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Can Concrete Containing High-Volume Recycled Concrete Aggregate Be Durable?

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*This paper evaluates the effect of recycled concrete aggregate (RCA) on concrete durability. Six RCA types procured from different sources were employed at 30 to 100% replacement rates by volume of virgin coarse aggregate. One fine RCA was also investigated and was used for up to 40% replacement by volume of virgin sand. In total, 33 mixtures were proportioned with these aggregates in concrete made with a binary or a ternary binder system and a water-cementitious materials ratio (*w/cm*) of 0.37 to 0.45. The mixtures were investigated for frost durability, electrical resistivity, sorptivity, and abrasion resistance. Test results indicate that concrete made with up to 100% coarse RCA from an air-entrained source can exhibit proper frost durability. No significant reduction (limited to 3%) in frost durability factor was observed when the fine RCA volume was limited to 15% of total sand. Increase in mass loss due to deicing salt scaling was observed in concrete made with 50% of RCA with high (over 4%) deleterious materials content and high mass loss during soundness test. For a given* w/cm *and binder type, the use of 50% coarse RCA resulted in up to 32% reduction in electrical resistivity. The reduction in* w/cm *from 0.40 to 0.37 and the use of ternary binder containing 35% Class C fly ash and 15% slag proved to be effective in mitigating the potentially negative impact of RCA on sorptivity and abrasion resistance, compared to concrete made without any RCA with* w/cm *of 0.40 and binary cement with 25% fly ash.*

Keywords: abrasion; air-void system; electrical resistivity; frost durability; recycled concrete aggregate; scaling resistance; sustainability.

INTRODUCTION

Concrete durability can significantly affect the maintenance cost and service life of transportation infrastructure. The degradation mechanisms are typically tied to the environmental conditions and exposure situation, including variations in seasonal temperature and relative humidity, and the availability of deleterious materials and ions. Frost action, scaling caused by deicing salts, ionic attacks, and surface damage caused by abrasion are some of the mechanisms that can result in deterioration of different segments of transportation infrastructure, including structural elements and pavement panels. Situations are more complicated while using recycled concrete aggregate (RCA) in concrete production. Typically, marginal quality of the RCAs, stemmed from residual mortar phase of the particles and the availability of impurities and deleterious materials, can cause uncertainties regarding the durability of concrete.[1]

Lower concrete quality, which can be reflected in greater porosity and water absorption, facilitates the saturation of the exposed surfaces. The water available in saturated concrete will freeze and expand in subzero environments, exerting internal pressure to the matrix which can result in cracking and degradation of concrete. Moreover, higher porosity can result in an increased rate of ion transport and greater risk of damage in aggressive environments, leading to accelerated accumulation of deteriorating agents in concrete and occurrence of chemical attacks.

Frost durability

It is a generally accepted fact that providing the minimum strength requirements, keeping moisture content lower than the critical saturation, and securing proper air entrainment in concrete can yield dependable durability against frost action. An efficient air entrainment requires adequate amount (% vol.) of air in fresh and hardened state and proper characteristics of the air void system in terms of spacing factor ($\bar{L}$) and specific surface (α), with values of $\bar{L}$ < 0.2 mm (0.008 in.) and α ≥ 24 mm^2/mm^3 (600 $in.^2/in.^3$) as recommended by ASTM C457.[2] Several studies have considered the effect of RCA on resistance of concrete to freezing and thawing cycles and exposure to scaling caused by deicing salts. Zaharieva et al.[3] investigated the frost durability of concrete made with 100% coarse and fine RCA, 400 kg/m^3 (675 lb/yd^3) of portland cement (OPC), and free water-cement ratio (*w*/*c*) of 0.27 to 0.37. The authors reported a durability factor over 82% for all investigated mixtures, regardless of the degree of saturation of the RCA. However, the highest durability factor of 100% was reported for the reference concrete cast without any RCA. Yildirim et al.[4] investigated the effect of up to 100% coarse RCA with 0, 50, and 100% saturation level on freezing-and-thawing resistance of concrete proportioned with 400 kg/m^3 (675 lb/yd^3) of cement and *w*/*c* of 0.5 to 0.7. No significant effect due to the use of RCA was observed, with 2.4 to 7.1% and 4.3 to 13.2% loss in mass and vibration frequency, respectively, after 300 cycles of freezing and thawing. Gokce et al.[5] incorporated 100% RCA obtained from either a source of air-entrained concrete or a concrete without any air entrainment to develop mixtures with *w*/*c* of 0.55. Up to 13% improvement in durability factor after 500 test cycles was reported with the use of RCA from an air-entrained source, regardless of the adhered mortar content and absorption rate of the RCA. This was believed to be due to pressure dissipation in porous structure of the aggregates with use of RCA from air entrained sources. However, a severe drop in durability factor to values lower than 60% after 200 test cycles was reported when non-air-entrained RCA or a

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combination of the two types of RCA were used as coarse aggregate. Such an observation was proved to be due to cracking of the non-porous residual mortar phase of the RCA, along with crack propagation in the old interfacial transition zone (ITZ), which was quantified through image analysis. In the case of the mixtures made with non-air-entrained RCA, the authors reported that even the reduction in water-cementitious materials ratio (*w*/*cm*) from 0.55 to 0.30, and the incorporation of binary cements with 10% silica fume or 10% metakaolin could not guaranty frost durability and values of durability factor lower than 60% were obtained after 300 test cycles for such modified mixtures.[5] Liu et al.[6] also reported increase in crack density due to freezing and thawing action in adhered mortar phase of RCA obtained from non-air-entrained sources. Such cracking behavior was believed to be the reason for reduced durability factor (80% versus 95%) of mixtures cast with non-air-entrained RCA while compared to that of the mixtures made with RCA obtained from air-entrained concrete.

In summary, and based on the data available in the literature, it may be concluded that the pore structure of the RCA can play an important role in frost durability of new concrete. Concrete made with RCA obtained from crushing air entrained concrete can exhibit proper resistance against frost action. The use of RCA from non-air-entrained origins, on the other hand, can have negative impacts on resistance against frost action.

Transport properties

Rapid chloride ion permeability (RCP), water absorption, and electrical resistivity are typically considered as indicators of transport properties of concrete.[7] Such tests are of great interest especially in the case of reinforced concrete elements, including the structural elements and substructure members, as well as reinforced concrete pavement. Gonzalez-Corominas and Etxeberria[8] investigated the electrical resistivity and RCP of concrete proportioned with 0.29 *w*/*cm* and 380 kg/m^3 (640 lb/yd^3) of OPC. The authors reported decrease in 28-day electrical resistivity from 26.8 to 25, 20.1, and 9.5 KΩ.cm corresponding to an increase in 28-day RCP values from 880 to 1050, 1200, and 2070 Coulomb with the use of 20, 50, and 100% coarse RCA, respectively. Kou et al.[9] investigated the effect of RCA as a full replacement for virgin coarse aggregate on durability of concrete prepared with 390 kg/m^3 (657 lb/yd^3) of binder and 0.5 *w*/*cm*. Increase in 90-day RCP from 3250 and 2200 to 4000 and 3800 Coulomb was reported with the use of RCA in mixtures made with 100% OPC or binary cement with 55% ground-granulated blast-furnace slag (GGBS), respectively. Duan and Poon[10] investigated the relation between the water absorption of RCA and RCP results for full coarse RCA replacement. The investigated mixtures were prepared with 485 kg/m^3 (817 lb/yd^3) of OPC and 0.34 *w*/*c*. The authors reported increase in total passed charge from 2050 to 2350, 2850, and 3850 Coulomb when RCA with water absorption of 3.24%, 6.61%, and 7.1% was used, respectively. Similar trends were reported by Kou et al.,[11] who examined concrete prepared with 410 kg/m^3 (691 lb/yd^3) of OPC and 0.55 *w*/*c* for chloride ion permeability at 90 days. Greater RCP values were observed with higher water absorption of RCA. Increase in RCP from 4200 to 5300, 6100, and 7600 Coulomb was observed when 20, 50, and 100% RCA with water absorption of 6.2% was incorporated. Such results were 4650, 5400, and 6150 Coulomb when virgin coarse aggregate was replaced with 20, 50, and 100% RCA with water absorption of 3.77%.

RESEARCH SIGNIFICANCE

The present study investigates the feasibility of using cost-effective methodologies, including the use of optimized binder compositions and lowered *w*/*cm* to develop durable concrete made with high-volume recycled aggregate. RCA materials obtained from various commercially recycled sources and a laboratory produced RCA were used to investigate concrete designated for transportation infrastructure. Six types of coarse RCA, and a source of fine RCA were used in the study. Two binder systems and three *w*/*cm* of 0.37, 0.40, and 0.45 were considered. Effect of RCA on concrete durability was investigated in terms of freeze and thaw resistance, resistance to scaling caused by deicing salts, electrical resistivity, sorptivity, abrasion resistance, and coefficient of thermal expansion (CTE).

EXPERIMENTAL PROGRAM

Material properties

The investigated concrete mixtures were proportioned with either a binary or a ternary cement. The former included 75% Type I/II portland cement and 25% Class C fly ash (FA-C), by mass of total binder. The ternary system contained 35% FA-C and 15% GGBS, by mass. The binary cement is similar to the concrete employed by the Missouri Department of Transportation (MoDOT) for rigid pavement construction.[12] The ternary system was optimized to enhance mechanical properties and reduce shrinkage of concrete equivalent mortar with 0.40 *w*/*cm*.[13] The incorporated cement, GGBS, and fly ash had a Blaine surface of 410, 590, and 490 m^2/kg and specific gravity of 3.14, 2.86, and 2.71, respectively.

Two types of crushed dolomite with nominal maximum aggregate size (NMAS) of 19 mm (0.75 in.) were used. Different coarse RCAs procured from six different sources, including five commercial recycling centers and one laboratory-produced RCA were considered. The laboratory-produced RCA was obtained by crushing concrete beam samples proportioned with 0.45 *w*/*cm* and fresh air content of 9.0%. The concrete had a compressive strength of 37.0 MPa (5365 psi) at the time of crushing. RCA2 was produced by crushing concrete from an airfield, with a high chance that the parent concrete was air-entrained.

The aggregate soundness test introduced by ASTM C88 was modified as proposed by Abbas et al.[14] to determine the resistance of coarse RCA materials against freezing-and-thawing cycles. The method involved: 1) obtaining a representative sample of different size portions of RCA as suggested by Abbas et al.[14]; 2) washing the aggregate with tap water, drying in an oven set at 110 ± 5°C (230 ± 10°F) until constant mass; 3) immersing the aggregates in a saturated solution of sodium sulfate; 4) exposing the samples to seven daily cycles of freezing and thawing with temperature range similar to requirements of ASTM C672[15] test on

Table 1—Virgin aggregate and RCA properties

Aggregate	Source	Oven-dry specific gravity	Absorption, %	Deleterious materials, % mass/type	Soundness mass loss, %	Los Angeles abrasion, %	NMAS*, mm
NC1	Dolomite 1	2.73	0.80	—	—	28	19
NC2	Dolomite 2	2.72	0.98	—	—	43	19
Sand	River-bed sand	2.63	0.40	—	—	—	4
Fine RCA	Residual concrete, airfield	2.11	7.33	—	—	—	4
RCA 1	Laboratory-produced RCA	2.35	4.56	0.3	21	41	19
RCA 2	Residual concrete, airfield	2.35	4.46	4.0/Bituminous	19	33	19
RCA 3	Commercial recycling, Missouri	2.25	5.75	4.5/Masonry	36	39	19
RCA 4	Commercial recycling, Kansas	2.24	6.05	2.2/Masonry	17	38	19
RCA 5	Commercial recycling, Missouri	2.17	7.58	1.3/Masonry	23	44	19
RCA 6	Commercial recycling, Missouri	2.21	7.13	1.9/Masonry	40	53	12.5

*Nominal maximum aggregate size.

Note: 1 mm = 0.0394 in.

deicing salt scaling; 5) washing the aggregates using tap water by the end of the freezing-and-thawing cycles, oven drying, and sieving on 4.75 mm (No. 4) mesh; and 6) calculating the total mass loss for each aggregate type based on loss obtained for each size fraction and aggregate particle size distribution.

Well-graded siliceous river-bed sand with fineness modulus of 2.47 was used. In addition, a fine RCA with fineness modulus of 2.53 was used. All RCA materials were in saturated state conditions before mixing. Table 1 presents the physical properties of the fine and coarse aggregates.

A lignum-based water-reducing admixture (WRA) with specific gravity of 1.2 and 40% solid content was used. WRA was incorporated to adjust the slump values of 50 ± 25 mm (2 ± 1 in.) and 150 ± 50 mm (6 ± 1 in.) for pavement and substructure applications, respectively. Air-entraining agent (AEA) was used to secure 6 ± 1% air in fresh state.

Concrete mixture proportions

In total, 33 concrete mixtures were prepared. Three *w/cm* of 0.37, 0.40, and 0.45 were considered in designing these mixtures. Tables 2 and 3 summarize the mixture proportioning of the investigated concrete. All mixtures were prepared with 323 kg/m^3 (545 lb/yd^3) of binder, except for the ones made with 0.45 *w/cm*, where 317 kg/m^3 (535 lb/yd^3) of cementitious materials was used. A coding system was adapted to label different concrete mixtures that indicates the RCA type and content, binder type, and *w/cm*. For instance, the "RCA1-50-B-40" mixture was proportioned with 50% (by volume) of RCA1, using binary cement (B), and *w/cm* of 0.40. The "RCA2-30-T-37-15F" refers to the concrete with 30% of RCA2, ternary cement (T), 0.37 *w/cm*, and 15% fine RCA. Details regarding the mixture proportions and properties are provided in Khayat and Sadati[13] and Volz et al.[16]

Specimen preparation and testing

A 110 L (4 ft^3) drum mixer was used. The batching sequence consisted of: 1) mixing the aggregate and one third of the water at low speed for 3 minutes to ensure homogenized distribution and saturation of the particles; 2) introducing the AEA diluted in one third of the mixing water and agitation at high speed for 1 minute; 3) introducing the cementitious materials and mixing for 1 minute at high speed; and 4) adding the WRA diluted with the rest of the water and mixing for 2 minutes at high speed. After 2 minutes of rest, the mixing was resumed for 3 minutes at high speed.

Slump and air content were determined according to ASTM C143[17] and ASTM C231,[18] respectively. A vibrating table was used to ensure proper consolidation of the specimens. All specimens were covered with wet burlap and plastic sheet up to 24 hours after casting. Two prismatic samples measuring 75 x 100 x 400 mm (3 x 4 x 16 in.) were used to determine the freezing-and-thawing durability of concrete according to ASTM C666 for each mixture.[19] The specimens were cured in lime-saturated water of 21 ± 2°C (70 ± 4°F). In the case of the mixtures cast with ternary cement, the curing period was 8 weeks before the start of the freezing and thawing cycles. The rest of the freeze and thaw specimens were cured for 28 days. Variations in ultrasonic pulse velocity as a function of freezing-and-thawing cycles were monitored to determine the durability factor as follows

$$DF = \left(V_n / V_0 \right)^2 \quad (1)$$

where V_n is the ultrasonic pulse velocity after n cycles of freezing-and-thawing capped at 300 cycles; and V_0 is the pulse velocity before starting the test cycles.

An automated image analysis system was employed to determine the air void parameters of hardened concrete, including total air content, spacing factor, and specific surface. Measurements were conducted in accordance with the linear-traverse method, described in ASTM C457.[2] Black coloring and white barium sulfate power were used to enhance the contrast of the polished concrete surfaces.

The resistance to deicing salt scaling was determined in accordance with ASTM C672.[15] Two slabs with surface areas of 200 x 225 mm (8 x 9 in.) and thicknesses of 75 mm (3 in.) were used for each concrete mixture. A dike was placed on the finished surface of the specimens for ponding with 4.0% aqueous solu-

Table 2—Mixture proportions and fresh properties of concrete made with RCA1 and RCA3-6

Mixture	Binder, kg/m³	OPC	GGBS	FA-C	*w/cm*	Water	DOL	RCA	Sand	RCA, % vol.	Air, %	Slump, mm	28-day f_c', MPa
		% mass				kg/m³							
DOL1-B-40	323	75	—	25	0.40	129	1120	0	782	0	6.2	85	38.5
DOL1-T-37	323	50	15	35	0.37	120	1136	0	793	0	7.2	65	50.0
DOL1-T-40	323	50	15	35	0.40	129	1120	0	782	0	5.0	85	41.5
DOL2-B-45	317	75	—	25	0.45	143	1089	0	772	0	7.2	150	35.5
RCA1-30-B-45	317	75	—	25	0.45	143	762	282	772	30	7.2	175	32.2
RCA1-50-B-45	317	75	—	25	0.45	143	544	469	772	50	6.6	135	30.8
RCA1-70-B-45	317	75	—	25	0.45	143	326	657	772	70	5.6	200	38.7
RCA1-100-B-45	317	75	—	25	0.45	143	0	939	772	100	5.4	210	38.2
RCA1-50-B-40	323	75	—	25	0.40	129	560	482	782	50	5.8	70	38.6
RCA1-50-T-37	323	50	15	35	0.37	120	568	488	793	50	6.8	65	45.0
RCA3-50-B-40	323	75	—	25	0.40	129	560	462	782	50	5.2	65	34.7
RCA3-50-T-37	323	50	15	35	0.37	120	568	466	793	50	5.4	70	43.4
RCA4-50-B-40	323	75	—	25	0.40	129	560	460	782	50	5.1	65	38.3
RCA4-50-T-37	323	50	15	35	0.37	120	568	466	793	50	5.6	35	43.9
RCA5-50-B-40	323	75	—	25	0.40	129	560	446	782	50	6.0	80	37.3
RCA5-50-T-37	323	50	15	35	0.37	120	568	451	793	50	5.2	50	35.0
RCA6-50-B-40	323	75	—	25	0.40	129	560	453	782	50	6.8	75	33.3
RCA6-50-T-37	323	50	15	35	0.37	120	568	460	793	50	6.0	50	37.4

Notes: 1 kg/m³ = 1.686 lb/yd³; 1 mm = 0.0394 in.; 1 MPa = 145.04 psi.

Table 3—Mixture proportions and fresh properties of concrete made with coarse RCA2 with or without fine RCA

Mixture	Binder, kg/m³	OPC	GGBS	FA-C	*w/cm*	Water	DOL	C-RCA	Sand	F-RCA	C-RCA	F-RCA	Air, %	Slump, mm	28-day f_c', MPa
		% mass				kg/m³					% vol.				
RCA2-30-T-37	323	50	15	35	0.37	120	795	293	793	0	30	0	6.8	85	44.1
RCA2-30-T-40	323	50	15	35	0.40	129	784	290	782	0	30	0	5.0	75	40.0
RCA2-50-B-40	323	75	—	25	0.40	129	560	482	782	0	50	0	7.2	115	47.1
RCA2-50-T-37	323	50	15	35	0.37	120	568	489	793	0	50	0	7.0	85	47.0
RCA2-50-T-40	323	50	15	35	0.40	129	560	482	782	0	50	0	5.4	50	40.5
RCA2-70-T-37	323	50	15	35	0.37	120	341	685	793	0	70	0	5.5	75	46.6
RCA2-70-T-40	323	50	15	35	0.40	129	336	675	782	0	70	0	6.9	85	50.3
RCA2-30-T-37-15F	323	50	15	35	0.37	120	795	293	674	96	30	15	5.0	85	49.0
RCA2-30-T-40-15F	323	50	15	35	0.40	129	784	290	665	94	30	15	5.0	40	37.0
RCA2-50-T-37-15F	323	50	15	35	0.37	120	568	489	674	96	50	15	6.8	85	41.5
RCA2-50-T-40-15F	323	50	15	35	0.40	129	560	482	665	94	50	15	5.6	65	38.5
RCA2-50-T-40-30F	323	50	15	35	0.40	129	560	482	548	188	50	30	5.0	85	32.0
RCA2-50-T-40-40F	323	50	15	35	0.40	129	560	482	469	250	50	40	5.0	50	31.4
RCA2-70-T-40-15F	323	50	15	35	0.40	129	336	675	665	94	70	15	5.4	50	35.0
RCA2-70-T-40-30F	323	50	15	35	0.40	129	336	675	548	188	70	30	5.2	25	37.0

Notes: 1 kg/m³ = 1.686 lb/yd³; 1 mm = 0.0394 in.; 1 MPa = 145.04 psi.

tion of calcium chloride. The specimens were subjected to 50 daily cycles of freezing and thawing. The curing regime included 28 days of curing in lime-saturated water followed by 14 days of drying in an environmental chamber conditioned at 23 ± 1°C (73 ± 2°F) and 50 ± 3% relative humidity. The degree of surface deterioration was rated qualitatively on a scale of 0 to 5, representing the best and the lowest performances, respectively, based on the criteria suggested by ASTM C672.[15] In addition, mass loss due to scaling was determined and reported as a quantitative measure (g/m²) of scaling resistance.

Bulk electrical resistivity was determined on two 100 x 200 mm (4 x 8 in.) cylindrical specimens as detailed in

Table 4—Frost durability of investigated mixtures

Mixture		Freezing-and-thawing durability factor, %	Deicing salt scaling	
			Rating	Mass loss, g/m²
Virgin aggregate	DOL1-B-40	96	1	100
	DOL2-B-45	86	1	—
	DOL1-T-37	94	1	415
	DOL1-T-40	93	3	730
Coarse RCA	RCA1-30-B-45	83	2	—
	RCA1-50-B-45	83	2	—
	RCA1-70-B-45	83	2	—
	RCA1-100-B-45	79	4	—
	RCA1-50-T-37	91	2	310
	RCA2-30-T-37	97	3	640
	RCA2-30-T-40	91	3	870
	RCA2-50-T-37	92	3	700
	RCA2-70-T-37	96	3	450
	RCA3-50-T-37	86	3	760
	RCA4-50-T-37	89	1	430
	RCA5-50-T-37	89	1	400
Fine and coarse RCA	RCA2-30-T-37-15F	96	3	1070
	RCA2-30-T-40-15F	95	3	1200
	RCA2-50-T-37-15F	96	3	800

Note: 1.0 g/m² = 0.0002 lb/ft².

ASTM C1760.[20] The specimens were cured in lime-saturated water up to the time of testing. Sorptivity measurement was conducted on two 50 mm (2 in.) thick slices of concrete, obtained from midheights of 100 x 200 mm (4 x 8 in.) cylinders in accordance with ASTM C1585.[21] The cylinders were cured in lime-saturated water for 56 days. The extracted discs were then cured in an environmental chamber with temperature of 50 ± 2°C (122 ± 4°F) and relative humidity of 80 ± 3% for 3 days. This was followed by storage in sealed containers for 15 days to ensure uniform internal moisture distribution. Specimens were then sealed on their sides, and the top surface and placed in a container with the free surface of the sample exposed to tap water of 23 ± 2°C (73 ± 4°F). Variation in mass of the specimen due to water absorption was monitored over time for a duration of 14 days.

Two cylindrical specimens measuring 150 mm (6 in.) in diameter and 300 mm (12 in.) in height were employed for determining the abrasion resistance after 56 days of curing. Testing was conducted in accordance with ASTM C944[22] with a rotating cutter covering an area with 82.5 mm (3.25 in.) diameter under fixed pressure of 197 N (44 lbf). The value of mass loss normalized to the abraded area was reported.

RESULTS AND DISCUSSION

Durability against freezing-and-thawing cycles

Table 4 presents the variations in durability factor of the investigated concrete. The DOL1-B-40 mixture made with 25% FA-C, dolomitic aggregate, and 0.40 *w/cm* exhibited

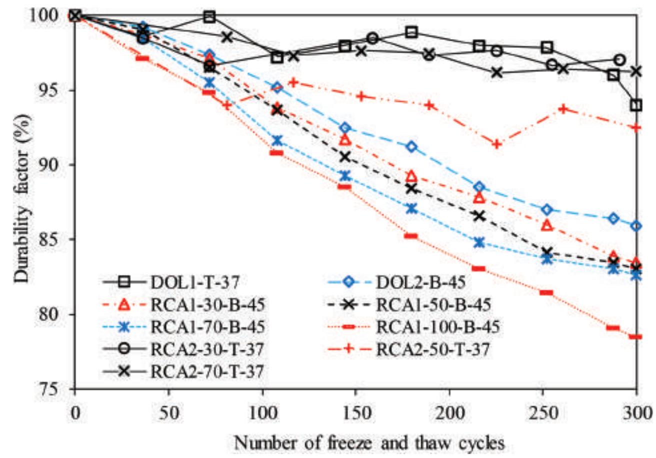

Fig. 1—Effect of coarse RCA content on durability factor.

the highest durability factor of 96%. The use of ternary cement with 50% SCM slightly reduced the durability factor; a marginal decrease to 94 and 93% for the concrete with *w/cm* of 0.37 and 0.40, respectively, was observed. The increase in *w/cm* from 0.40 to 0.45 had a more pronounced effect on durability to freezing and thawing. A drop in durability factor from 96 to 86% was observed for the DOL2-B-45 concrete, where the *w/cm* increased from 0.40 to 0.45.

Effect of coarse RCA content—Figure 1 summarizes the test results obtained for mixtures prepared with different contents of coarse RCA. The first set of the mixtures was proportioned with up to 100% of RCA1, a binary cement, and 0.45 *w/cm*. The second group was prepared with up to 70% of RCA2, a ternary cement, and 0.37 *w/cm*. Comparable durability factors were observed for concrete prepared with 0 to 100% of RCA1 in mixtures with 0.45 *w/cm* and binary cement. The reduction in durability factor was limited to 3%—that is, a decrease from 86 to 83%, with up to 70% RCA1 replacement—while the full replacement of RCA1 reduced the durability factor to 79%. The air void system of concrete made with up to 100% RCA1 and 0.45 *w/cm* was investigated. Results are summarized in Table 5 for both cases of the voids with chord length of lower than 1.0 or lower than 0.5 mm.

Results indicated excellent air-void properties for the investigated concrete, with $\bar{L}$ values lower than 200 μm (0.008 in.) and α greater than 0.24 mm^{-1} (600 in.$^{-1}$). Even though the air content in the fresh state ranged between 5.4 and 7.2%, the air content in hardened state was increasing from 6.3 to 11.2% with increasing the RCA content from 0 to 100%. This is believed to be due to the availability of air voids in the residual mortar phase of the RCA particles. Such a mechanism also led to reduction in spacing factor and increase in specific surface area. For instance as in the case of chords smaller than 0.5 mm, the highest spacing factor of 170 μm was observed for DOL1-B-45 concrete made without any RCA. However, the use of 100% RCA1 reduced the $\bar{L}$ to 80 μm (0.003 in.). Similar trends were observed when all chords smaller than 1.0 mm (0.0394 in.) were investigated, with a reduction in $\bar{L}$ from 170 to 70 μm (0.0067 to 0.0028 in.) as a result of 100% RCA incorporation. These observations were in line with the theory of pres-

Table 5—Air-void system of concrete made with 0 to 100% of RCA1

Mixture		DOL1-B-45	RCA1-30-B-45	RCA1-50-B-45	RCA1-70-B-45	RCA1-100-B-45
Fresh air, %		7.2	7.2	6.6	5.6	5.4
<0.5 mm	Air, %	4.3	6.8	6.3	6.5	8.6
	$\bar{L}$, mm	0.17	0.09	0.10	0.12	0.08
	α, mm^{-1}	29.1	38.2	37.2	30.1	37.5
<1.0 mm	Air, %	6.3	8.8	9.6	9.4	11.2
	$\bar{L}$, mm	0.17	0.09	0.08	0.11	0.07
	α, mm^{-1}	21.9	30.75	31.1	22.5	30.0

Note: 1 mm = 0.0394 in.

sure dissipation due to the use of RCA from air-entrained source proposed by Gokce et al.[23] Given the proper air-void system of the mixtures prepared with 0 to 100% RCA1, reduction in durability factor of concrete made with RCA1 can be attributed to the propagation of microcracks already available in residual mortar phase of RCA particles.

Concrete with RCA2 achieved excellent freezing-and-thawing durability. Durability factors of 97, 92, and 96% were obtained for the mixtures prepared with 30, 50, and 70% RCA2, respectively, compared to 94% for the corresponding concrete made with 100% dolomitic aggregate.

Effect of coarse RCA type—Table 4 presents the variations in durability factor for concrete made with ternary cement, 0.37 *w/cm*, and 50% of different types of RCA. All mixtures made with 50% RCA exhibited excellent freezing-and-thawing resistance with durability factors ranging from 86 to 92%. Even though the RCA4 was procured from an area with aggregate generally known as susceptible to frost damage, the RCA4-50-T-37 mixture had an acceptable resistance to freezing-and-thawing cycles, with durability factor of 89%. This was in agreement with RCA soundness test results presented in Table 1, where RCA4 exhibited the lowest mass loss of 17%. The durability factor of 86% was obtained for the concrete made with RCA3. This RCA showed the highest concentration of deleterious materials (4.5%) that were mainly composed of masonry, and the maximum mass loss obtained from the soundness test. Based on the findings, the incorporation of up to 50% coarse RCA can lead to slight variations (2 to 8%) in the frost durability factor of concrete proportioned with *w/cm* of 0.37, regardless of the RCA source.

Effect of fine RCA—Data obtained from testing concrete with up to 15% fine RCA are presented in Table 4. The mixtures were prepared with 30 or 50% coarse RCA2, ternary cement, and 0.37 or 0.40 *w/cm*. Excellent performance was obtained for such concrete with durability factor of 95% and 96%. Similar results were reported by Bogas et al.[24] who investigated the effect of 0, 20, 50, and 100% fine RCA in mixtures prepared with 0.35 *w/c*. The authors of that study reported durability factors ranging from 89% to 93%, with slight increase when using fine RCA. Results presented in Table 4 also indicate that the increase in *w/cm* from 0.37 to 0.40 resulted in 1 to 6% lower durability factor for mixtures prepared with dolomitic aggregate, 30% coarse RCA, or a combination of 30% coarse and 15% fine RCA.

In general, modifications in concrete mixture design leading to 28-day compressive strength values ranging from 30 to 50 MPa (4350 to 7250 psi), proper air entrainment in new concrete, and pressure dissipation due to use of RCA resulted in acceptable resistance to freezing-and-thawing cycles. Frost durability factor results suggest that the use of 50% coarse RCA from unknown sources, or the use of up to 70% coarse RCA obtained from air-entrained concrete can yield in concrete with proper resistance to freezing and thawing.

Deicing salt scaling

Effect of coarse RCA content—Table 4 presents a summary of surface damage ratings after 50 cycles of exposure to scaling caused by deicing salts. Concrete prepared with binary cement exhibited the best resistance to scaling. For instance, DOL1-B-40 concrete made with binary cement and 0.40 *w/cm*, exhibited accumulative mass loss of 100 g/m^2 (0.02 lb/ft^2). The use of ternary cement with 50% SCM increased the degree of sensitivity to scaling, leading to an increase in scaling from 100 to 730 g/m^2 (0.02 to 0.15 lb/ft^2). However, the reduction in *w/cm* from 0.40 to 0.37 in such concrete enhanced the resistance to scaling damage, with mass loss reduced from 730 to 415 g/m^2 (0.15 to 0.08 lb/ft^2).

Despite the satisfactory durability factor values, an increase in scaling was observed with using 70 and 100% RCA1 replacement in concrete made with binary cement and 0.45 *w/cm*. For these mixtures, scaling rates of 2 and 4 were observed with 70% and 100% RCA1, respectively, compared to 1 for the corresponding reference mixture (DOL2-B-45) prepared without any RCA.

The use of up to 70% RCA2 in concrete with ternary cement and 0.37 *w/cm* increased the degree of surface damage. An increase from 415 to 640, 700, and 450 g/m^2 (0.08 to 0.13, 0.14, and 0.09 lb/ft^2) was observed with the use of 30, 50, and 70% RCA2, respectively, in concrete made with ternary cement and 0.37 *w/cm*.

Effect of coarse RCA type—Figure 2 presents the variations in mass loss due to scaling as a function of test cycles for concrete prepared with 50% of different coarse RCA types. The mixtures prepared with 50% RCA1, RCA4, and RCA5 exhibited similar performance to that of the corresponding reference concrete, with accumulative values limited to 430 g/m^2 (0.09 lb/ft^2). As stated earlier (Table 1), these RCA sources contained relatively low (limited to 2.2%) deleterious materials and exhibited comparable soundness values ranging from 17 to 23%. The concrete made with 50% RCA3, with the highest deleterious materials content of 4.5% and highest soundness value of 36%, exhibited a deicing salt mass loss of 760 g/m^2 (0.16 lb/ft^2). In general, it can be concluded that the use of 50% coarse RCA in concrete with 0.37 *w/cm* resulted in acceptable resistance against deicing salt scaling, with mass loss limited to 500 g/m^2 (0.10 lb/ft^2). However, care must be taken regarding the scaling resistance of such concrete especially in the case of the RCA with over 4% deleterious materials content or high mass loss due to the soundness test.

Effect of fine RCA—Results presented in Fig. 3 indicate that the use of up to 15% fine RCA can lead to greater mass loss due to deicing salt scaling. The incorporation of 15% fine RCA increased the scaling in mixture with

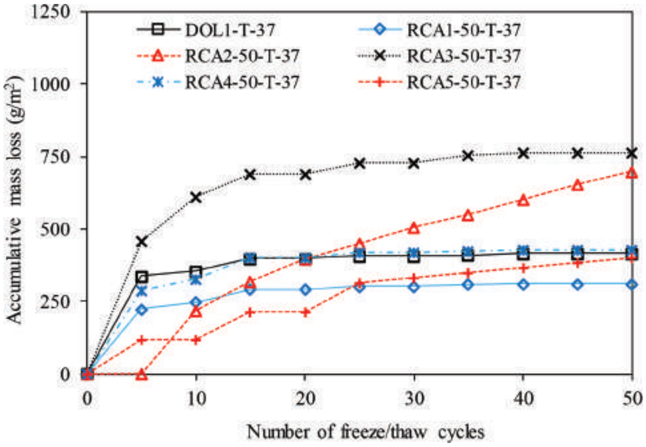

Fig. 2—Effect of coarse RCA type on accumulative mass loss of deicing salt scaling samples. (Note: 1 g/m² = 0.0002 lb/ft².)

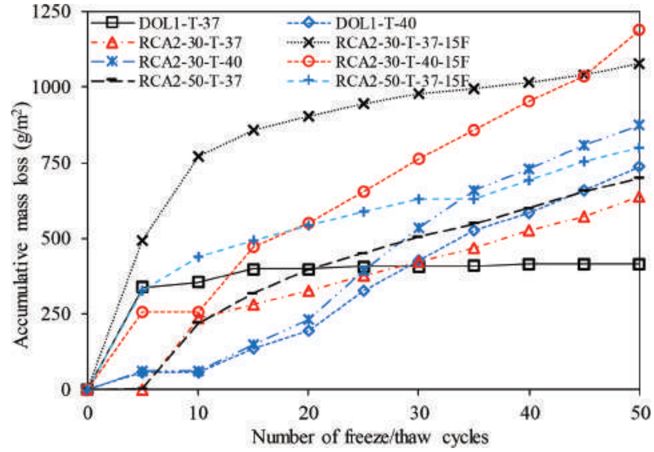

Fig. 3—Effect of fine RCA content on deicing salt scaling mass loss of concrete made with different coarse RCA and w/cm. *(Note: 1 g/m² = 0.0002 lb/ft².)*

30% of RCA2, ternary cement, and 0.40 *w/cm* from 870 to 1190 g/m² (0.18 to 0.24 lb/ft²). Similar trends were observed for the mixtures with 30% or 50% of RCA2, ternary cement, and 0.37 *w/cm*, where the use of 15% fine RCA increased the accumulative mass loss from 640 to 1080 g/m² (0.13 to 0.22 lb/ft²) and from 700 to 800 g/m² (0.14 to 0.16 lb/ft²), respectively. In summary, it can be concluded that even though the incorporation of up to 15% fine RCA did not have a negative impact on durability factor, the resistance to scaling can be affected by fine RCA incorporation. This might be due to the fact that the fine RCA materials typically contain considerable amount of impurities that can react with the binder and deicing salts. Moreover, the incorporation of fine RCA can increase the permeability of the mortar and reduce its compressive strength, resulting in severe scaling damage.

In general, it was concluded that the use of RCA can enhance the risk of damage caused by deicing salts. This is in agreement with the increase in permeability due to the use of RCA which can result in accelerated penetration of chloride ions into concrete, despite the fact that some of the chloride ions can get bound to the mortar phase of the RCA.[25,26]

Electrical resistivity

Effect of coarse RCA content—Figure 4 presents the effect of coarse RCA content on electrical resistivity. Two RCA types were used in two groups of concrete mixtures prepared with either a ternary cement and 0.37 *w/cm* or a binary cement and 0.45 *w/cm*. An increase in electrical resistivity was observed with time, regardless of the RCA content. Such a time-dependent rate of increase in electrical resistivity was more significant in the case of the T-37 mixtures, which could be attributed to advanced pozzolanic activity at later age. For instance, in the case of the mixtures prepared with 50% RCA, the resistivity values were enhanced from 7.4 to 11.1 KΩ.cm for concrete made with binary cement and 0.45 *w/cm* compared to an increase from 16.5 to 31.2 KΩ.cm for the mixture prepared with ternary cement and 0.37 *w/cm*.

Regardless of the binder system, a tendency to decrease in electrical resistivity was observed with greater use of RCA. The reduction in electrical resistivity was more pronounced for concrete prepared with ternary cement and 0.37 *w/cm*. In other words, the sensitivity to using RCA was higher for concrete prepared with the ternary binder. For instance, the use of 70% coarse RCA reduced the 91-day electrical resistivity from 35.0 to 29.2 KΩ.cm in concrete made with ternary cement and 0.37 *w/cm*. Such a reduction was limited to 2.8 KΩ.cm (from 13.1 to 10.3 KΩ.cm) for concrete made with 0.45 *w/cm* and binary cement.

Results obtained for mixtures prepared with ternary cement indicated higher sensitivity to variation in *w/cm* for mixtures prepared without any RCA. The 91-day resistivity of concrete made with ternary cement and DOL1 coarse aggregate was 27.4 and 35.0 KΩ.cm for mixtures made with 0.40 and 0.37 *w/cm*, respectively. This corresponds to over 21% increase in resistivity due to reduction in *w/cm* from 0.40 to 0.37. The incorporation of 50% RCA2 in these mixtures resulted in 91-day electrical resistivity of 30 and 31 KΩ.cm at 0.40 and 0.37 *w/cm*, respectively, as indicated in Fig. 4 and 5.

Effect of coarse RCA type—Figure 5 presents the electrical resistivity measurements for concrete made with 50% RCA from various sources. The mixtures were proportioned with either binary cement and 0.40 *w/cm* or ternary cement and 0.37 *w/cm*. The mixtures made with 0.40 and 0.37 *w/cm* and dolomitic aggregate exhibited 91-day electrical resistivity of 18.7 and 35.0 KΩ.cm, respectively. Results obtained for 91-day measurements of the B-40 mixtures with 50% coarse RCA ranged from 14.8 to 19.1 KΩ.cm, corresponding to up to 21% reduction or up to 2% increase in electrical resistivity. The resistivity of the T-37 mixtures made with 50% coarse RCA were lower than the concrete without any RCA, with values ranging from 27.4 to 31.2 KΩ.cm, corresponding to an 11 to 22% decrease compared to the DOL1-T-37 mixture. As indicated in Fig. 5, the increase in water absorption of the RCA reduces the 91-day resistivity. This was in line with observations of Duan and Poon[10] and Kou et al.[11]

In general, it may be concluded that the electrical resistivity of concrete made with 50% coarse RCA can be up to 32% lower than that of the mixture prepared with virgin coarse aggregate, regardless of the RCA source. Such a behavior can be attributed to higher permeability, presence of potentially porous and cracked residual mortar, potential ionic contamination, and the availability of damaged ITZ in

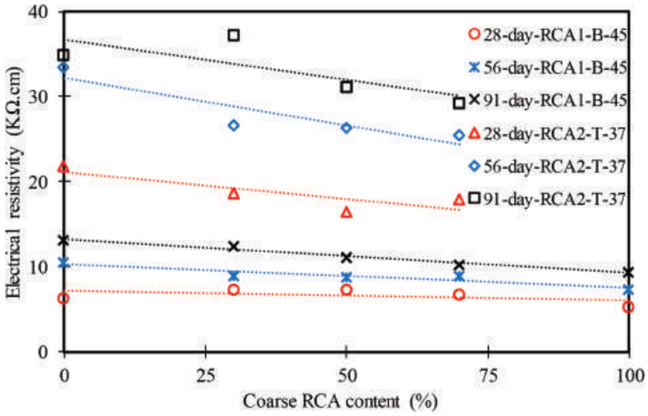

Fig. 4—Effect of coarse RCA content on electrical resistivity.

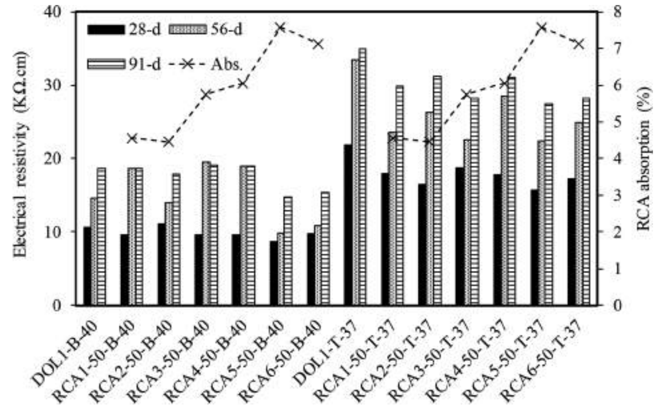

Fig. 5—Electrical resistivity of concrete made with 50% coarse RCA.

RCA materials. However, proportioning the RCA in concrete with lower *w*/*cm* of 0.37 and ternary cement was effective in mitigating the negative impacts of RCA on electrical resistivity compared to concrete with binary cement, 0.40 *w*/*cm*, and 100% dolomitic virgin coarse aggregate. The minimum 91-day resistivity of concrete made with ternary cement, 0.37 *w*/*cm*, and 50% of coarse RCA (27.4 KΩ.cm) was higher than that of the concrete made with binary cement, 0.40 *w*/*cm*, and without any RCA (18.7 KΩ.cm).

Effect of fine RCA content—Figure 6 presents the effect of fine RCA on electrical resistivity of concrete proportioned with ternary cement and 0.40 *w*/*cm*. It was generally observed that the use of fine RCA tends to reduce the electrical resistivity, especially at earlier ages. However, the rate of reduction was not significant for up to 40% fine RCA replacement. The use of up to 40% fine RCA in concrete made with 50% coarse RCA reduced the 56- and 91-day electrical resistivity from 25.4 to 22.2 KΩ.cm, and from 29.7 to 26.4 KΩ.cm, corresponding to 13 and 11% reduction, respectively. This can be due to the advanced hydration of the ternary cement at 91 days that results to a more densified pore structure, hence compensating for the impact of the fine RCA on resistivity. Another justification for such observations can be the fact that the incorporated fine RCA was obtained from airfield concrete where chloride bearing salts are not used as deicing agents.

Sorptivity

Table 6 and Fig. 7 present the results of sorptivity measurements for concrete made with ternary cement and different amounts of coarse and fine RCA. Results are compared to concrete prepared without any RCA, proportioned with binary or ternary cement and 0.40 *w*/*cm*. The highest water absorption was observed for the DOL1-B-40 mixture that exhibited initial and secondary sorptivity values of 2.23×10^{-6} and 0.89×10^{-6} $mm.s^{-0.5}$, respectively. The initial and secondary sorptivity values of DOL1-T-40 concrete were 1.49×10^{-6} and 0.55×10^{-6} $mm.s^{-0.5}$, respectively. A slight increase in sorptivity was observed with the use of 30% coarse RCA or a combination of 30% coarse RCA and 15% fine RCA in concrete with 0.40 *w*/*cm*. The secondary sorptivity values were 0.60×10^{-6} and 0.62×10^{-6} $mm.s^{-0.5}$ for the RCA2-30-T-40 and RCA2-30-T-40-15F mixtures, respectively, corresponding to up to 13% increase. The use of a greater amount of coarse RCA in mixtures with 0.37 *w*/*cm* resulted in negligible increase in water absorption, with secondary sorptivity values of 0.51×10^{-6}, 0.50×10^{-6}, and 0.53×10^{-6} $mm.s^{-0.5}$ for concrete made with 30, 50, and 70% coarse RCA, respectively. This is in agreement with observations of Medina et al.,[27] who reported an increase in 28-day sorptivity due to RCA use in concrete made with 323 kg/m^3 OPC and 0.65 *w*/*c*. The authors reported sorptivity values of 0.68, 0.67, and 0.79 $mm/h^{0.5}$ for concrete made with 0, 30, and 50% coarse RCA.[27] In summary, the sorptivity values obtained for mixtures made with ternary cement, 0.37 *w*/*cm*, and various amounts of RCA were generally lower than that of concrete made with binary cement, 0.40 *w*/*cm*, and 100% virgin aggregate.

Abrasion resistance

Table 6 presents the abrasion resistance results of mixtures prepared with different amounts of coarse RCA2 with or without fine RCA. Mixtures prepared with 100% virgin aggregate and 0.40 *w*/*cm* exhibited similar mass loss values of 225 g/m^2 (0.045 lb/ft^2), regardless of the binder type. An increase in mass loss from 225 to 245 g/m^2 (0.05 to 0.49 lb/ft^2), corresponding to a 9% increase, was observed for the concrete containing 30% coarse RCA and proportioned with 0.40 *w*/*cm* and ternary cement. However, all mixtures prepared with 0.37 *w*/*cm* had lower abrasion mass loss regardless of the fine and coarse RCA content. For instance, the mass loss obtained for the RCA2-70-T-37 mixture was limited to 130 g/m^2 (0.026 lb/ft^2), corresponding to a 42% reduction in comparison with the DOL1-T-40 concrete. In addition to the higher paste quality, such an observation can be due to the higher quality of the incorporated coarse RCA that have a Los Angeles abrasion value of 33% in comparison with the virgin coarse aggregate with Los Angeles resistance of 28%. Based on the obtained data, it can be concluded that reducing the *w*/*cm* and using RCA with relatively low Los Angeles abrasion value can reduce the risk of wear damage of concrete.

Coefficient of thermal expansion

Table 6 summarizes the CTE values obtained for mixtures prepared with different amounts of coarse RCA2, made with or without fine RCA. Slight variations in CTE were observed for the investigated mixtures. In general, the spread in CTE was limited to 0.66×10^{-6} m/m/°C. The concrete prepared with dolomitic aggregate, binary cement, and 0.40 *w*/*cm*

Table 6—Mass loss due to abrasion, coefficient of thermal expansion, and sorptivity results

Mixture	Mass loss, g/m^2	CTE, E-6 m/m/°C	Initial sorptivity, E-6 mm/s$^{0.5}$	Secondary sorptivity, E-6 mm/s$^{0.5}$
DOL1-B-40	225	9.40	2.23	0.89
DOL1-T-40	225	9.07	1.49	0.55
RCA2-30-T-37	150	9.34	1.23	0.51
RCA2-30-T-40	245	9.14	1.89	0.60
RCA2-30-T-37-15F	130	9.12	0.86	0.37
RCA2-30-T-40-15F	205	8.90	1.59	0.62
RCA2-50-T-37	95	9.25	1.23	0.50
RCA2-50-T-37-15F	130	—	1.13	0.49
RCA2-70-T-37	130	8.74	1.29	0.53

Notes: 1.0 g/m^2 = 0.0002 lb/ft^2; 1.0 ×10^{-6} m/m/°C = 0.556 E-6 in./in./°F; 1 mm = 0.0394 in.

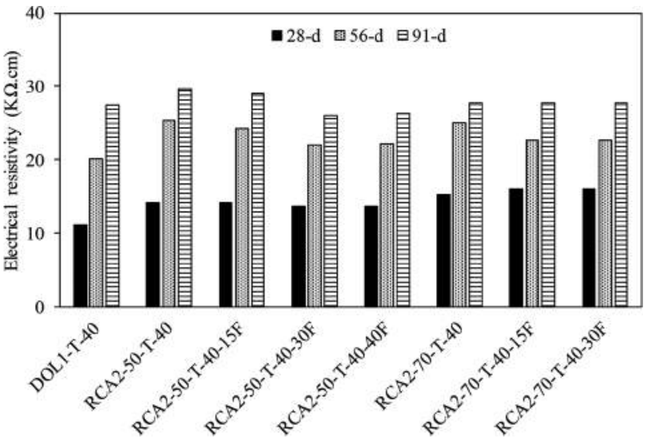

Fig. 6—Effect of fine RCA content on electrical resistivity.

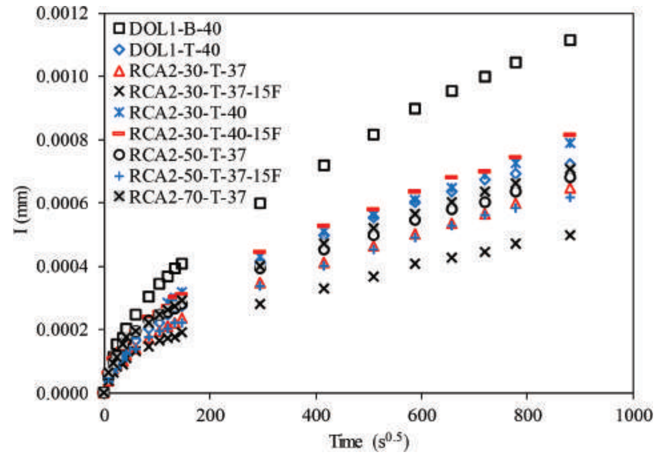

Fig. 7—Effect of coarse and fine RCA on sorptivity results. (Note: 1 mm = 0.0394 in.)

exhibited the highest CTE of 9.40 × 10^{-6} m/m/°C. The use of ternary cement reduced the CTE to 9.07 × 10^{-6} m/m/°C. In general, a lower coefficient of thermal expansion was observed for the mixtures prepared with RCA, with the lowest CTE of 8.74 × 10^{-6} m/m/°C obtained for the concrete made with 70% coarse RCA, ternary cement, and 0.37 *w/cm*. These results are contrary to the observations reported by Sadati and Khayat[12] where an increase in 56-day CTE from 7.88 × 10^{-6} to 8.68 × 10^{-6} m/m/°C was observed in concrete made with 40% coarse RCA replacement of limestone virgin coarse aggregate, binary cement, and 0.40 *w/cm*.

It should be noted that the mineral composition of the old virgin aggregate available in RCA materials was not determined in this study. However, given the fact that CTE is highly dependent on the coarse aggregate properties, the relatively close CTE values suggest comparable mineralogical properties of the old virgin aggregates.

SUMMARY AND CONCLUSIONS

Durability of concrete made with RCA was investigated. RCA from five commercial recycling centers, along with one laboratory-produced RCA were employed at replacement rates of 30, 50, 70, and 100% by volume. Up to 40% fine RCA was also used. The reference mixtures were proportioned with 25% fly ash, without any RCA, and with either 0.40 or 0.45 *w/cm*. Concrete with a lower *w/cm* of 0.37 and ternary cement was also prepared to compensate for anticipated loss of durability stemming from the use of RCA. Based on the results of this study, the following conclusions are warranted.

1. The use of up to 70% coarse RCA from a high-quality air-entrained concrete source used in airfield construction or laboratory-produced air-entrained concrete did not cause any significant variation in frost durability. The use of 50% commercially produced RCA in concrete proportioned with 0.37 *w/cm* reduced the durability factor from 94 to 86%, although both values are considered to provide adequate frost durability. On the other hand, such concrete exhibited greater deicing salt scaling with increase in mass moss from 415 to up to 760 g/m^2 (0.08 to 0.16 lb/ft^2).

2. An increase in volume of air in hardened state from 6.3 to 11.2% was observed with 100% replacement of virgin coarse aggregate with RCA from an air-entrained source. A reduction in spacing factor from 170 to 70 µm (0.0066 to 0.0028 in.), and an increase in specific surface from 21.9 to 30 mm^{-1} was observed for such concrete.

3. No reduction in frost durability factor was observed when the fine RCA volume was limited to 15%, regardless of the *w/cm* (0.37 or 0.40). However, the use of 15% fine RCA in concrete made with ternary binder and 0.40 *w/cm* increased the mass loss due to scaling from 870 to 1190 g/m^2 (0.18 to 0.24 lb/ft^2).

4. The increase in fine and coarse RCA reduced the electrical resistivity, and the effect is dependent on the RCA content, binder type, and *w/cm*. The use of up to 40% fine RCA in

concrete prepared with ternary cement and 0.40 *w/cm* reduced the 91-day electrical resistivity by up to 10%. Concrete with lower *w/cm* (0.37) and ternary cement was more sensitive to the use of RCA. Up to 32% reduction in electrical resistivity was observed with 50% coarse RCA replacement in such mixtures.

5. The maximum sorptivity of 8.9×10^{-7} $mm.s^{-0.5}$ was observed for the concrete made with binary cement, 0.40 *w/cm*, and without any RCA. Even though a slight increase in sorptivity was observed with the use of RCA, the use of ternary binder and reduction in w/cm from 0.40 to 0.37 reduced the sorptivity.

6. Concrete made with RCA exhibited lower abrasion resistance. However, the use of lower *w/cm* of 0.37 was effective in reducing the abrasion damage. The mass loss dropped from 225 g/m^2 (0.05 lb/ft^2) in the case of concrete with 0.40 *w/cm* and 100% virgin aggregate to 130 g/m^2 (0.026 lb/ft^2) for concrete with 0.37 *w/cm* and 70% coarse RCA. A slight reduction, limited to 7%, was observed in CTE of concrete made with up to 70% coarse RCA.

7. Based on the data obtained through the study, the use of RCA with low water absorption, high specific gravity, and low mass loss due to abrasion can be recommended for use in transportation infrastructure. It is also recommended to consider modifications in mixture design, including the use of optimized binder compositions and low *w/cm* to ensure durability.

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