and after approximately 60% of the water was

FIGURE 2.1. Cooling-heating graphs showing the freeze-thaw regime (Dark colored spheres indicate contact surface between the solution and the sample).



added, mixing was continued for a further 1.5 minutes. Subsequently, superplasticizer was added approximately to 70% of the remaining water and mixing was continued for another 1.5 minutes. Eventually, AEA was added approximately to 30% of the remaining water and the mixing was continued for a further 1.5 minutes. After the mixture was rested for 1 minute, the concrete production was completed by mixing for 2 minutes.

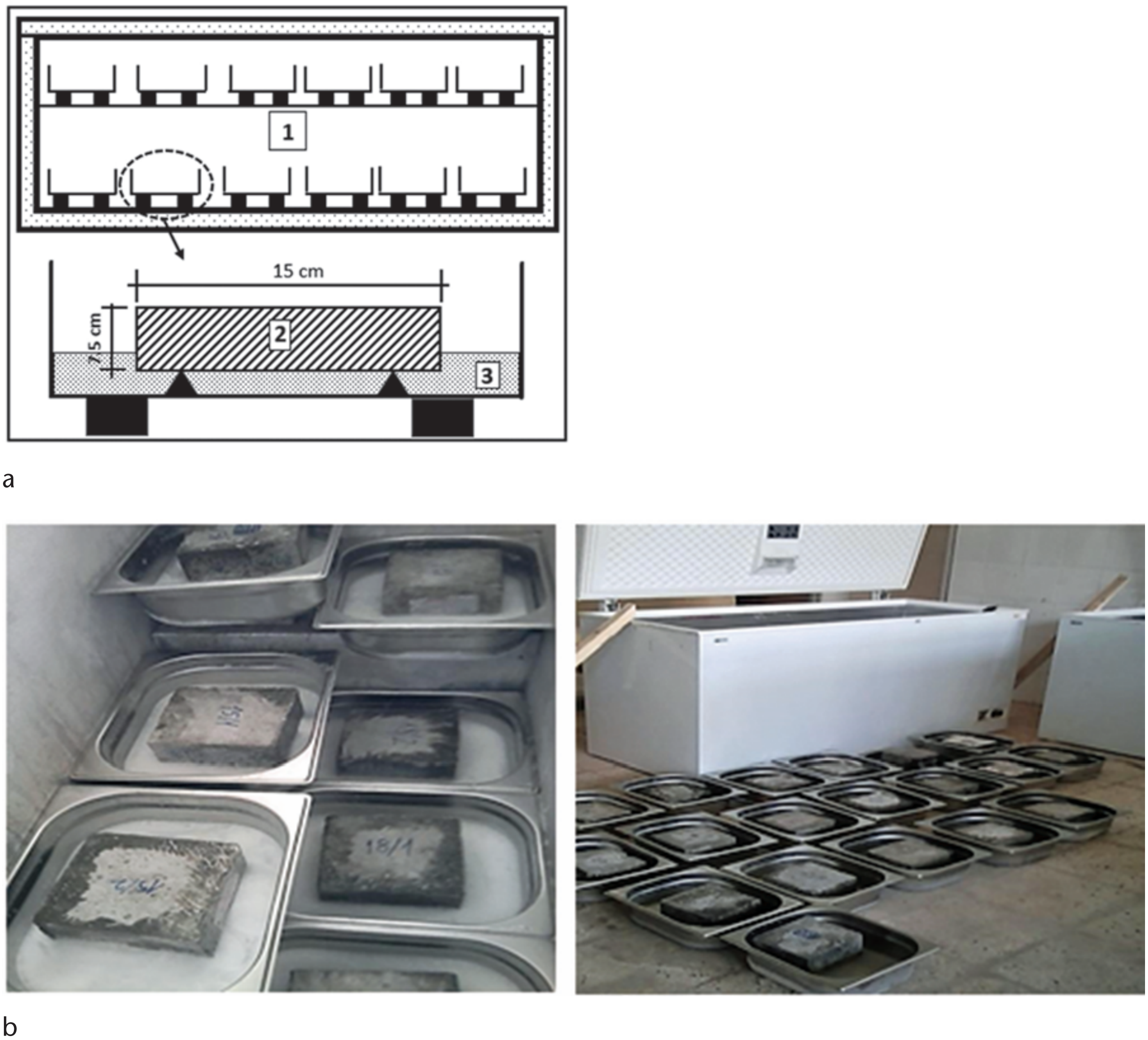
Slump [24] and air content [25] tests were performed on fresh concrete within the scope of the experimental studies. Density [26], determination of resistance of capillary absorption [27 and 28], compressive strength [29] and F/T tests were carried out on hardened concrete samples. Detailed information has been provided in the following paragraphs on the freeze-thaw experiments that constitute the main theme of this study.

F/T experiments were carried out according to TSE CEN/TS 12390-9 [30]. Molds of 15 × 15 × 15 cm were divided in two by using a centrally polytetrafluoroethylene (PTFE) plate as per standard specifications. Both samples produced were exposed to F/T cycles by partially soaking in a 3% NaCl solution. The damage caused in the concrete due to the F/T effect was evaluated by measuring the mass moving away by scaling at the end of 4th, 8th, 14th and 28th cycle. The tested surface of each sample was 15 × 15 cm.

In the F/T experiments, it is important to determine the variation in the temperature that the samples have been subjected to over time. The cooling-heating graphs obtained from thermocouples placed in the freezer cabinet and the surface of the sample are given in Figure 2.1. The graphs show the temperatures measured by virtue of a thermocouple placed on the contact surface of the 3% NaCl solution and the sample when the freezer cabinet was completely full. Figure 2.1 shows that the F/T temperature range was between +20° C and –20° C, while the freezing duration was 16 hours and the thawing duration was 8 hours.

The schematic representation of the experimental setup for each sample is provided in Figure 2.2.

FIGURE 2.2. a: The schematic representation of the experimental setup (1: Freezer cabinet; 2: Sample; 3: 3% NaCl solution) b: A photograph of the experimental setup showing freezer cabinet and the samples



3. RESULTS AND DISCUSSION

3.1 Results of fresh and hardened concrete tests

Fresh and hardened concrete test results obtained within the scope of the study are provided in Table 3.1. Based on Table 3.1, the following evaluations were made on the results.

Samples in which RCA and AEA were used together have the highest air content. The increases in the maximum aggregate particle size, RCA ratio, and the amount of AEA also increased the air content of the concretes.

Because of the low density of RCA and the use of AEA, the unit weights of the concrete samples have been low compared to the normal concretes. The increases in maximum aggregate particle sizes, RCA ratio and AEA amount reduced the unit weight of the concretes.

TABLE 3.1. Test results of fresh and hardened concrete.

CODE	Air Content (%)	Unit Weight (g/cm^3)	Slump (cm)	Comp. Stren. (MPa)	CWAC (K×10^{-7}) (cm^2/sn)	CODE	Air Content (%)	Unit Weight (g/cm^3)	Slump (cm)	Comp. Stren. (MPa)	CWAC (K×10^{-7}) (cm^2/sn)
16D0G6A	0.9	2.24	22	34.7	18.67	22D30G20A	10.5	2.01	23	14.1	7.11
16D0G13A	1.15	2.19	23	29.4	12.00	22D45G6A	8.5	2.08	23	25.7	16.44
16D0G20A	5.3	2.13	24	27.4	15.78	22D45G13A	13	1.96	24	16	12.22
16D15G6A	6.5	2.18	23	32.2	22.67	22D45G20A	13	1.98	25	16.8	9.78
16D15G13A	12	2.02	23	20.7	21.78	22D60G6A	8	2.08	20	25.6	15.11
16D15G20A	10	2.08	23	23.5	22.89	22D60G13A	10	1.98	23	16.6	10.44
16D30G6A	10	2.13	23	28.2	17.78	22D60G20A	8.5	1.99	22	18.9	12.22
16D30G13A	10.5	2.04	24	23	16.89	31D0G6A	8	2.21	17	25.4	12.67
16D30G20A	13	1.88	25	12.9	15.56	31D0G13A	12	1.96	21	13.7	10.89
16D45G6A	10	1.97	23	21.2	24.00	31D0G20A	12	1.98	23	14	9.11
16D45G13A	11.5	1.92	24	15.9	23.78	31D15G6A	11	2.05	22	20.4	7.33
16D45G20A	13	1.9	25	15.1	10.44	31D15G13A	13	1.98	23	15.7	5.56
16D60G6A	9.2	2.04	23	20.4	16.44	31D15G20A	12	1.92	25	12.3	6.89
16D60G13A	12	1.89	23.5	13.4	14.89	31D30G6A	8.5	1.97	21	16	7.33
16D60G20A	12	1.95	24	17.1	16.00	31D30G13A	13	1.89	24	10.6	6.44
22D0G6A	5.3	2.2	20	27.9	14.67	31D30G20A	10.5	1.98	23	17.6	12.89
22D0G13A	11	1.99	23	19	16.89	31D45G6A	9	2.08	20	17.3	7.33
22D0G20A	10.5	2.05	23	21.8	15.78	31D45G13A	9	2.04	21	18.3	5.78
22D15G6A	9	2.15	21	28.2	17.33	31D45G20A	11	2.01	23	14.7	5.78
22D15G13A	13	1.99	22.5	18.2	12.00	31D60G6A	10	2.04	21	21.1	8.00
22D15G20A	12	1.99	23	15.3	13.33	31D60G13A	10.5	2.05	21	19.7	6.89
22D30G6A	9	2.12	22	21.4	10.89	31D60G20A	8.5	2.05	20	19.6	7.33
22D30G13A	13	2.04	23	17.9	11.33	CWAC: Capillary Water Absorption Coefficient					

No significant differences were seen in workability of the concretes. This result is thought to be due to the fact that the air entraining agent increases the workability of the concrete and the use of the superplasticizer additive at the upper limits to reduce workability loss caused by the high water absorption capacity of RCA.

The increase of the RCA ratio caused a decrease in the compressive strength of the concretes. The RCA ratio is recommended as 15%, while the AEA ratio is recommended as 0.06% for the maximum compressive strength of the concretes containing RCA. The porosity of the concretes increased due the increase in the RCA ratio and the amount of AEA, and therefore the mechanical properties of the samples were reduced.

As the increase in RCA ratio increased the porosity of the concretes, the capillary water absorption coefficient of the concretes decreased. For the lowest capillary water absorption, the maximum aggregate particle size of 31.5 mm, the RCA ratio of 45% and the AEA ratio of 0.13% have been determined as the optimum values.

As the maximum aggregate particle size increased, the amount of slump, workability, unit weight, and density of the concretes decreased. However, the air content of fresh concrete increased with increasing maximum aggregate particle size. The increase in maximum aggregate particle size did not yield a result in a significant increase or decrease in water absorption. In accordance with Jurin's law, it was concluded that increasing the maximum aggregate particle size increased the amount and diameter of the voids in the concretes, but decreased the capillarity of the concretes.

A detailed evaluation on results of the compressive strength of the concretes obtained from the study can be found in Tosun and Şahin [31].

3.2 Freeze-thaw test results

The results obtained from the F/T tests conducted on concrete samples are provided in Table 3.2.

Based on the findings given in Table 3.2, the effects of the parameters on the freezing and thawing of the concrete samples are evaluated below.

3.2.1 The effects of maximum aggregate particle size on the surface scaling resistance of concretes

The total surface scaling amounts of the concretes according to maximum aggregate particle size and RCA ratio are shown in Figure 3.1. The graphs were plotted by summing the scaling amounts seen in mixtures with the same levels of the same two parameters. For instance, the value of 7.77 kg/m^2 given for the 28th cycle of 0% RCA in Figure 3.1(a) is the sum of surface scaling measured in the 16D0G6A, 16D0G13 and 16D0G20 coded mixtures in Table 3.2.

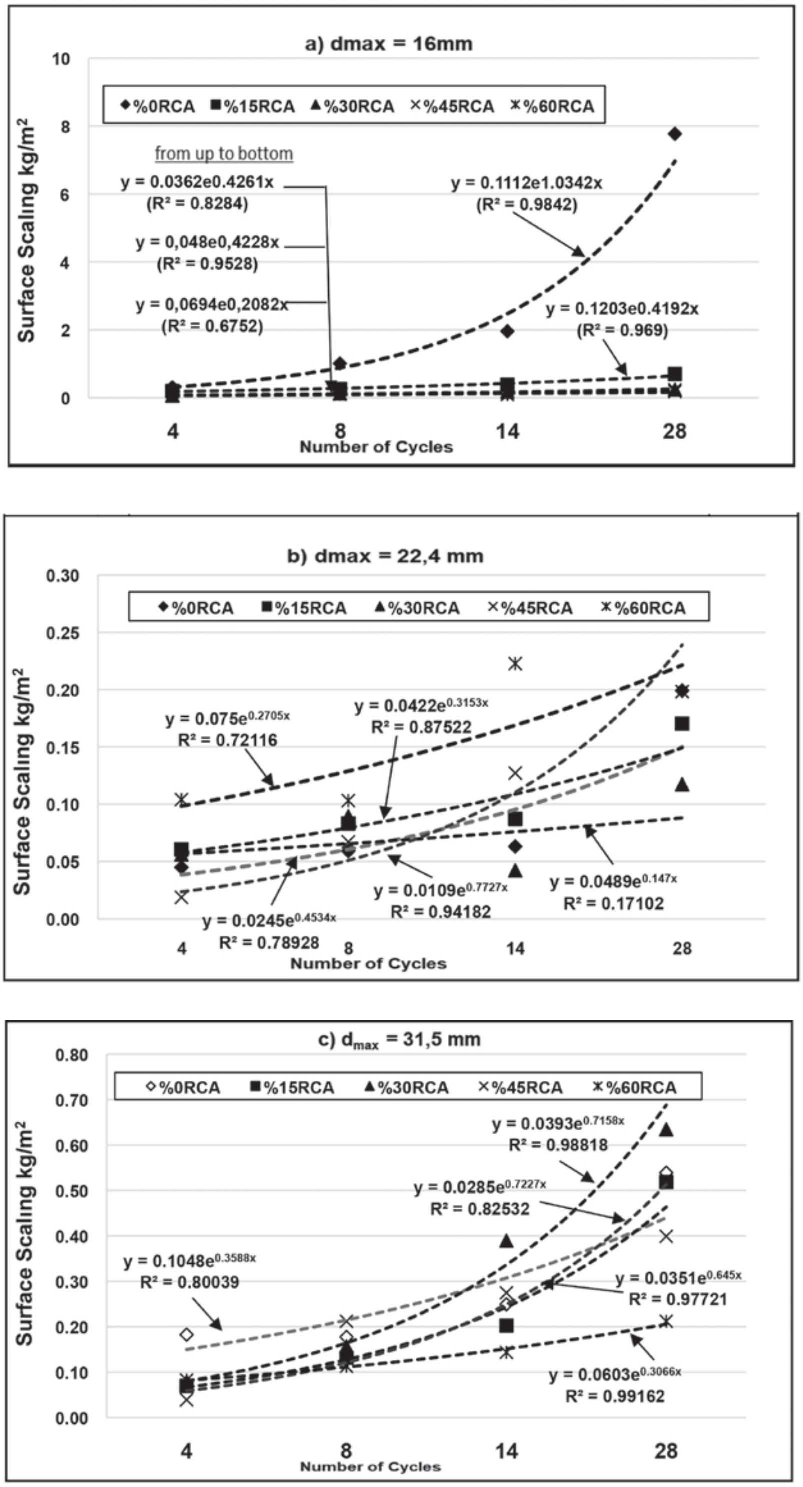
As seen from the graphs, the highest scaling (7.77 kg/m^2) in all F/T experiments has been observed in concretes with d_{max} = 16 mm and without RCA. It had been determined that there was a significant decrease in scaling amounts with the addition of RCA to groups with d_{max} = 16 mm compared to the control concrete containing 0% of RCA. It can be said that scaling generally decreases with the increase in the amount of RCA. At the end of the 28th cycle, scaling in the concretes containing 15% RCA was 0.70 kg/m^2 while scaling decreased to 0.24 kg/m^2 in the concretes containing 60% RCA.

Compared to the sizes of the other two maximum aggregate particles there has been a significant difference in mixtures with d_{max} = 22.4 mm. The amount of scaling in this series was lower than the other groups. Thus, at the end of the 28th cycle, scaling values of mixtures with

TABLE 3.2. The surface scaling amounts of concretes with the number of cycles.

CODE	Surface Scaling (kg/m^2)				S_n^* (kg/m^2)	CODE	Surface Scaling (kg/m^2)				S_n (kg/m^2)
	4. cycle	8. cycle	14. cycle	28. cycle			4. cycle	8. cycle	14.cycle	28. cycle	
16D0G6A	0.12	0.67	1.49	6.27	8.55	22D30G20A	0.04	0.06	0.02	0.07	0.19
16D0G13A	0.09	0.22	0.32	1.16	1.79	22D45G6A	0.01	0.04	0.07	0.13	0.25
16D0G20A	0.09	0.12	0.15	0.34	0.7	22D45G13A	0.00	0.02	0.05	0.06	0.13
16D15G6A	0.06	0.08	0.13	0.30	0.57	22D45G20A	0.01	0.01	0.01	0.01	0.04
16D15G13A	0.03	0.04	0.04	0.07	0.18	22D60G6A	0.01	0.01	0.04	0.06	0.12
16D15G20A	0.12	0.14	0.21	0.33	0.8	22D60G13A	0.08	0.08	0.13	0.16	0.45
16D30G6A	0.02	0.04	0.06	0.09	0.21	22D60G20A	0.01	0.01	0.05	0.06	0.13
16D30G13A	0.02	0.06	0.09	0.12	0.29	31D0G6A	0.08	0.10	0.17	0.28	0.63
16D30G20A	0.02	0.03	0.03	0.04	0.12	31D0G13A	0.07	0.04	0.05	0.20	0.36
16D45G6A	0.04	0.04	0.05	0.09	0.22	31D0G20A	0.03	0.05	0.03	0.07	0.18
16D45G13A	0.02	0.03	0.03	0.04	0.12	31D15G6A	0.03	0.04	0.09	0.25	0.41
16D45G20A	0.03	0.05	0.01	0.06	0.15	31D15G13A	0.01	0.04	0.04	0.06	0.15
16D60G6A	0.02	0.04	0.02	0.05	0.13	31D15G20A	0.03	0.05	0.08	0.21	0.37
16D60G13A	0.02	0.04	0.04	0.06	0.16	31D30G6A	0.01	0.03	0.06	0.22	0.32
16D60G20A	0.02	0.03	0.03	0.12	0.2	31D30G13A	0.03	0.06	0.17	0.22	0.48
22D0G6A	0.01	0.02	0.03	0.14	0.2	31D30G20A	0.04	0.07	0.16	0.19	0.46
22D0G13A	0.02	0.02	0.03	0.04	0.11	31D45G6A	0.02	0.10	0.18	0.23	0.53
22D0G20A	0.01	0.01	0.01	0.02	0.05	31D45G13A	0.01	0.07	0.05	0.10	0.23
22D15G6A	0.02	0.04	0.03	0.06	0.15	31D45G20A	0.01	0.03	0.04	0.06	0.14
22D15G13A	0.01	0.02	0.02	0.04	0.09	31D60G6A	0.03	0.04	0.05	0.08	0.20
22D15G20A	0.03	0.02	0.03	0.07	0.15	31D60G13A	0.04	0.05	0.06	0.09	0.24
22D30G6A	0.01	0.01	0.01	0.03	0.06	31D60G20A	0.01	0.02	0.04	0.05	0.12
22D30G13A	0.01	0.01	0.01	0.02	0.05	*Sn: Surface Scaling (Amount of total scaling obtained from unit area)					

FIGURE 3.1. Relationship between number of cycles and surface scaling quantities of the concretes classified according to maximum aggregate particle size (d_{max}).



d_{max} = 16 mm and d_{max} = 31.5 mm were measured as 7.77 kg/m^2 and 0.63 kg/m^2 respectively, while the maximum scaling values in the group with d_{max} = 22.4 mm remained as 0.20 kg/m^2. On the other hand, the maximum surface scaling amount in this group (i.e., d_{max} = 22.4 mm) for all cycles was observed in mixtures containing 60% RCA. It has been determined that change in the amount of surface scaling by adding RCA to the concrete varied according to the number of cycles and the lowest scaling amounts were in mixtures containing 30% RCA as of the 14th and 28th cycles. Furthermore, the lowest scaling amount (0.004 kg/m^2) in all series has been observed in this group (in 22D45G13A coded mixture) in all cycles in the evaluations made according to the maximum aggregate particle size.

In the mixtures with d_{max} = 31.5 mm, the maximum surface scaling was determined in samples containing 30% RCA. This result most clearly occurred at the end of the 14th and 28th cycles. Apart from those containing 30% RCA, it was observed clearly in the evaluation made at the end of the 28th cycle that with the increase of the RCA ratio the surface scaling resistance of the concrete caused by the F/T have increased. In this group, mixtures with 60% RCA have given the best result in almost all cycles and this result is exactly the opposite of the mixtures with d_{max} = 22.4 mm. However, at the end of the first four cycles, it is seen in Figure 3.1(c) that mixtures containing 45% RCA had a very small amount (0.04 kg/m^2) of scaling.

3.2.2 The effects of AEA ratio on the surface scaling resistance of concretes

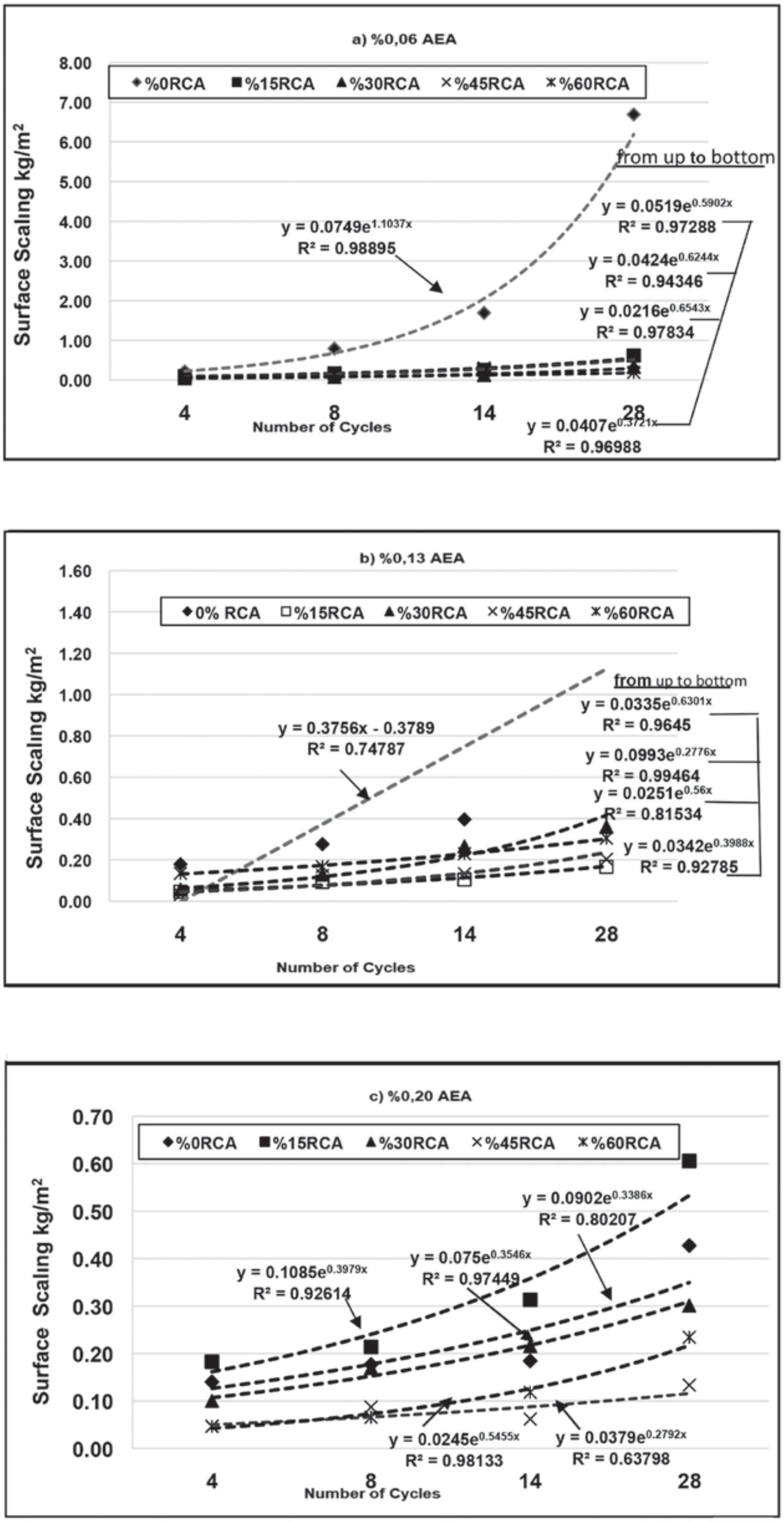
In consequence of the experiments, the change in the amount of surface scaling of concretes according to the content of AEA is drawn in Figure 3.2.

When the three graphs given in Figure 3.2 were examined, the effect of the amount of AEA on the scaling resistance of concretes is obvious. The effect of each ratio of AEA is evaluated separately below.

It has been determined that the group having the maximum amount of scaling (6.69 kg/m^2) in the concretes containing 0.06% AEA were mixtures containing 0% RCA. This group is also the same group with the most scaling during all cycles. The groups with the lowest scaling in the concretes containing RCA are those containing 30% and 60% RCA. By the end of the 28th cycle, concretes containing 30% and 60% RCA have scalings of 0.33 kg/m^2 and 0.19 kg/m^2, respectively. By the comparison with two ratios, it was determined that concretes containing 30% RCA had low scaling in the first eight cycles, whereas concretes containing 60% RCA had lower scaling than the mixtures with 30% RCA in the following cycles. It can be seen from Table 3.1 that the group with the lowest air content in fresh concrete was the group with 0.06% AEA. Consequently, these concretes were the most damaged group under the F / T effect, as they did not have a sufficient number of independent spheroidal voids.

The highest amount of scaling in concretes containing 0.13% AEA was observed in concretes without RCA (control group). However, the amount of scaling in this group was much lower for all cycles compared to mixtures containing 0.06% AEA. The maximum scaling amount at the end of the 28th cycle in this group was 1.39 kg/m^2. This result was evaluated to be related to the air content of fresh concrete. The air content of mixtures containing 0.13% AEA was higher than those containing 0.06% AEA. Thus, this difference accounted for up to 50% in some mixtures (see Table 3.1). In this group, minimum scaling (0.17 kg/m^2) was observed in mixtures containing 15% RCA. Except for the first four cycles, this was valid for all remaining cycles. Mixtures containing 45% RCA had a similar amount of scaling to mixtures containing 15% RCA. On the other hand, in this group (i.e., mixtures with 0.13%AEA), it was interesting to determine that scaling of mixtures containing 30% and 60% RCA were lower than those of

FIGURE 3.2. Relationship between number of freezing and thawing cycles and scaling amount of the concretes classified according to AEA ratio.



the mixtures containing 0.06% AEA, whereas the mixtures containing the same ratios of RCA were further damaged in the mixtures with 0.06% AEA.

The highest amount of scaling took place in mixtures containing 15% RCA during all cycles in mixtures with 0.20% AEA, unlike in the first two groups. Mixtures containing 0% RCA had the second highest amount of scaling. In this group, the minimum scaling amount for all cycles was found primarily in mixtures containing 45% RCA and then in mixtures containing 60% RCA. At the end of the 28th cycle, the minimum scaling amount in mixtures containing 45% RCA was 0.13 kg/m^2.

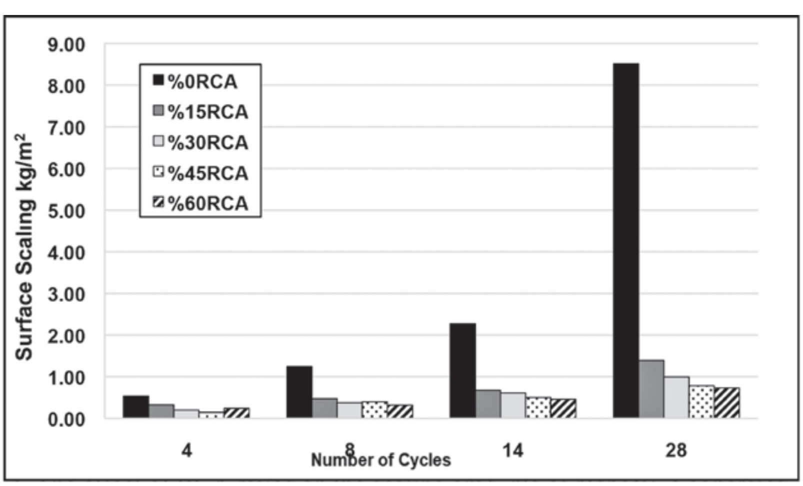
Air voids created in concrete by use of the air entrainment method helped relieve the buildup of pressure due to osmosis and difference in vapor pressure over liquid water and ice [32]. On the other hand, although the pore system in non-air entrained concrete has a generally fractal character and cross each other [33, 34], the pores which have formed by air-entrainment have spherical character and separate each other. This different structure is one of the most positive factors affecting concrete exposed to freezing and thawing effect [35]. The affecting mechanisms of AEA on the frost resistance of concrete is discussed in more detail by other researchers [36, 37, 38, 39].

3.2.3 The effects of RCA ratio on the surface scaling resistance of concretes

The effects of RCA ratio on the total surface scaling resistance of concretes are provided in Figure 3.3. As can be seen from Figure 3.3, the F/T resistance of concrete has increased with the addition of RCA, and the surface scaling of mixtures without RCA was much higher than those of the others. In concretes without RCA, as the number of cycles increased, the total scaling amount also increased. So, the scaling amount was measured after the 4th, 8th, 14th and 28th cycles as 0.54 kg/m^2, 1.25 kg/m^2, 2.27 kg/m^2 and 8.51 kg/m^2, respectively.

On the other hand, F/T resistances of concretes also increased as the RCA ratio increased in the mixtures containing RCA. This increase became obvious with the increase in the F/T cycle. Although it cannot be observed directly in the first eight cycles, it is clearly seen in the graphs in Figure 3.3 that the amount of scaling decreases continuously as the RCA ratio in the mixtures increase after the 14th and 28th cycles.

FIGURE 3.3. The effect of RCA ratios on the scaling amounts of respective concretes with increasing number of freezing and thawing cycles.



The optimum value of the ratio of RCA to be used in concrete in the literature (e.g. Oikonomou, [1], Topçu and Şengel [40] and Çakır and Sofyanlı [41]) was marked with the value of 30%. However, depending upon the findings acquired in this study, it can be said that this ratio is not very precise in terms of F/T resistance, and higher ratios (such as 45%) can be used. It should be emphasized that this result is provided with regard to F/T, which constitutes the main theme of the study. In construction applications, it is desirable to have high mechanical properties as well as the durability properties of concrete. As mentioned in the paragraphs above, a slight decrease has been observed in the compressive strength of concrete with the addition of RCA to concrete in this experimental study.

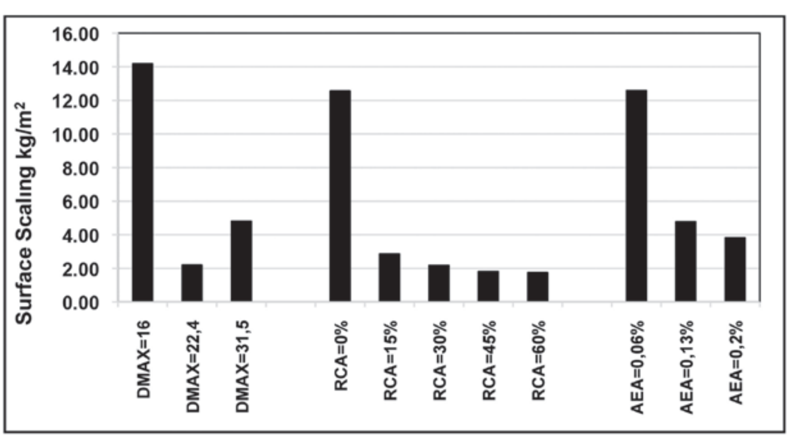
3.2.4 The effects of all parameters on the surface scaling of concretes

The effects of all parameters (i.e., RCA ratio, maximum aggregate particle size and AEA ratio) on total scaling of concretes are given in Figure 3.4.

As can be seen in the graphs in Figure 3.4, the highest surface scaling amount occurred in the samples with small maximum aggregate particle size, not containing RCA and with less AEA. The optimum value for the maximum aggregate particle size has been found to be 22.4 mm. As mentioned above, as the amount of RCA used increases, the surface scaling resistance also increases. It can be seen in Table 3.2 that the mixture with the highest surface scaling resistance in the study (0.04 kg/m^2) is the mixture coded as 22D45G20A. The maximum aggregate particle size is 22.4 mm, the ratio of RCA is 45% and the ratio of AEA is 0.20% of this mixture. Considering the evaluations about RCA rates noted previously (see 3.2.3), along with this result, it can be said that the optimum ratio for RCA is 45%. On the other hand, it can be seen in the same table that the mixture with the lowest scaling resistance (8.55 kg/m^2) in the study is the mixture coded as 16D0G6A. The maximum aggregate particle size is 16 mm; the ratio of RCA is 0% and the ratio of AEA is 0.06% of this mixture. Considering that there is very little reduction in the total amount of scaling with the addition of 0.20% AEA to the mixture (see Figure 3.4), and that there is a negative effect of AEA at this rate on the compressive strength of the concrete, an optimum value for AEA can be recommended as 0.13%.

As stated in the introduction, incompatible results have been proposed in the literature related to the effect of RCA on the freeze-thaw resistance of concrete. For instance, Richardson et al. [11], Petkovic et al. [12], Abbas [42], Debieb et al. [43], and Hwang et al. [44] have stated

FIGURE 3.4. Total surface scaling graphs versus selected parameters and their levels.



that F/T resistance of concrete increases as the amount of RCA increases, while Zaharieva et al. [13], Medina et al. [14], Topçu and Şengel [38], Gökçe et al. [45], and Tuyan et al. [46] have defended that the increase in RCA ratio decreases the F/T resistance of concrete. The research findings and results obtained from this experimental study also confirmed that the F/T resistance of concrete will increase with the increase of RCA ratio, provided that it does not exceed a certain RCA ratio.

4. CONCLUSION

This study provides an evaluation of sustainable concrete made with recycled concrete aggregate (RCA). The following conclusions can be summarized based on the experimental observations:

Water absorption, abrasion and F/T resistance of the recycled coarse aggregates gave more negative results compared to the natural (virgin) coarse aggregate due to cement pastes residues on the surface of RCA and some non-concrete materials within them.

Increases in maximum aggregate particle size, RCA ratio, and AEA amount increased the air content but decreased the unit weight of the fresh concrete. The increase in RCA ratio decreased the compressive strength and the capillary water absorption coefficient of the concretes.

The use of AEA in the mixtures has created independent air voids in the concrete, so the F/T resistance of the concrete samples has increased. Furthermore, it has been determined that the use of RCA in the mixtures increased the surface scaling resistance of concrete because it caused the formation of extra air pores (in addition to the voids coming from AEA) in the concrete and decreased the capillary permeability. Thus, the increase in RCA ratio has also increased the surface scaling resistance of the concretes.

The best results for the F/T resistance have been obtained from the series with maximum aggregate particle size (d_{max}) of 22.4 mm. The surface scaling resistances of the concrete samples, which have been formed by replacing 45% RCA with normal aggregate have been quite high. It can be said that the use of AEA admixture as 0.13% will be appropriate for the F/T resistance of concrete samples by taking into consideration all the experiments conducted within the scope of this study. So, the most suitable values for the F/T resistance of the concretes can be recommended as d_{max} = 22.4 mm, RCA ratio = 45% and AEA ratio = 0.13%. Because the F/T resistance of the concretes with the specified ratios will be high, it is recommended to use recycled aggregates for almost all types of concrete pavement applications including roadways, highways, parking facilities, industrial facilities, and other non-structural concrete elements subjected to severe winter conditions.

For further studies, it is recommended to characterize comprehensively the pore structures of RCA-containing concretes with appropriate instrumental and computer analysis methods.

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