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Mechanical and Durability Properties of Concrete Produced with Treated Recycled Concrete Aggregate

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The presence of attached mortar is the main reason for lower quality of recycled concrete aggregate (RCA) compared to that of natural aggregate. Hence, its use is limited up to 30% replacement of natural aggregate at present. The attached mortar of the RCA can be removed by mechanical treatment, acid treatment, thermal treatment (500 to 750°C [932 to 1382°F]), and microwave treatment. There are difficulties—such as achieving high temperature and treating larger quantities of RCA with acid and a microwave oven—in applying these treatments at field level. Hence, the present study focuses on a combination of heating (250°C [482°F]) and mechanical treatment to improve the quality of the RCA. This method removed 70 to 80% of attached mortar of the RCA. Properties of RCA such as bulk density, specific gravity, water absorption, and crushing value were discussed in detail. Post-treatment, it was observed that the properties of treated RCA improved compared to untreated RCA, but still they were found to be poorer than natural aggregate. The experimental studies were carried out to overcome the aforementioned drawbacks of the recycled aggregate concrete by incorporation of mineral admixtures. It was found that the use of mineral admixtures in concrete produced with treated RCA enhances both the mechanical and durability properties. Thus, the concrete produced with treated RCA and mineral admixture will lead to sustainable development.

Keywords: durability; mechanical properties; mineral admixtures; sustainable concrete; treated recycled concrete aggregate.

INTRODUCTION

Concrete has been one of the main construction materials for more than a century. Fine and coarse aggregates generally occupy 60 to 75% of the concrete volume. The global consumption of natural aggregate (NA) is estimated to be 9 to 10 billion tonnes (10 to 11 billion tons) each year. Of this, approximately 7.2 billion tonnes (8 billion tons) of aggregate (sand, gravel, and crushed rock) are being used in portland-cement concrete every year. There will be a critical shortage of natural aggregate in the future; hence, there is a need to find an alternative material for natural coarse aggregate. One of the sources for alternative aggregate is recycled concrete aggregate (RCA) from construction and demolition wastes.[1,2]

Construction and demolition waste consists of inert material such as concrete, plaster, metal, glass, wood, and plastics. These wastes are usually dumped in unauthorized landfills which will not only affect the landfills but the environment as well. In India, the Central Pollution Control Board has estimated solid waste generation to be about 43.5 million tonnes (48 million tons) per year, of which 25% is from the construction industry.[3] About 181 to 272 million tonnes (200 to 300 million tons) of solid waste are generated annually in the United States.[4] In Shanghai, China, the quantity of such waste is 19.1 million tonnes (21.1 million tons) per year, which is 45% of the city's total annual solid waste production.[5] The construction waste disposed of in landfills in Hong Kong was reported to be 3251 tonnes (3584 tons) per day, which accounted for 26% of Hong Kong's total daily solid waste production.[6] There are significant ecological advantages in recycling the waste concrete from construction and its demolition into aggregates. It is seen from the literature[7,8] that the properties such as density, water absorption, specific gravity, and crushing value have a negative influence on recycled aggregate concrete quality. Grabiec et al.[9] concluded that the method of bio-deposition of calcium carbonate improved the quality of recycled aggregate. It led to reduction in the water absorption of RCA. The acid concentration of 0.1M proposed in the acid presoaking method developed by Tam et al.[10] was reported to result in only 7.27 to 12.17% reduction in the water absorption of the RCA samples tested. The acid concentration of 2M proposed in the method developed by Akbarnezhad et al.[11] was reported to result in less than 1% of water absorption of the RCAs. It is very difficult to implement these chemical treatments in field applications, where large quantities of aggregates are used.

RESEARCH SIGNIFICANCE

Recycled aggregates from construction and demolition wastes consist of natural aggregate and attached cement mortar. Due to the old, attached mortar, recycled aggregates have poor physical and mechanical properties. Hence, their use is limited to up to 30% replacement of natural aggregate with RCA in structural applications.[12,13] To the extent of the authors' knowledge, the treatment methods to remove the attached mortar are mechanical treatment, acid treatment, microwave treatment, and thermal treatment. By using mechanical treatment, only 10 to 20% of the attached mortar can be removed. The acid treatment is difficult to apply for field applications, where the quantity of aggregate treated is large. However, this method can be applied for the evaluation of total mortar content of RCA in the laboratory. Microwave treatment removes the attached mortar, but to achieve good results, this application needs a lot of knowledge or experience to understand and moderate effects such as uneven heating or the thermal runaway; addition-

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ally, adoption of this method for field application is difficult, where the quantity of RCA treated will be more than in a laboratory. Similarly, the heating treatment can be used to remove the total attached mortar content by heating the RCA to 500 to 750°C (932 to 1382°F). However, to the best of the authors' knowledge, only a few laboratory studies[14,15] have been reported to evaluate the physical and mechanical properties of RCA treated using heat treatment, and no information is available on the mechanical and durability properties of concrete prepared using heat-treated RCA in the literature. There will be some difficulties in achieving high temperature (500 to 750°C [932 to 1382°F]) at field level; hence, the present study focused on the combination of heating and mechanical treatment, and was extended to study mechanical and durability properties of concrete. In this method, recycled aggregate was heated to a temperature of 250°C (482°F) and then the aggregates were dry-mixed in a pan mixture to remove the attached mortar. This method removed 70 to 80% of attached mortar of the RCA. Concrete mixtures were prepared by using 50% and 100% RCA and 50% and 100% treated recycled concrete aggregate (TRCA) in place of natural aggregate. Influences of supplementary cementations materials, such as fly ash and silica fume, on concrete prepared using TRCA were studied.

EXPERIMENTAL PROGRAM

Materials

Demolition waste was obtained from a 30-year-old residential building. Recycled coarse aggregates were prepared by crushing the demolished concrete in a jaw crusher. Crusher products from each of the demolished concretes were screened into two sizes (20 and 10 mm [0.78 and 0.39 in.]) and recombined (that is, 60% of 20 mm [0.78 in.] and 40% of 10 mm [0.39 in.] aggregate) into an RCA. To improve the quality of the recycled aggregates, a heating and rubbing treatment described in the next section was used. Ordinary 53 Grade portland cement conforming to IS 12269[16] was used. Fly ash from a thermal power plant near Chennai, India, and a commercially available silica fume were used. Specific gravity and fineness of cement were measured as per IS 4031.[17] Specific gravity and fineness of fly ash and silica fume were measured as per IS 1727.[18] The specific gravity of cement, fly ash, and silica fume were 3.15, 2.2, and 2.1, respectively. Fineness (measured using Blaine's air permeability apparatus) of cement, fly ash, and silica fume were 365, 385, and 16,000 m^2/kg (1782, 1879, and 78,118 ft^2/lb), respectively. Locally available river sand passing through a 4.75 mm (0.18 in.) sieve was used as fine aggregate. Blue granite crushed stone aggregate of sizes 20 and 10 mm (0.78 in.) and 10 mm (0.39 in.) was used at the same ratio of 60:40 by volume as natural aggregate.

Heating and rubbing treatment for RCA

The presence of mortar was the main reason for the lower quality of the recycled aggregate compared to natural aggregate. Quality of the recycled aggregates can be improved by heating and rubbing treatment. In this method, the recycled concrete aggregates were first heated to a temperature of 250°C (482°F) for 4 hours, and then the heated aggregates were immediately immersed in water, causing a sudden reduction in the aggregate temperature and creating internal thermal stresses. The interface between the aggregate and attached mortar became weak after the application of the heating treatment. The thermal expansion coefficient of a natural aggregate (5 to 13 × 10^{-6}/°C [32.000009 to 32.0000234/°F]) is quite smaller than that of cement mortar (11 to 20 × 10^{-6}/°C [32.0000198 to 32.000036/°F]). Therefore, heating and cooling a sample can weaken the interface between grains and thereby promote preferential breakage along the grain boundaries.[19] After that, these aggregates were dry-mixed in a pan-type mixer for 2 to 3 minutes to remove the adhered mortar. Then, the mixture of RCA and separated mortar sieved through standard sieves for preparation of TRCA.

Fig. 1—Oven used for heating recycled concrete aggregate.

Figure 1 shows the oven used for heating recycled aggregate to a temperature of 250°C (482°F). It was also observed that in some of the recycled aggregate, weak parts of the attached mortar separated during the rubbing process and the size of the cement mortar decreased. This method removed 70 to 80% of the adhered mortar by mass with weight loss of 32% and 35% for 20 and 10 mm (0.78 and 0.39 in.) RCA, respectively. The heating and rubbing treatment used in the present study was found to be effective in improving the quality of RCA. It is difficult to implement acid treatment for field applications where the aggregates are used in large quantities, whereas it is possible to treat large quantities of RCA using heating and the rubbing treatment method; thus, it can be applied for field applications.

To determine the mortar content of RCA, the aggregates were heated to a temperature of 500°C (964°F) for 2 hours, then the aggregates were immersed in water. After cooling, the attached mortar of the RCA was separated manually by using a rubber hammer. The weights of the attached mortar and original aggregates were used to determine the mortar content of the RCA and it was found to be approximately 42%.

Mixture proportion and test specimens

The concrete mixture proportions were designed in accordance with IS 10262,[20] with a common target slump of 70 ± 10 mm (2.75 ± 0.39 in.). A high-range water-reducing

Table 1—Mixture proportions per 1 m³ (35.3 ft³) of concrete

Serial No.	Specimen ID	Cement, kg/m³ (lb/ft³)	Fly ash/silica fume, kg/m³ (lb/ft³)	Sand, kg/m³ (lb/ft³)	Natural coarse aggregates, kg/m³ (lb/ft³)	Recycled coarse aggregates, kg/m³ (lb/ft³)	Water, kg/m³ (lb/ft³)
1	NAC	362 (22.59)	—	832 (51.94)	1030 (64.30)	—	170 + 9 (10.61 + 0.56)
2	RAC-50	362 (22.59)	—	812 (50.69)	515 (32.15)	460 (28.71)	170 + 28 (10.61 + 1.74)
3	RAC-100	362 (22.59)	—	793 (49.5)	—	921 (57.49)	170 + 47 (10.61 + 2.93)
4	TRAC-50	362 (22.59)	—	817 (51)	515(32.15)	487 (30.4)	170 + 13 (10.61 + 0.81)
5	TRAC-100	362 (22.59)	—	803 (50.12)	—	974 (60.8)	170 + 19 (10.61 + 1.18)
6	TRAC-50-FA	362 (22.59)	41 (2.56)	808 (50.44)	515 (32.15)	414 (25.84)	170 + 12 (10.61 + 0.74)
7	TRAC-100-FA	362 (22.59)	83 (5.18)	782 (48.81)	—	828 (51.69)	170 + 16 (10.61 + 0.99)
8	TRAC-50-SF	362 (22.59)	22 (1.37)	809 (50.5)	515 (32.15)	437 (27.28)	170 + 13 (10.61 + 0.81)
9	TRAC-100-SF	362 (22.59)	44 (2.75)	784 (48.94)	—	875 (54.62)	170 + 17 (10.61 + 1.06)

Notes: NAC is natural aggregate concrete; RAC is recycled aggregate concrete; TRAC is treated recycled aggregate concrete; FA is fly ash; SF is silica fume; and numeric digit (50 and 100) = % of recycled aggregate.

admixture made of sulfonated naphthalene formaldehyde was used. The content was 0.5% by weight of the binder. To adjust the higher water absorption of recycled aggregate based on trial tests, 75% of the maximum water absorption capacity of the aggregates was determined and this additional amount of water was added to the water content required for the designed mixture to prepare RAC.

A series of nine concrete mixtures were prepared in the present study. The first concrete mixture was prepared using natural aggregate for reference and designated as natural aggregate concrete (NAC). The second and third concrete mixtures were prepared using 50% and 100% RCA in place of natural aggregate and designated as RAC-50 and RAC-100, respectively. The fourth and fifth concrete mixtures were prepared using 50% and 100% TRCA in place of natural aggregate and designated as TRAC-50 and TRAC-100, respectively. The sixth and seventh concrete mixtures were prepared by incorporating 10% fly ash (by volume of RCA) in addition to cement and using 50% and 100% TRCA in place of natural aggregate, and were designated as TRAC-50-FA and TRAC-100-FA, respectively. The eighth and ninth mixtures were prepared by incorporating 5% silica fume (by volume of RCA) in addition to cement and using 50% and 100% TRCA in place of natural aggregate, and were designated as TRAC-50-SF and TRAC-100-SF, respectively. The details of the mixtures are given in Table 1.

Mechanical and durability properties of recycled aggregate concrete

Cubes of size 100 mm (3.94 in.) were tested in compression under surface-dry condition, and cylinders with a 100 mm (3.93 in.) diameter and 200 mm (7.87 in.) length were tested for split tensile strength. Bulk density, absorption after immersion, and volume of permeable pore space (voids) of hardened concrete were determined according to ASTM C642.[21] The rate of water absorption of concrete was determined using 50 mm (1.96 in.) thick circular slices that were cut from the cylinders having a diameter of 100 mm (3.93 in.) and height of 200 mm (7.87 in.). The Rapid Chloride Permeability Test was used to record the amount of charge that passes through a sample of concrete to calculate its permeability. In the present study, ASTM C1202[22] was used to determine the amount of charge that passed through the samples of concrete.

Modulus of elasticity

Cylinders of 150 mm (5.9 in.) diameter and 300 mm (11.81 in.) height were cast to determine the modulus of elasticity of recycled aggregate concrete. The top and the bottom surface of the cylinders were smoothened with the help of grinding machine and subsequently capped with sulfur to obtain a truly horizontal surface. The testing was done in a 2500 kN (562 kip) servo-controlled universal testing machine. Two linear variable displacement transducers (LVDTs) were placed diametrically opposite to measure the displacement. The displacement was measured between the two platens. The LVDTs were connected to an online data acquisition system. The cylinder was placed concentrically in the testing machine, as shown in Fig. 2.

RESULTS AND DISCUSSION

Physical and mechanical properties of recycled concrete aggregate

Sieve analysis was conducted to confirm that all the aggregates used for the mixture met the specifications of IS 2386.[23] The grading for RCA and TRCA are shown in Fig. 3. The grading of RCA and TRCA was found to be similar to that of the natural aggregate.

Bulk density (dry) and specific gravity

One of the most remarkable differences between recycled concrete aggregate and natural aggregate is bulk density (dry). Recycled concrete aggregates have lower dry density when compared to natural aggregates. This was due to the presence of adhered mortar in the recycled aggregates. Dry bulk density and specific gravity (saturated surface-dry condition [SSD]) of natural and recycled aggregate is presented in Table 2. Reductions in bulk density (dry) were observed as 9% and 12% for RCA of size 10 and 20 mm (0.39 and 0.78 in.), respectively, in comparison to natural aggregates. The increase in bulk density (dry) of recycled aggregates when heating and rubbing treatment was used was 8% and 10% for aggregates of size 10 and 20 mm (0.39 and 0.78 in.),

Fig. 2—Modulus of elasticity test setup.

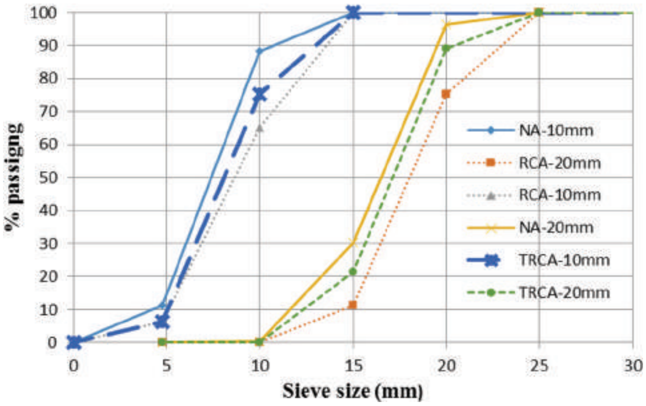

Fig. 3—Gradation of natural and recycled concrete aggregate. (Note: 1 mm = 0.0394 in.)

respectively. From Table 2, it can be clearly seen that the specific gravity (SSD) of recycled aggregates was 10% to 11% less when compared with natural aggregate. The low specific gravity (SSD) of the recycled aggregate compared to the natural aggregate was due to the high porosity and low density of the attached mortar on the surface of the old aggregates.[24,25] The specific gravity of TRCA is 5% to 7% greater when compared with RCA, which was similar to the results of Quan et al.[26]

Water absorption

Water absorption of natural and recycled aggregate is presented in Table 3. Recycled concrete aggregate of sizes 10 and 20 mm (0.39 and 0.78 in.) had very high percentages of water absorption. The water absorption of recycled concrete aggregate was 6.8 times greater than that of natural aggregate, while many investigations found the water absorption to be approximately six to 10 times.[27-29] This was due to the porous characteristics of the mortar residue adhering to the original aggregate particles. The high water absorption of recycled aggregate increases the water absorption of concrete. The water absorption of TRCA was around 66% less when compared with RCA. This was due to the heating and abrasion treatment method that removed 70 to 80% of attached mortar of the recycled concrete aggregate. Similar findings were reported by other researchers.[30,31] This indicates that at a temperature of 250°C (482°F) internal stresses developed due to thermal expansion of RCA and finally affected the mechanical properties. Therefore, RCA suffers widely from degradation, and there is a breakdown and mass loss of concrete due to exposure to high temperature.[32] Therefore, water absorption of RCA reduced drastically after the heating and rubbing treatment method.

Table 2—Bulk density and specific gravity of RCA and treated RCA

Aggregate type	Bulk density, kg/m^3 (lb/ft^3)		Specific gravity	
	10 mm (0.39 in.)	20 mm (0.78 in.)	10 mm (0.39 in.)	20 mm (0.78 in.)
NA	1572 (98.13)	1690 (105.50)	2.77	2.75
RCA	1430 (89.27)	1483 (92.58)	2.41	2.42
TRCA	1550 (96.76)	1664 (103.88)	2.52	2.59

Notes: NA is natural aggregate; RCA is recycled concrete aggregate; and TRCA is RCA treated using heating and rubbing treatment.

Table 3—Water absorption of RCA and treated RCA

Aggregate type	Water absorption, %	Water absorption, %
	10 mm (0.39 in.)	20 mm (0.78 in.)
NA	0.69	0.7
RCA	4.67	4.8
TRCA	1.59	1.62

Notes: NA is natural aggregate; RCA is recycled concrete aggregate; and TRCA is RCA treated using heating and rubbing treatment.

Crushing value

The standard aggregate crushing test was performed on aggregate passing through a 12.5 mm (0.49 in.) sieve and retained on a 10 mm (0.39 in.) sieve as per IS 2386.[23] The crushing value of RCA was found to be 29.49%, which was marginally higher than that of natural aggregate (26.56%). The resistance against crushing of RCA is relatively lower than of natural aggregate, as observed by other researchers,[33,34] due to the separation and crushing of porous mortar. The heating and rubbing treatment method reduced the crushing value of RCA to 27.44%. It is clear from the results that the resistance against crushing of RCA is improved after heating and rubbing treatment method.

RESULTS OF MECHANICAL AND DURABILITY PROPERTIES OF RECYCLED AGGREGATE CONCRETE

Compressive and split tensile strength

Table 4 shows the compressive and split tensile strength of concrete prepared with natural, recycled, and treated recy-

Table 4—Compressive and split tensile strength of recycled aggregate concrete

Serial No.	Specimen ID	Compressive strength, MPa (psi)	Split tensile strength, MPa (psi)
1	NAC	38.25 (5547)	2.98 (432)
2	RAC-50	34.04 (4937)	2.59 (375)
3	RAC100	31.74 (4603)	2.53 (366)
4	TRAC-50	35.95 (5214)	2.83 (410)
5	TRAC-100	35.57 (5158)	2.74 (397)
6	TRAC-50-FA	45.13 (6545)	2.68 (388)
7	TRAC-100-FA	45.51 (6600)	3.33 (482)
8	TRAC-50-SF	46.28 (6712)	2.71 (393)
9	TRAC-100-SF	44.75 (6490)	3.39 (491)

Notes: NAC is natural aggregate concrete; RAC is recycled aggregate concrete; TRAC is treated recycled aggregate concrete; FA is fly ash; SF is silica fume; and numeric digit (50 and 100) = % of recycled aggregate.

cled concrete aggregate tested at 28 days of age. The results show that the addition of recycled aggregate resulted in a significant reduction in concrete compressive strength when compared with the control concrete. This reduction increased as the percentage of recycled aggregate increased. A reduction in compressive strength of 17% and 11% was observed when 100% and 50% by volume of the coarse aggregate was replaced by natural aggregate, respectively. It was similar to the study of other researchers.[35,36] The split tensile strength of recycled aggregate concrete decreased with increased recycled aggregate content in a manner similar to that observed in the compressive strength tests. The reason for this strength reduction is due to the attached mortar remaining on the surface of the aggregate as well as the weaker interfacial zone between new cement mortar and aggregate. Another reason for lower strength of RCA or TRCA bearing mixtures is the presence of weak, old interfacial zones in these aggregates that may further weaken during crushing operation. The compressive strength of concrete prepared using TRCA increased by 12% (TRAC-100) and 6% (TRAC-50) when compared with recycled aggregate concretes RAC-100 and RAC-50, respectively. The splitting tensile strength of the recycled aggregate concrete increased when the TRCA was used in a similar manner to that observed in the compressive strength tests. The improvement in strength with the addition of fly ash and silica fume when 50% of the coarse aggregate was replaced by natural aggregate was 18% (TRAC-50-FA) and 21% (TRAC-50-SF) when compared to conventional concrete. The improved strength with the addition of fly ash and silica fume when 100% of the coarse aggregate was replaced by recycled aggregate was 19% (TRAC-100-FA) and 17% (TRAC-100-SF) when compared with conventional concrete, respectively. The use of TRCA improved the compressive strength of recycled aggregate concrete because the treatment method removed weaker attached mortar of RCA. Treatment improves the bond between recycled aggregate and the new cement matrix.[33] Also, addition of fly ash/silica fume in concrete acts as a microfiller, filling the transition zone between the aggregate surface and the bulk cement matrix, and could fill in the voids of concrete.[37]

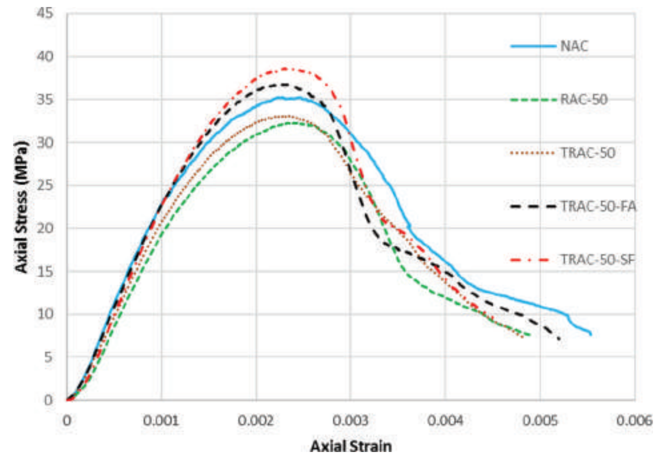

Fig. 4—Stress-strain curves for recycled aggregate concrete produced with 50% RCA. (Note: 1 MPa = 145 psi.)

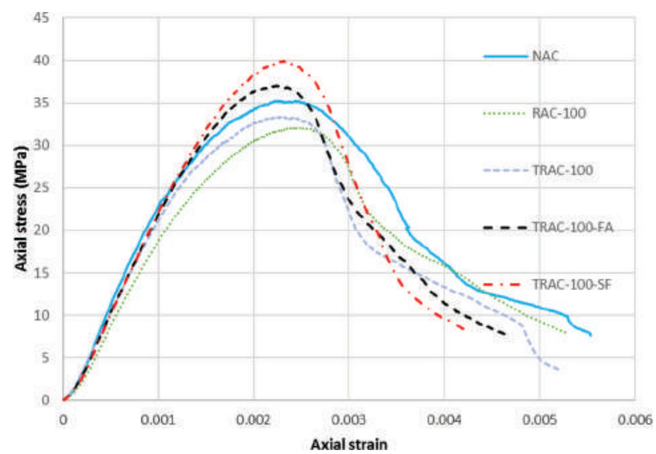

Fig. 5—Stress-strain curves for recycled aggregate concrete produced with 100% RCA. (Note: 1 MPa = 145 psi.)

The additional reason for improved strength of these mixtures is the pozzolanic reaction of the mineral admixtures. Shima et al.[30] reported that the heating and rubbing treatment method increased the quality of RCA to comply with the Japan Concrete Institute (JCI) standards for high-quality recycled concrete aggregates.

Modulus of elasticity

Figures 4 and 5 give the typical stress-strain plots for the cylinders under compression. Table 5 presents the results of modulus of elasticity and peak strain of natural, recycled, and treated recycled concrete aggregate tested at 28 days of age. From the results it can be seen that the shape of the stress-strain curve for the recycled aggregate concrete was similar to that of the natural aggregate concrete. When the RCA replacement percentage is 100%, the elastic modulus is reduced by 19% and the peak strain is increased by approximately 8%. As certain studies pointed out,[38,39] the modulus of elasticity of aggregate is proportional to the square of its density. Because RCAs have lower density, the density of the recycled aggregate concrete particles is reduced and its modulus of elasticity is reduced. The strains were higher than those of the natural aggregate concrete under the same loads, mainly due to the lower elastic modulus of the recycled

Table 5—Modulus of elasticity and peak strain of recycled aggregate concrete

Serial No.	Specimen ID	Modulus of elasticity, MPa	Peak strain
1	NAC	34,279	0.0022
2	RAC-50	30,639	0.0024
3	RAC-100	27,895	0.0024
4	TRAC-50	30,073	0.0023
5	TRAC-100	30,026	0.0021
6	TRAC-50-FA	34,818	0.0023
7	TRAC-100-FA	32,217	0.0022
8	TRAC-50-SF	31,901	0.0023
9	TRAC-100-SF	29,789	0.0023

Notes: NAC is natural aggregate concrete; RAC is recycled aggregate concrete; TRAC is treated recycled aggregate concrete; FA is fly ash; SF is silica fume; and numeric digit (50 and 100) = % of recycled aggregate. 1 MPa = 145 psi.

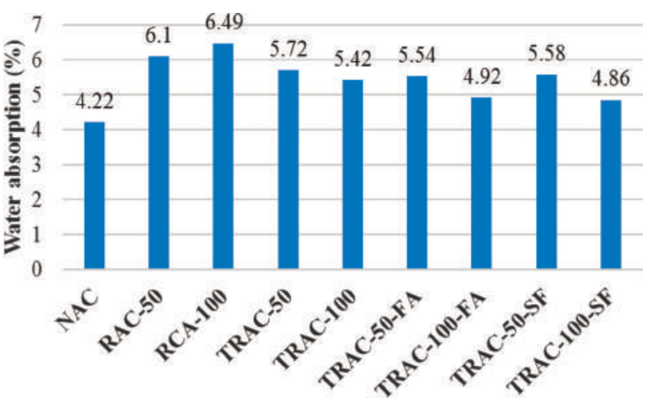

Fig. 6—Water absorption of concrete produced with RCA and TRCA.

Table 6—Bulk density and volume of permeable pore space of recycled aggregate concrete

Serial No.	Specimen ID	Bulk density of concrete, kg/m^3 (lb/ft^3)	Volume of permeable pore space (voids, %)
1	NAC	2413 (150)	9.61
2	RAC-50	2237 (139)	12.99
3	RAC-100	2226 (138)	13.92
4	TRAC-50	2261 (141)	12.48
5	TRAC-100	2269 (141)	12.72
6	TRAC-50-FA	2268 (141)	11.92
7	TRAC-100-FA	2287 (142)	11.07
8	TRAC-50-SF	2275 (142)	12.13
9	TRAC-100-SF	2305 (143)	10.86

Notes: NAC is natural aggregate concrete; RAC is recycled aggregate concrete; TRAC is treated recycled aggregate concrete; FA is fly ash; SF is silica fume; and numeric digit (50 and 100) = % of recycled aggregate.

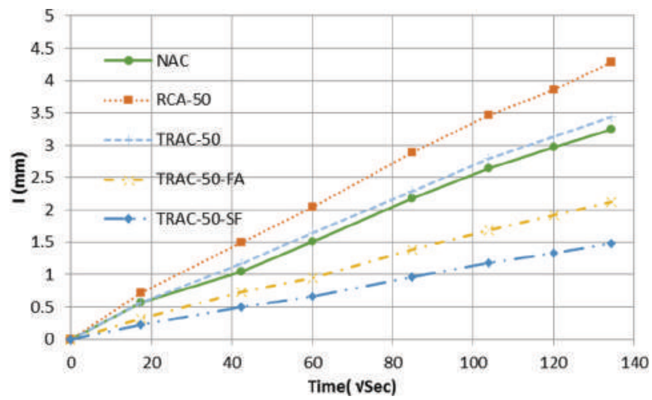

Fig. 7—Rate of water absorption of concrete with 50% recycled concrete aggregate. (Note: 1 mm = 0.0394 in.)

aggregate concrete. The presence of interface between the new cement mortar and old cement mortar may give rise to a progressive development of microcracks at this interface. There are numerous such interfaces in concrete containing a higher proportion of recycled coarse aggregate. Thus, the strain increases at a faster rate than the applied stress.[8]

Water absorption

Figure 6 shows the water absorption of recycled aggregate concrete tested at 28 days, which increased with the increasing percentage of recycled aggregates. Water absorption of concrete RAC-100 and TRAC-100 were 6.49% and 5.42%, respectively, whereas for natural aggregate concrete (NAC), the water absorption was found to be 4.2%. The highest absorption value was attained by 100% RCA specimens, which is 1.5 times higher than that of the NAC. This result was similar to that of other researchers, who reported that the water absorption capacities of recycled aggregate concrete were 1.3 to 1.6 times higher than the NAC.[40] This was due to the high absorption capacity of the recycled concrete aggregate itself. The water absorption of concrete prepared with TRCA and with the addition of fly ash or silica fume was 4.92% (TRAC-100-FA) and 4.86% (TRAC-100-SF), respectively. Table 6 lists the bulk density and volume of permeable pore space of recycled aggregate concrete tested at 28 days of age. As can be seen in Table 6 that the volume of permeable pore space of RAC-100 and TRAC-100 was found to be 13.92% and 12.72%, respectively, which were 44% and 32% higher than that of NAC (9.61%). The heating and rubbing treatment resulted in almost 37% (from 44% to 32%) reduction in the permeable pore space of RAC. The reduction in permeable pore space in TRAC with fly ash or silica fume is due to the removal of weaker attached mortar after treatment and refinement of the pore structure as a result of the pozzolanic reaction and the filler effect of small particles of fly ash. Hence, a significant reduction in water absorption and permeable pore space was observed with the use of TRCA and the addition of mineral admixtures in concrete.

Rate of water absorption

Rate of water absorption of natural and recycled aggregate concrete was conducted at 0, 5, 30, 60, 120, 180, 240, and 300 minutes. From the test results, it can be seen that rate of water absorption increases as the percentage of recycled aggregate increases. Figures 7 and 8 show the rate of water absorption of concrete with 50% and 100% RCAs, respectively. The rate of water absorption of conventional concrete and 100% recycled concrete were 0.0241 and

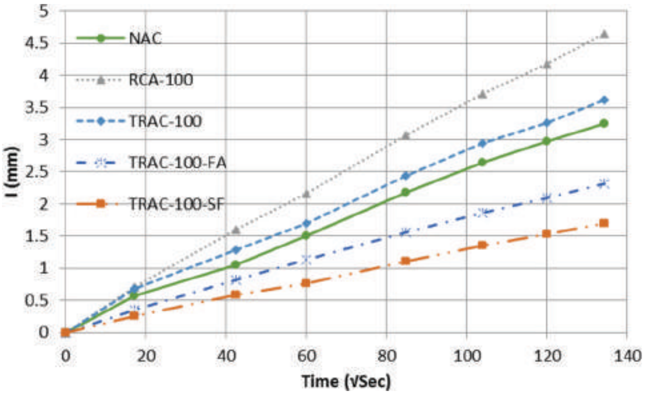

Fig. 8—Rate of water absorption of concrete with 100% recycled concrete aggregate. (Note: 1 mm = 0.0394 in.)

0.0346 mm/√s (0.00094 and 0.00136 in./√s), respectively. de Brito and Fatima[41] reported that there is a strong impact of the higher porosity of the RCA on the rate of water absorption. This confirms durability as the performance aspect of concrete with recycled aggregates where the losses are greatest, after volumetric instability. Further, it can be seen that with the use of TRCA and the addition of fly ash or silica fume, capillary absorption was reduced to 0.0172 and 0.0126 mm/√s (0.00067 and 0.0049 in./√s), respectively. The use of TRCA and the addition of fly ash or silica fume reduced the porosity and thereby improved the durability of recycled aggregate concrete.

Rapid chloride permeability

Table 7 shows the average charge passed in the concrete produced with RCA and TRCA. It was seen that the charge passed in concrete specimens RAC-100 and TRAC-100 were higher than that of the NAC specimens. The chloride ion permeability of RAC-100 and TRAC-100 was higher by 51.7% and 14.82%, respectively, when compared to NAC specimens. The volume of pores in TRAC-100 was reduced, as the attached mortar of the RCA decreased, the concrete became more impermeable and the resistance to chloride ion penetration increased accordingly. The average charge passed in the 100% recycled aggregate concrete with the addition of fly ash was 1152 coulombs (TRAC-100-FA), and with the addition of silica fume, it was 603 coulombs (TRAC-100-SF). From the results, it can be seen that chloride ion permeability of recycled aggregate concrete with the addition of fly ash or silica fume was low and very low, respectively, as per ASTM C1202. The treatment method removed the weaker attached mortar of the RCA. Also, the use of fly ash or silica fume improved the distribution of pore size, the pore shape of concrete, and blocked the ingress path.[42] In addition to reduced permeability and improved pore structure, the other reason for lower chloride ion permeability of a mixture containing fly ash or silica fume is the chloride ion binding capacity of the mineral admixtures. Hence, a significant improvement in durability properties was observed in concrete produced with TRCA and with addition of mineral admixtures.

Table 7—Rapid chloride permeability test on recycled aggregate concrete

Serial No.	Specimen ID	Average charge passed, Coulombs	Chloride ion permeability
1	NAC	2232	Moderate
2	RAC-50	3197	Moderate
3	RAC-100	3386	Moderate
4	TRAC-50	2541	Moderate
5	TRAC-100	2563	Moderate
6	TRAC-50-FA	1142	Low
7	TRAC-100-FA	1152	Low
8	TRAC-50-SF	906	Very low
9	TRAC-100-SF	603	Very low

Notes: NAC is natural aggregate concrete; RAC is recycled aggregate concrete; TRAC is treated recycled aggregate concrete; FA is fly ash; SF is silica fume; and numeric digit (50 and 100) = % of recycled aggregate.

Cost-benefit analysis

A cost-benefit analysis was performed to show the economic feasibility of reusing construction waste. The costs evaluation was carried out at present (year 2017), Chennai, India. Natural aggregates were acquired from a local supplier, whereas RCA and TRCA were prepared in the laboratory. Natural aggregates costs about Rs 4500 per 100 ft^3 (\$69.58/2.83 m^3), recycled aggregate costs around Rs 2882 per 100 ft^3 (\$44.56/2.83 m^3) (Table 8), and treated RCA costs around Rs 5490 per 100 ft^3 (\$84.89/2.83 m^3) (Table 9). The recycled concrete aggregate preparation cost was 36% less when compared to the natural aggregate prepartion. The treated recycled concrete aggregate preparation cost was 22% higher compared to the natural aggregates. The treated recycled concrete aggregate cost was higher when compared to the natural aggregates mainly due to higher labor cost in Chennai.

Besides the traditional cost of aggregates, it would be important to account for the expenses necessary to eliminate the environmental impact caused by the extraction of natural aggregates from quarries and also the expenses to eliminate the environmental load caused by accumulation of C&D waste. The high price of land associated with densely populated areas, where future demand for aggregates is likely to be greatest, means that primary aggregates extracted close to cities will be more expensive.[43,44] By considering the environmental costs, it can be predicted that the treated recycled aggregate in the future could become less expensive than the natural aggregate because the former could have a decreasing market price whereas the latter may have an increasing one. However, as can be seen from Tables 2 and 3, the quality of the recycled aggregates produced from heat-treated waste concrete is better than that of the recycled aggregates produced from raw waste concrete. Hence, a small increase in cost may be acceptable if economic profits can be realized by employing heat treatment to produce high-quality recycled aggregates from waste concrete.

Therefore, in general, the recycled aggregate concrete and treated recycled aggregate could result in remarkably cheaper concrete than the natural aggregate concrete, where the costs of the concretes are reported by taking into account

Table 8—Total cost for preparing 2.83 m^3 (100 ft^3) of recycled concrete aggregate

Aggregate type	Total labor charges,* Rs	Equipment (crusher, screener) maintenance cost, Rs	Electricity consumed (jaw crusher and vibrating sieves) per day	No. of days	Electricity charges per kwh (Rs)	Total electrical charges (Rs)	Other charges (electricity), Rs	Total cost, Rs
NA†	—	—	—	—	—	—	—	4500
RCA	2400	100	24 kwh	3	6	432	50	2882

*Labor charges per day are Rs 400; to prepare 2.83 m^3 (100 ft^3) of RCA, two laborers worked for 3 days.

†Cost of NA provided by a local supplier in Chennai, India.

Notes: Labor and electrical charges provided in the table are local rates in Chennai, India; 1 Rs = $0.02.

Table 9—Total cost for preparing 2.83 m^3 (100 ft^3) of treated recycled concrete aggregate of quantity

Aggregate type	Electricity consumed, kwh/day	Electricity charges per kwh, Rs	Total electrical charges, Rs	Labor charges per day, Rs	No. of laborers	No of days	Total labor charges, Rs	Equipment (thermal cyclic chamber, screeners) maintenance cost, Rs	Heating and rubbing treatment cost, Rs	Total cost (by considering the RCA cost), Rs
TRCA	18	6	108	400	2	3	2400	100	2608	5490

Notes: Labor charges per day are Rs 400; to prepare 2.83 m^3 (100 ft^3) of RCA, two laborers worked for 3 days. Labor and electrical charges provided in the table are local rates in Chennai, India; 1 Rs = $0.02.

only the expenses necessary to eliminate the environmental impact (waste transportation cost savings and cost saving from landfill fees, in addition to benefits such as saving landfill space, a decreasing chance of soil and ground water contamination, improved public image, and environmental concern).

CONCLUSIONS

In this research, heating and rubbing treatment method is used to remove the attached mortar of the RCA. In this method, RCAs were heated to a temperature of 250°C (482°F), then the RCAs were immediately immersed in water to rapid reducing temperature and create stresses. The attached mortar of the RCA with weak interface got separated after rubbing in a pan mixer. The mixture of RCA and separated mortar then was sieved through standard sieves in preparation of TRCA. The physical and mechanical properties of the RCA, TRCA, and mechanical and durability properties of concrete prepared using RCA and TRCA have been discussed in detail. Further, the influence of mineral admixtures (fly ash or silica fume) on the mechanical and durability properties of concrete prepared using TRCA have been studied.

From the experimental work carried out in this study, the following conclusions are drawn:

1. The presence of attached mortar was the main reason for lower quality of the RCA. Heating and rubbing treatment method improved the quality of the RCA by removing 70 to 80% attached mortar present on it.

2. The increase in bulk density and specific gravity of RCA after treatment was around 9% and 6%, respectively.

3. The water absorption of RCA was reduced by approximately 66% after the heating and rubbing treatment method. This was due to the removal of separated weaker attached mortar on the RCA after treatment.

4. Mechanical properties (compressive strength, split tensile strength, and modulus of elasticity) of concrete produced with treated recycled concrete aggregate, and with addition of fly ash/silica fume, showed significant improvement when compared with conventional concrete.

5. The addition of either fly ash or silica fume in concrete produced with TRCA improved resistance to water absorption, rate of water absorption, and chloride ion permeability characteristics.

6. A cost-benefit analysis was performed to show the economic feasibility of reusing construction waste.

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