Chapter 3
Properties of Recycled Aggregates

3.1 Introduction

Concrete is an end product of intimate mixture of mainly three components namely cement, water and aggregates. Around 70–80% of the total volume of concrete is occupied by aggregates. Because of its large proportion in concrete, properties of aggregates are of considerable importance as they can affect the workability, strength, durability and structural performance of concrete. Aggregate was initially treated as inert and cheaper material in the concrete as it contributes to the large volume of concrete. However, the performance of concrete is influenced by the physical, chemical and thermal properties of aggregate. The inclusion of aggregate in concrete not only contributes to the economy, but also gives considerable advantage of higher volume stability, better durability and higher strength than hydrated cement paste alone (Neville and Brooks 2005). Aggregates are derived from rock, either by naturally or artificially crushed. Thus, the properties of the aggregate depend on the chemical and mineral composition, petrographic classification, specific gravity, hardness, strength, pore structure, etc., of the parent rock. In addition, the size, shape and surface texture of aggregates also influence considerably the fresh and hardened properties of concrete (Neville and Brooks 2005).

The basic difference between recycled aggregate and natural aggregate is lies in the presence of attached old mortar in the recycled aggregate (Fig. 3.1). This adhered old mortar changes the properties of recycled aggregate and consequently the properties of fresh and hardened concrete made with these recycled aggregate. In general, the density and water absorption of recycled aggregates are greatly influenced by the quantity of adhered old mortar.

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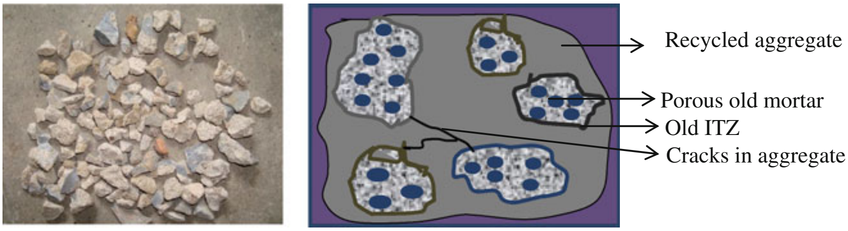


Fig. 3.1 Recycled aggregate and its pictorial representation

3.2 Physical Properties of Recycled Aggregates

3.2.1 *Grading, Shape and Surface Texture*

Buck (1973) reported that the recycled aggregate does not have a high amount of flaky and elongated particles. Frondistou-Yannas (1977) reported that good particle size distribution of recycled aggregate can be produced from uncontaminated concrete rubbles. Hasaba et al. (1981) ascertained that depending on the quality of the concrete from which recycled aggregate derived, the recycled coarse aggregate contains 1.3–1.7% particles finer than 88 μm size in maximum 25 mm size aggregates. Hansen and Narud (1983) reported that using jaw crusher with a single passing of 100 mm maximum size concrete rubble, well-graded recycled aggregate of good shape can be produced. Ravindrarajah (1987) observed that the recycled aggregate obtained by crushing the old concrete in a jaw crusher was more angular than natural aggregate. Bairagi et al. (1990) reported that the recycled coarse aggregates were angular with porous and rough texture and they were relatively coarser than natural aggregates due to the presence of old mortar in recycled aggregate. Prasad and Kumar (2007) had reported similar result. Buyle-Bodin (2002) and Hadjieva-Zaharieva (2002) observed that the recycled fine aggregate was relatively coarser than natural sand and its fineness modulus was little higher than acceptable limits for normal concrete sand. Zaharieva et al. (2003) reported that the recycled fine aggregate was occasionally coarser than natural fine aggregate. Salem et al. (2003) reported that well-graded recycled aggregate that abides by ASTM could be produced without much difficulty. In addition, it was reported that the recycled aggregates were more angular and the surface texture was porous and rough due to the existence of old mortar. Katz (2003) studied the influence of crushing age on the properties of aggregates and concrete and it was reported that using a jaw crusher set at a specific opening, similar grading and other properties of aggregates can be produced irrespective of the age of crushing. Zega et al. (2010) studied the influence of different types of coarse aggregates and w/c ratio on the properties of recycled aggregate. The authors ascertained that the grading of recycled aggregate does not depend on the w/c ratio of the concrete from which the recycled aggregate derived and the shape and texture of parent concrete aggregate.

Chakradhara Rao (2010) reported the particle size distribution of natural coarse aggregate and recycled coarse aggregates obtained from different sources through Figs. 3.2, 3.3 and 3.4 along with the minimum and maximum limits specified by BIS (IS: 383-1970) for natural aggregate used in concrete. Figure 3.2 shows the grading curves of natural coarse aggregate and recycled coarse aggregates obtained from Source 1 (RCC culvert Medinipur), and it was observed that the recycled coarse aggregates are relatively finer than natural coarse aggregates. Hence, the fineness modulus of recycled coarse aggregate (6.692–6.77) was less than that of natural coarse aggregate of 6.782. It was also observed that the particles of size less than 4.75 mm in a mix with maximum size of recycled coarse aggregate of 20 mm are approximately 2.3%. Similarly, the grading curves of both natural and recycled

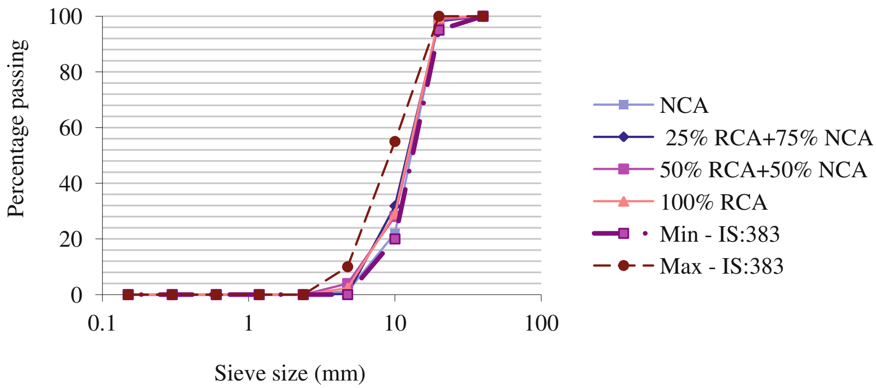


Fig. 3.2 Particle size distribution of natural coarse aggregate and recycled coarse aggregate obtained from RCC culvert near Medinipur (Source 1) (Chakradhara Rao 2010)

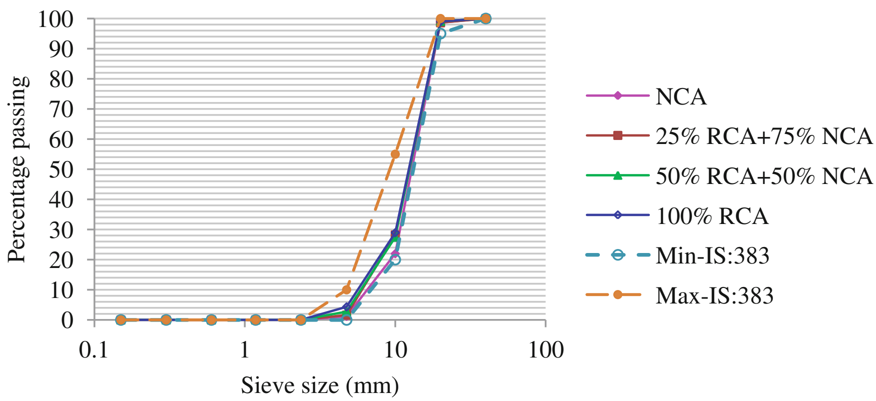


Fig. 3.3 Particle size distribution of natural coarse aggregate and recycled coarse aggregate obtained from RCC culvert near Kharagpur (Source 2) (Chakradhara Rao 2010)

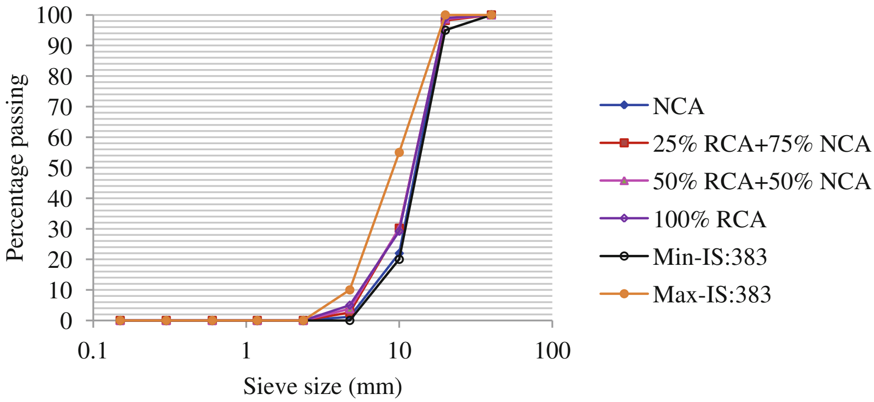


Fig. 3.4 Particle size distribution of recycled coarse aggregate obtained from RCC slab of an old residential building near Vizianagaram (Source 3) (Chakradhara Rao 2010)

coarse aggregates for all coarse aggregate replacement percentages obtained from Source 2 (RCC culvert at Kharagpur) and Source 3 (RCC slab of an old residential building at Vizianagaram) are presented in Figs. 3.3 and 3.4, respectively.

The grading curves show that the recycled coarse aggregates obtained from both Sources are relatively finer than those of natural coarse aggregates. This may be due to the combination of aggregates crushed both manually as well as by jaw crusher. The percentage of particles finer than 4.75 mm in 20 mm maximum sized recycled coarse aggregate is 4.34 and 5 in Sources 2 and 3, respectively. However, it is observed that the grading curves of recycled coarse aggregates for all the coarse aggregate replacement percentages obtained from all the three Sources are within the grading limits specified by BIS (IS: 383-1970). Hence, the recycled coarse aggregates may be used in the production of concrete from the consideration of grading of aggregates; however, other properties are to be examined before arriving at the concluding remarks.

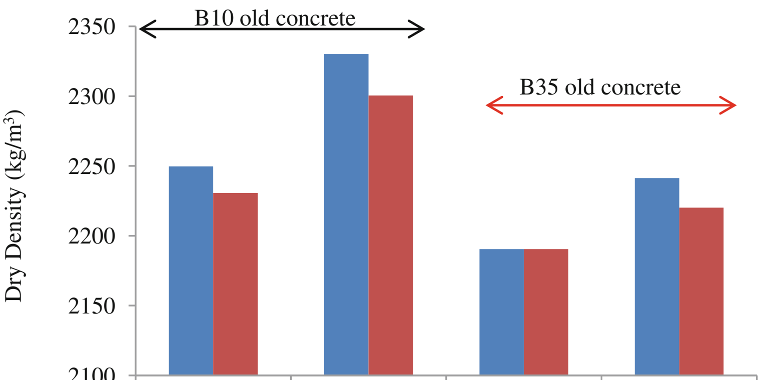
The visual observation (Fig. 3.1) reveals that the surface texture of recycled coarse aggregates is porous and rough due to the adherence of old cement paste to the recycled aggregates after the recycling process. This may demand more water for achieving the required workability. Also, this will improve the interlocking between mortar and aggregates and thereby improves the bond between them.

3.2.2 Density and Specific Gravity

The density is one of the important physical properties of aggregate. In short, it defines how densely the material is packed in a given volume. This parameter is useful in proportioning the concrete mixes by volume. In general, due to lower density of old mortar adhered to recycled aggregate, the saturated-surface-dry (SSD) density of recycled aggregates is always less than that of natural aggregate.

BCSJ (1978); Hasaba et al. (1981); Hansen and Narud (1983) have reported that irrespective of the quality of concrete from which the recycled aggregates derived, for same grinding machine and process, SSD density of recycled aggregate was increased with the increase in size of the particles. Most of the researchers reported that the recycled aggregates have SSD density in the range of 2290–2510 kg/m^3. In addition, it was reported that the density of recycled aggregate depends on the strength of the concrete from which the recycled aggregate derived. Bairagi et al. (1990) reported that the recycled coarse aggregate had lower SSD density compared to natural aggregate. The authors reported that this may be attributed to the adherence of old mortar to natural aggregate. Hasse and Dahm (1998) concluded that for the same particle size, higher the strength of concrete from which the recycled aggregate derived, lower is the density of recycled aggregates (Fig. 3.5). This is due to the fact that in higher strength of concrete from which the recycled aggregates derived, lower quantity of low-density old mortar adhered to aggregates.

For the same particle size, higher the strength of concrete from which the recycled aggregate derived, lower is the density of recycled aggregates (Padmini et al. 2009; Pedro et al. 2014). This was due to the fact that in higher strength of concrete from which the recycled aggregates derived, lower quantity of low-density old mortar adhered to the aggregates. When the RCA obtained from 30–100 MPa strength concrete, the density of 10 and 20 mm size aggregate does not follow any specific trend with the increase in strength of parent concrete (PC) (Kou and Poon 2015). Whereas Nagataki (2000) concluded that for the same quantity of cement



	2-8 mm	8-16 mm	2-8 mm	8-16 mm
Pycnometer method	2249.735	2330.159	2190.476	2241.27
Under-Water weighing	2230.68	2300.529	2190.476	2220.106

Size of aggregate

Fig. 3.5 Density of recycled aggregate as a function of size and strength of concrete from which recycled aggregate derived (Hasse and Dham 1998)

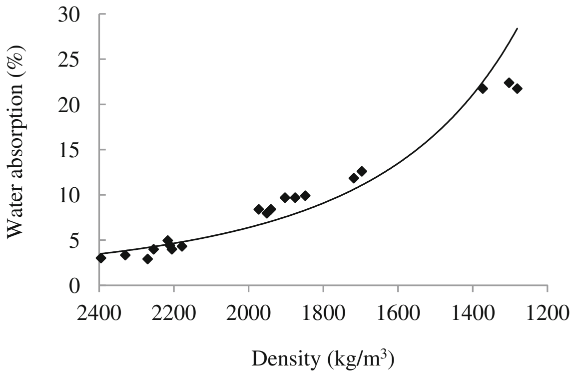


Fig. 3.6 Water absorption as a function of density of recycled concrete aggregates (Kreijger 1981)

mortar content, the recycled aggregates obtained from higher strength concrete had higher density. Buyle-Bodin and Hadjieva-Zaharieva (2002) reported that the density and porosity of recycled aggregate were lower and higher, respectively, than those of natural aggregate due to the presence of old mortar and light impurities in recycled aggregates. Zaharieva et al. (2003) had reported similar results. In a study by Katz (2003), it was reported that the bulk-specific gravity of recycled fine to coarse aggregates was ranged from 2.23 to 2.60 when compared to 2.70 for natural aggregate. This may be attributed to the presence of adhered mortar in aggregates after crushing. In addition, it was reported that the bulk density of recycled fine aggregate was higher than that of medium size recycled aggregate despite the lower specific gravity of former. This was due to the better grading of recycled fine aggregate over a large range of sizes leading to a dense packing. Tu et al. (2006) concluded that the specific gravity and density of recycled aggregates were always lower than that of natural aggregates due to the presence of loose mortar and brick content in construction & demolished waste.

In a study by Gonzalez-Fonteboa and Martinez-Abella (2008), it was reported that the density of recycled aggregate size ranging from 4–12 mm and 10–25 mm were 11.4 and 10.1% lower than that of corresponding natural aggregate. Juan and Gutierrez (2009) concluded that the density of recycled aggregate was a function of adhered cement mortar and the authors found that the density decreased with the increase in percentage of adhered mortar content. In a study by Zega et al. (2010) concluded that the specific gravity and density of recycled aggregate were lower when higher specific gravity of natural aggregate used in original concrete. This attributes to the larger amount of adhered mortar to the recycled aggregate. The density and specific gravity (SSD) of natural fine and coarse aggregates and recycled coarse aggregate obtained from different Sources were examined in accordance with BIS (IS: 2386-1963 (Part 3)) and the results are shown in Table 3.1 (Chakradhara Rao 2010). It was observed that the specific gravity (SSD) of natural fine and coarse aggregates were 2.617 and 2.75, respectively. The specific gravity of recycled coarse aggregates obtained from all the three Sources demonstrates lower values with the increase in percentage of recycled coarse aggregate. The SSD specific gravity of 100% RCA obtained from Sources 1, 2, and 3 are 2.51, 2.47, and 2.417, respectively, against 2.75 for natural coarse aggregate. It was reported in the literature that the specific gravity of recycled coarse aggregate was in the range of 2.23 to 2.6. The reduction in specific gravity of recycled coarse aggregate obtained from the Sources 1, 2, and 3 are 8.7, 10.2, and 12.1%, respectively, compared to natural coarse aggregate. Mortar is generally adhered to the recycled aggregate surface. The attached mortar is light porous in nature. Therefore, it is obvious that the specific gravity of recycled coarse aggregate is relatively less when compared to natural coarse aggregate. The specific gravity of RCA obtained from Sources 2 and 3 was little lower than those obtained from Source 1. This may be due to fact that the recycled coarse aggregates obtained from these Sources have 4–5% particles finer than 4.75 mm. This may be attributed to the adherence of relatively higher quantity of old cement mortar to the recycled aggregates. Due to lower specific gravity of recycled coarse aggregates, there is a reduction in the amount of recycled coarse aggregate to be used in the recycled aggregate concrete.

The results of both compact and loose bulk densities of natural fine and coarse aggregate and recycled coarse aggregates are presented in Table 3.1.

It shows that the natural aggregate has higher packing capacity than recycled coarse aggregate obtained from different Sources. The compact density of natural coarse aggregate is 1.581 kg/l when compared to 1.413, 1.34 and 1.35 kg/l for recycled coarse aggregates obtained from the Sources 1, 2, and 3, respectively. The compact density of RCA obtained from all the three Sources are 10.6%, 15.2% and 14.6%, respectively, lower than that of natural coarse aggregate. Similarly, the loose bulk density of RCA obtained from the Sources 1, 2, and 3 are 12.2, 17 and 12.3% lower than that of natural coarse aggregate. As the old cement mortar adhered to aggregate in recycled coarse aggregate is light and porous in nature, it is obvious that the bulk density of recycled coarse aggregates are lower than that of natural coarse aggregate. However, the recycled coarse aggregates are found to be relatively finer than natural aggregate as explained earlier, yielding lesser voids when packed, therefore, increasing the bulk density of the mix and partially compensate the lower bulk density due to adhered cement paste in recycled aggregate and therefore reduced the difference of this characteristic in comparison to natural aggregate. It is observed from Table 3.1 that there is a difference in bulk density of recycled coarse aggregates obtained from different Sources. This is probably that the bulk density of recycled coarse aggregate depends on the cement content of the adhered mortar which in turn depends on the quality of source concrete.

3.2.3 Water Absorption

The water absorption is one of the major differences between natural and recycled aggregates. The water absorption of recycled aggregate is much higher than that of

Table 3.1 Physical characteristics of natural fine and coarse aggregate and recycled coarse aggregate obtained from different Sources (Chakradhara Rao 2010)

Property	Natural Fine Aggregate	Natural CA	Source 1 Recycled coarse aggregate			Source 2 Recycled coarse aggregate			Source 3 Recycled coarse aggregate			IS: 383-1970 limits
			25% RCA + 75% NCA	50% RCA + 50% NCA	100% RCA	25% RCA + 75% NCA	50% RCA + 50% NCA	100% RCA	25% RCA + 75% NCA	50% RCA + 50% NCA	100% RCA	
Bulk density (compact) (kg/l)	1.618	1.581	1.56	1.5	1.413	1.53	1.45	1.34	1.5	1.44	1.35	–
Bulk density (Loose) (kg/l)	1.544	1.495	1.45	1.45	1.312	1.47	1.39	1.24	1.42	1.39	1.31	–
Specific gravity (SSD)	2.617	2.75	2.66	2.602	2.51	2.71	2.64	2.47	2.671	2.617	2.417	–
Apparent specific gravity	2.63	2.827	2.804	2.78	2.803	2.82	2.808	2.701	2.822	2.817	2.672	–
Water absorption (%)	0.201	1.129	1.911	2.63	3.92	1.515	1.92	3.009	2.005	2.704	3.934	–
Flakiness Index (%)	–	24.1	–	–	6.27	–	–	7.4	–	–	4.65	25
Elongation Index (%)	–	20.06	–	–	11.63	–	–	13.5	–	–	13.29	30

natural aggregate due to high absorption capacity of old mortar adhered to aggregate in recycled aggregate. Water absorption of recycled aggregate is a function of size, strength of original concrete, adhered mortar content and density.

In a study by BCSJ (1978), it was ascertained that the water absorption was 3.6–8% and 8.3–12% for recycled coarse and fine aggregates, respectively. Hasaba et al. (1981) had observed similar results and it was reported that the water absorption of recycled aggregate was around 7% for 5–25 mm size and 11% for below 5 mm size aggregates. Hansen and Narud (1983) found that irrespective of the quality of concrete from which the recycled aggregate derived the water absorption of recycled coarse aggregate size ranging from 16–32 mm and 4–8 mm were 3.7% and 8.7%, respectively. In addition, the relationship between the density and water absorption of recycled aggregates for different w/c ratios was reported and is presented in Table 3.2.

Bairagi et al. (1993) found that the water absorption of recycled aggregates in the first 30 min was 76% and the 4 h absorption was 96% of the absorption in 24 h, respectively. Katz (2003) found that the water absorption was ranging from 3.2–12% for coarse to fine recycled aggregates. Also, it was reported that the crushing age of original concrete from which the recycled aggregate produced does not influence much on water absorption of recycled aggregate. As already mentioned, the density and adhered mortar content are the function of concrete from which the recycled aggregate derived, the water absorption is also a function of the strength of parent concrete. Poon et al. (2004) reported that the water absorption was higher for

Table 3.2 Properties of natural gravel and recycled aggregates according to Hansen and Narud (1983)

Type of aggregate	Size fraction (mm)	Specific gravity SSD (kg/m^3)	Water absorption (%)	Los Angeles abrasion loss (%)	Volume percent of mortar attached to natural gravel
Original natural gravel	4–8 8–16 16–32	2500 2620 2610	3.7 1.8 0.8	25.9 22.7 18.8	0 0 0
Recycled aggregate (H) (w/c = 0.4)	4–8 8–16 16–32	2340 2450 2490	8.5 5.0 3.8	30.1 26.7 22.4	58 38 35
Recycled aggregate (M) (w/c = 0.7)	4–8 8–16 16–32	2350 2440 2480	8.7 5.4 4.0	32.6 29.2 25.4	64 39 28
Recycled aggregate (L) (w/c = 1.2)	4–8 8–16 16–32	2340 2420 2490	8.7 5.7 3.7	41.4 37 31.5	61 39 25
Recycled aggregate (M) (w/c = 0.7)	<5	2280	9.8	–	–

Note: H—High strength, M—Medium strength, L—Low strength recycled aggregates obtained from normal strength concrete than those obtained from high-performance concrete (HPC). Tu et al. (2006) in their study observed that the water absorption of recycled fine and coarse aggregates were 10 and 5%, respectively, as compared to 1 and 2% for natural fine and coarse aggregate. Padmini et al. (2009) concluded that the water absorption increased with the increase in strength of concrete from which the recycled aggregate derived. This was due to high amount of old mortar content adhered to recycled aggregates obtained from higher strength of concrete.

Tam et al. (2008) in a study concluded that the current British Standards (BS) method for water absorption measurement of natural aggregate was not suitable for recycled aggregate, as patches of cement pastes adhered to the surface of recycled aggregate may affect the water absorption. In addition, the 24 h of saturation was not enough for recycled aggregate, as it was influenced by the amount of cement paste adhered to the recycled aggregate which varies from site to site. The authors proposed a new technique called real-time assessment of water absorption (RAWA) for accurately measuring the water absorption of recycled aggregate. The proposed new technique gives the water absorption at different time intervals and it can avoid the removal of cement paste during soaking and drying process of the recycled aggregate samples. Zega et al. (2010) in their study concluded that the water absorption of recycled aggregate depends on the type of natural aggregate used in the original concrete. It was reported that higher specific gravity of natural aggregate used in original concrete, higher the adhered mortar content in recycled aggregate and hence higher was the water absorption of recycled aggregate.

Yang et al. (2008) found that the water absorption and adhered cement paste on the surface of the aggregates were directly proportional to each other. Juan and Gutierrez (2009) observed similar result and the authors found the following relationship between them.

$$\mathrm{y} = 0.18\mathrm{x} + 0.36 \left(\mathrm{R}^2 = 0.5\right) \tag{3.1}$$

Where y and x are the water absorption and adhered mortar content in percentages, respectively.

The density of recycled aggregates also influences the water absorption capacity of recycled aggregates. Lower the density higher is the water absorption. The relationship between water absorption and density is presented in Figs. 3.6 and 3.7 and Eqs. 3.2 and 3.3, based on the results presented by Kreijger (1981) and three German firms, namely BAM, HOLZMANN, TEL (Kun 2005), respectively.

$$y = 7 \times 10^{11} \times x^{-3.347} \left(R^2 = 0.927\right) \tag{3.2}$$

$$y = 3 \times 10^{18} \times x^{-5.283} \left(R^2 = 0.893\right) \tag{3.3}$$

Some of the researchers suggested that it was better to use the presoaked recycled aggregates in the production of concrete to maintain the uniform quality due to high absorption capacity of recycled aggregates. Before carrying out the mix

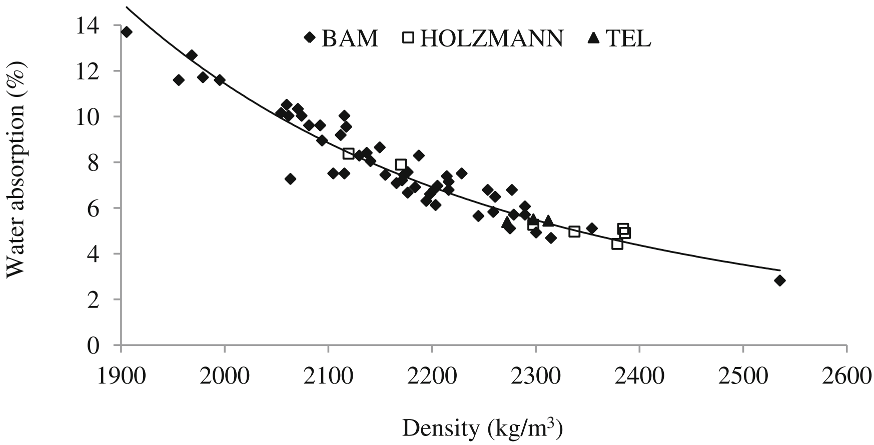


Fig. 3.7 Relationship between water absorption and density of recycled aggregate produced by three German firms (Kun 2005)

design for production of concrete, the density and water absorption of recycled coarse and fine aggregates must be studied.

It is worth noting that the water absorption of recycled coarse aggregate is higher than that of natural coarse aggregate irrespective of the source of recycled coarse aggregate (Chakradhara Rao 2010). This is expected due to porous and high absorption capacity of old mortar adhered to aggregate in recycled aggregate. The absorption capacity of recycled coarse aggregates obtained from the Sources 1, 2, and 3 are 3.92, 3.009, and 3.934%, respectively, when compared to 1.121% for natural coarse aggregate. This indicates that the recycled coarse aggregate has 2.7–3.5 times higher water absorption than that of natural aggregate. It was reported in the literature that the absorption capacity mainly depends on the strength of concrete from which the recycled coarse aggregate derived and the size of the coarse aggregate. The aggregate obtained from higher strength concrete will have higher cement paste and thereby higher water absorption.

3.2.4 Flakiness and Elongation Indices

The aggregates are flaky if their thickness is less than 0.6 times the mean sieve size of the size fraction to which the particle belongs. Similarly, an aggregate is said to be elongated, when a particle whose longest dimension is greater than 1.8 times the average sieve size of the size fraction. The test results of flakiness and elongation indices of natural coarse aggregate and recycled coarse aggregate obtained from different Sources are presented in Table 3.1. It is observed that the flakiness and elongation indices of natural aggregate are 24 and 20%, respectively. These values are just satisfying the requirements for normal concrete. On the other hand, the flakiness index of RCA obtained from the Sources 1, 2, and 3 are 6.27, 7.4, and 4.65%, respectively. Similarly, the elongation index of RCA obtained from the Sources 1, 2, and 3 are 11.13, 21.5, and 13.29%, respectively. These values are well below the requirements for aggregates for normal concrete. The results reveal that the recycled coarse aggregates demonstrate better indices when compared to natural aggregates. It is felt that these improvements may be due to the use of crushing methodology namely manual crushing along with jaw crushing.

3.3 Mechanical Properties of Recycled Aggregates

In general, the recycled aggregates are found to be weaker than the natural aggregates against mechanical resistance such as aggregate crushing value, ten percent fines value, impact value and Los Angeles abrasion loss value. This was due to the weaker old cement mortar adhered to the recycled aggregates and weaker bond between old mortar and aggregate in recycled aggregates. These values mainly depend on the strength of concrete from which the recycled aggregate derived, amount of old mortar adhered to the aggregate and the quality of aggregate employed in the original concrete. In addition, the method of crushing also influences these properties. Ravindrarajah (1987) reported the mechanical strengths of recycled aggregate were low when they were derived from low strength concrete. Bairagi et al. (1993) found the mechanical properties of recycled aggregate depend on the age of concrete from which the recycled aggregate produced. In a study by Padmini et al. (2009) reported, for a given strength of concrete from which the recycled aggregate derived, the resistance against mechanical actions decreased with the reduction in maximum size of aggregate. This can be attributed to the higher surface area of smaller size aggregates facilitating higher amount of mortar adhered.

3.3.1 Aggregate Crushing Value

Hasaba et al. (1981) reported that British Standards (BS) aggregate crushing value for 5–25 mm size recycled aggregate was 23 and 24.6% when they were derived from high strength concrete and low strength concrete, respectively. In addition, it was reported that the corresponding BS ten percent fines values were 13.3 and 11.3 tonnes, respectively. Bairagi et al. (1993) found that the crushing value increased and the ten percent fines value decreased with the age of original concrete from which the recycled aggregate produced. This may be attributed to the presence of weak adhered mortar which increased with the age of parent concrete. Shayan and Xu (2003) found that the crushing value of recycled coarse aggregate was 24%. Poon et al. (2004) observed that the ten percent fines value of recycled aggregate was lower when the recycled aggregates derived from normal strength concrete than those from high-performance concrete.

3.3.2 Los Angeles Abrasion Resistance Value

As discussed earlier, the Los Angeles abrasion loss depends on the strength of concrete from which the recycled aggregates derived, size of aggregate and the amount of adhered mortar. Hansen and Narud (1983) reported the Los Angeles abrasion loss values for recycled aggregates obtained by crushing 40 MPa strength concrete had lower abrasion than those obtained by crushing 16 MPa strength concrete and is presented in Table 3.3.

Hasaba et al. (1981), BCSJ (1978) and Yoshikane (2000) had reported similar results. Here the crushing details are unknown. For lower size recycled aggregates, the abrasion loss was more due to high amount of adhered mortar. Shayan and Xu (2003) found that the Los Angeles abrasion value of recycled aggregate was 32%. Juan and Gutierrez (2009) found that the abrasion loss is directly proportional to the adhered mortar content. Zega et al. (2010) reported that the w/c ratio of original concrete from which the recycled aggregate derived was less significant than that of the abrasion loss of natural aggregate used in original concrete on the loss of abrasion of the corresponding recycled aggregate.

Chakradhara Rao (2010) studied the mechanical characteristics, namely aggregate crushing value, ten percent fines value, aggregate impact value and Los Angeles abrasion resistance, are assessed for both natural and recycled coarse aggregates obtained from different Sources in accordance with BIS (IS: 2386-1963 (Part 4)). The test results of all coarse aggregates along with the limits specified by BIS (IS: 383-1970) are presented in Table 3.4.

From the table, it is observed that the aggregate crushing value of natural coarse aggregate is 17.52% against 33.5, 34.4, and 36.7%, respectively, for recycled coarse aggregate obtained from all the three Sources. This indicates that the crushing value of recycled coarse aggregates is almost double than the natural aggregate. The aggregate crushing value is an indication of resistance of gradually applied compression load. Higher the aggregate crushing value, lower is the

Table 3.3 Los Angeles abrasion loss of recycled aggregates obtained from 40 and 16 MPa strength concrete by different researchers

Author(s)	Los Angeles abrasion loss percentage							
	40 MPa strength concrete				16 MPa strength concrete			
	16–32 mm	8–16 mm	4–8 mm	5–25 mm	16–32 mm	8–16 mm	4–8 mm	5–25 mm
Hansen and Narud (1983)	22.4	26.7	30.1		31.5	37	41.4	
Hasaba et al. (1981)				23				24.6
BCSJ (1978)[a]	25.1–35.1							
Yoshikane (2000)				20.1				28.7

[a]Recycled coarse aggregates obtained from 15 different concrete of different strengths

Table 3.4 Mechanical characteristics of natural and recycled coarse aggregates obtained from different Sources (Chakradhara Rao 2010)

Property	Natural CA	Recycled coarse aggregate			IS: 383-1970 limits
		Source 1	Source 2	Source 3	
Crushing value (%)	17.52	33.57	34.4	36.7	Less than 30% for wearing surfaces and less than 45% for other than wearing surfaces
Ten percent fines value (kN)	231.3	115.3	120.5	118.7	
Los Angeles abrasion resistance (%)	21.56	38.8	36.7	44.16	Less than 30% for wearing surfaces and less than 50% for other concretes
Impact value (%)	17.37	35.81	35.95	38.42	Less than 30% for wearing surfaces and less than 45% for other than wearing surfaces

strength of the aggregate. Therefore, the resistance against crushing of recycled coarse aggregate obtained from all the three Sources is weaker than that of natural coarse aggregate. This attributes the formation of finer particles due to the adhered old cement mortar during the application of compressive load. However, the crushing values of recycled coarse aggregates are within the limits specified by BIS (IS: 383-1970) for various applications of normal concrete aggregates. Similarly, the minimum load required to produce ten percent fines value in case of natural coarse aggregate is 231.3 kN. Whereas, the load required in case of recycled coarse aggregates obtained from the Sources 1, 2, and 3 are 115.3, 120.5, and 118.7 kN, respectively. Unlike the crushing value, a higher value indicates higher the strength of aggregate. According to the British Standards (BS: 882-1992), the minimum load required to produce ten percent fines for heavy duty floors is 150 kN, for wearing surfaces is 100 kN and for other concrete works is 50 kN.

The results of toughness and hardness of recycled coarse aggregate revealed a similar trend. The aggregate impact value of recycled coarse aggregate obtained from Sources 1, 2, and 3 are 35.81, 35.95, and 38.42%, respectively. These values are almost double when compared to natural aggregates of 17.37%. However, these are within the limits of BIS (IS: 383-1970) for natural aggregate concrete of different applications. Similarly, the Los Angeles abrasion resistance of recycled coarse aggregates is almost twice than that of natural aggregate. As it is reported by several researchers in the literature that the mechanical properties of recycled coarse aggregates are relatively weaker compared to natural aggregates due to separation and crushing of light porous mortar adhered from recycled aggregates during testing.

3.4 Summary

The physical properties, viz: grading, size and texture, density, specific gravity, water absorption, flakiness, and elongation indices of recycled aggregates are highlighted. The various factors affecting these properties of RA are also discussed. In general, the recycled aggregates are found to be weaker than the natural aggregates against mechanical resistance such as aggregate crushing value, ten percent fines value, impact value and Los Angeles abrasion loss value. The results of mechanical properties of RA reported by various researchers are discussed in this chapter. Based on these discussions, the following are the important conclusions drawn.

- Using jaw crusher, one can produce reasonably well-graded recycled coarse aggregates of good shape from the uncontaminated demolished concrete rubble. These recycled aggregates are more angular and the surface texture is rough and more porous due to the presence of old mortar. The recycled fine aggregates obtained from the crusher are somewhat coarser and angular than desirable, for production of good quality concrete mixes. Therefore, the concrete made exclusively with fine and coarse recycled aggregates tend to be harsh and unworkable. However, by adding a certain percentage of natural fine aggregate to the recycled aggregate, it is possible to bring the fine recycled aggregates within the grading limits and at the same time, the workability is greatly improved.
- The amount of adhered cement paste on the aggregate surface depends mainly on the grinding process, aggregate size, and strength of original concrete. The quantity of adhered paste increases with the decrease in size of aggregate. The recycled aggregates obtained from the concrete having lower strength have the higher quantity of adhered cement paste for the given size of aggregate.
- The saturated-surface-dry (SSD) density of recycled aggregates were lower than that of natural aggregates due to the low density of cement mortar, that was attached to the concrete from which the recycled aggregates derived and many researchers found that the range is in between 2340–2490 kg/m^3. Due to better grading of recycled fine aggregate over a large range of sizes, the bulk density of recycled fine aggregate was higher than that of medium size recycled aggregate despite the lower specific gravity of former.
- Like the density and SSD specific gravity, the water absorption of recycled aggregate is also a function of strength of parent concrete. The water absorption of recycled aggregate was inversely proportional to the strength of parent concrete. The water absorption of coarse recycled aggregates was much higher than that of natural aggregates due to higher absorption capacity of old cement mortar adhered to the recycled aggregates. The water absorption capacity of fine recycled aggregate is still higher than the coarse recycled aggregates. Due to high water absorption, it was proposed to use presoaked aggregates for production of RAC so that uniform quality may be maintained during the preparation of the mix.

- The recycled aggregates are found to be weaker than natural aggregates against mechanical resistance such as aggregate crushing value, the ten percent fines value and Loss Angeles abrasion loss value due to the weaker old mortar adhered to the recycled aggregates and weaker bond between recycled aggregate and old mortar. These values mainly depend on the strength of parent concrete, the quality of aggregate employed in the parent concretes and the method of crushing.

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