Chapter 2

Literature Review

2.1 General

Recycling of building materials started around the end of the Second World War. Demolition waste of buildings was utilized as aggregate in concrete, and rubbles produced by bombing buildings and other structures were later used for construction purposes, especially in Germany and Britain. There was very little research on using RCA in concrete until the 70's when industrialization boomed up, and the requirement of natural aggregate (NA) by the construction industry increased drastically. Old buildings were demolished for new construction, and the possible scarcity of NA in future increased the interest in research on RCA [30]. Since then, extensive research has been done on RCA, and a major focus has been emphasized on utilizing those aggregates for construction practices.

New concrete produced up to 25% to 30% RCA replacement of NA possess comparable fresh and hardened properties with that of NA-concrete [26, 31]. The properties degrade with the increasing percentage of recyled concrete aggregate (RCA) in concrete, and with 100% replacement of NA has lower compressive strength, high shrinkage and creep, higher porosity with lower density [32]. Studies have been done to establish the maximum replacement percentage of RCA without affecting the properties of the resulting concrete. Two important approaches have been reported in the literature to maximize the use of RCA in structural concrete: a) by minimizing the adhered mortar content [25, 33] (b) by strengthening the adhered mortar/strengthening of old ITZ [34, 35]. All the approaches applied to improve RCA properties have been successful up to a different extent. Surely, by using above mentioned approaches, the physical and mechanical properties of

RCA-concrete can be improved and sometimes better than NA-concrete.

In literature, it has been shown that RCA-concrete can be used in all the foundation level and low strength construction work; in the case of use of RCA-concrete, it has been accepted that RCA can replace NA by 50% to 60% for medium strength concrete and 100% in lower strength concrete. And research is continuous for its maximum utilisation in structural concrete. Even though the use of C-RCA is currently accepted to some extent in a good number of civilized countries, the finer fraction is still strongly restricted or even banned. The reasons for such restrictions arise from earlier research that classified F-RCA as highly heterogeneous, having high water absorption rates and levels of contaminants, leading to unacceptable performance losses. However, recent researches seem to contradict that FRA cannot be used in concrete production. Investigations conducted by [35], [36,37] among others, have shown that F-RCA can be used for concrete production if some specific care is taken, both in the design as well as in the production stage of these concretes. This literature review discusses variations between RCA and NA for their various properties. Review is divided into nine segments, namely 1) Physical properties of RCA, 2) Mechanical properties of RCA, 3) Quality improvement techniques process of RCA, 4) Fresh properties of RCA-concrete, 5) Hardened properties of RCA-concrete, 6) Durability of RCA-concrete, 7) Microstructural analysis of RCA-concrete.

2.2 Physical properties of RCA

The quality of fresh and hardened concrete depends on the physical properties of aggregates involved. RCA as an aggregate for fresh concrete possesses degraded properties compared to NA [23,30,37]. The presence of adhered mortar on RCA has been accepted as the reason behind almost all the degradation in it [25, 26, 38], also the quality and quantity of adhered mortar present induce the behavioural variations between different type of RCA [27,29]. Comparatively, RCA has been found to have lower density/specific gravity, high water absorption capacity, high abrasion value, higher porosity, and rougher surface than NA [34,39,40].

2.2.1 Adhered Mortar

Concrete is the accumulation of cement, fine aggregate (natural sand), and coarse aggregate. Cement acts as the adhesive medium for fine aggregate and coarse aggregate. Old mortar is a hardened state of sand bonded with cement. Crushing of hardened concrete produces both coarse and fine aggregates. F-RCA comprises old mortar, cement particles, and broken pieces of stone (individually or with adhered old mortar). Adhered mortar is the old mortar cohered on the coarse aggregate. Mostly cement is in hydrated state, but unhydrated cement particles are also present in a small amount. The old mortar itself is non-homogeneous, and when combined with coarse aggregate, it brings more non-homogeneity in the unified mass. The presence of old mortar brings all the differences between RCA and NA.

The quality of RCA differs from C-NA due to the existence of old adhered mortar, which ultimately affects the quality of concrete made from it [29, 41, 42]. The quantity of adhered mortar on RCA is dependent on the crushing processes adopted, the strength of old concrete from which it is processed, and also on the size of RCA [25, 43–46]. It has been reported that multi-stage crushing process proves better than single-stage crushing for RCA production [43]. Quantity of adhered mortar on RCA increases if the strength of source concrete increases [46–48], and also when the size of aggregate decreases [23,47,49]. Adhered mortar on RCA is responsible for almost all its negative attributes. High water absorption, low density/specific gravity, and presence of micro-cracks in adhered mortar induce large variation in qualities of RCA [50, 51]. It can be clearly said that the quality of RCA is inversely proportional to the amount of adhered mortar present on it. The volume of the adhered mortar in RCA varies from 25% to 70% depending upon the size of the aggregate [33, 51, 52]. Smaller size RCA contains a higher amount of adhered mortar because of the availability of larger surface area cite [48].

It is suggested that for proper mix design, adhered mortar content should be known [35, 53], and in literature, several methods have been proposed for its quantification.

The thermal treatment method is one of those methods in which aggregates are passed through various cycles of thermal heating and soaking in cold water. Also, this method can be used with almost all types of aggregates (including limestone) [54]. [42] used thermal treatment in which the amount of mortar attached to 4/8 mm RCA (33–55%) was found to be higher than 8/16 mm (23–44%). In another study, RCA samples were passed through five daily cycles of freeze and thawing in a sodium sulphate solution (mechanical and chemical stresses to remove adhered mortar content). They reported that two sources of adhered mortar content on RCA were between 21 to 43% for various sizes [55]. The acid method for adhered mortar content was also determined by using HCl (hydrochloric dissolution method [27,43], similarly in another study, sulphuric acid of 2M was used [56]. Image analysis is another method which has been efficiently used [52, 53].

RCA having adhered mortar content under 44%, possesses physical properties like bulk specific density higher than 2160 kg/m^3, Los Angeles abrasion loss under 40% and water absorption value lower than 8% which results in the RCA-concrete of comparable strength with that of NA-concrete [42]. RCA-concrete performs similarly to the NA-concrete if the new mortar mix is stronger than the adhered mortar on RCA [43]. The presence of old clinging mortar adhered to the RCA diminishes its properties compared to NA. However, using a proper recycling process, the content of adhered mortar can be easily reduced to the acceptable limit.

2.3 Specific gravity

Specific gravity, one of the principal parameter of aggregate for mix design of concrete, controls various properties of the new concrete produced. The specific gravity of RCA follows opposite trends with the quantity of adhered mortar on it [29], which decreases if adhered mortar's content increases and vice-versa. RCA had been reported to have 7 to 14% lower relative density than NA in saturated surface dry (SSD) state, reflecting the porosity of adhered mortar [57]. The specific gravity of RCA depends on the strength of old NA-concrete, size of the aggregate and crushing process, same as of adhered mortar [48]. The specific gravity in saturated surface dry, oven dried and in dry state presented in different studies is tabulated in Table 2.1. In an experimental study, RCA obtained from source concrete with different compressive strengths (28.3 MPa, 49.0 MPa and 60.7 MPa) with the same recycling process; it was observed that the density of RCA increased with the increase in the strength of source concrete. Still, the difference was not more than 3% [58]. Density of C-RCA in saturated surface dry (SSD) condition ranges from 2310 kg/m^3 (4-8mm) to 2490 kg/m^3 (for 16-32mm) in comparison to density of original C-NA ranging from 2500 to 2900 kg/m^3 [23, 40, 59]. The specific gravity (SSD) of RCA

Table 2.1: Density of RCA from different studies

Author	Origin	Size of aggregate	Density (kg/m^3)	
			RCA	NA
Bairagi et al. (1993)	Laboratory crushed	20 mm (max)	2660 (a) (SSD), 2890 (b),1330 (C)	2920 (a) (SSD), 2990 (b), 1540(C)
Limbachiya et al. (200)	Rejected structural precast elements	10-20 mm	2410 (a) (SSD), 1210 (C) (OD)	2600(a) (SSD), 1360 (C) (OD)
		5 -10 mm	2400 (a) (SSD), 1170 (C) (OD)	2600 (a) (SSD), 1360 (C) (OD)
Sagoe Crentsil et al. (2001)	Commercially graded unwashed coarse recycled aggregate	14 mm (max)	2394	2890
Gomez- Soberon (2002)	Laboratory prepared	10-20 mm	2280 (Dry), 2410 (SSD)	2570 (Dry), 2590 (SSD)
		5-10 mm	2260 (Dry), 2420 (SSD)	2640 (Dry), 2640 (SSD)
Xiao et al. (2005)	Concrete waste from airport runway	5-31.5 mm	2520 (b), 1290(C)	2820 (b), 1453 (C)

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Table 2.1 – continued from previous page

Author	Origin	Size of aggregate	Density (kg/m^3)	
			RCA	NA
Exebeeria et al. (2006)	Recycling plant		2430 (SSD)	2674 (SSD)
kou et al. (2007)	Recycling plant	10 mm	2490	2620
		20 mm	2570	2620
Sato et al. (2007)	Laboratory prepared from two different w/c ratio old concrete: A = 0.45; B= 0.63	20 mm	A: 2410 (SSD), 2290 (OD); B: 2412 (SSD), 2290 (OD)	2660 (SSD); 2640 (OD)
		10 mm	A: 2320 (SSD), 2110 (OD); B: 2310 (SSD), 2070 (OD)	2630 (SSD); 2560 (OD)
Casuccio et al. (2008)	Laboratory recycled from : A= High strength parent concrete; B= Normal strength parent concrete		A: 2520; B: 2510	2704
Domingo Cabo et al. (2009)		4-20 mm	2338 (Dry)	4-10 mm: 2622 (Dry); 2659 (SSD)

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Table 2.1 – continued from previous page

Author	Origin	Size of aggregate	Density (kg/m^3)	
			RCA	NA
			2460 (SSD)	10-20 mm : 2647 (Dry); 2673 (SSD)
Padmini et al. (2009)	Laboratory recycled from concrete of three different strength: A: 35 MPa; B: 49 Mpa; C: 56 Mpa	10 mm	A: 2460, 1338(C); B: 2400, 1327 (C); C: 2380, 1327 (C)	2800, 1408(C)
		20 mm	A: 2520, 1432(C); B: 2510, 1421(C); C: 2480, 1394(C)	2800, 1462(C)
		40 mm	A: 2560, 1341(C); B: 2530, 1334(C); C: 2520, 1329(C)	2800, 1406(C)
Paine and Dhir (2010)	Laboratory crushed from concrete of two strength: A: 35 MPa; B: 60 Mpa	20 mm (max)	A: 2385(a), 1360(C); B: 2390(a), 1250(C)	2550(a), 1485(C)

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Table 2.1 – continued from previous page

Author	Origin	Size of aggregate	Density (kg/m^3)	
			RCA	NA
Rao et al. (2011)	Recycled from demolished RCC culvert (15 years old)	20 mm (max)	2470(SSD)(a), 1340 (loose)(C)	2750 (SSD)(a), 1581(Loose)(C)
Dilbas et al.(2014)	Recycled from rubble of a demolished building	4-8 mm	2330 (SSD)	2750(SSD)
		8-32 mm	2230(SSD)	2720(SSD)
Cakir (2014)	Commercially recycled	12-22 mm	2315	2635
Parthiban et al. (2017)	Laboratory recycled			

decreases with increment in its replacement ratio; for 0% replacement that is for NA it was 2.75, for 25%, it was 2.66, for 50% it was 2.60, for 100% replacement, it was 2.51 [46]. Density difference in oven-dried conditions is around 9% and 30% lower for RCA and CCB (crushed clay brick), respectively, compared to the density of NA [60]. The higher porosity of adhered mortar on RCA results in lower values of specific gravity. Still, a considerable increment was observed in the value of apparent specific gravity over the specific gravity when RCA was in saturated surface dry condition [61]. This may be due to the greater porosity of RCA [38]. The bulk density (loose and rodded) of RCA had a reduction of 14% compared to the corresponding bulk density of NA, irregular shape and texture with adhered mortar of RCA were reported to be the possible reason for this reduction [38]. The dry density (both bulk and loose) of RCA was also found to be less than that of NA, and it decreases with the increase in C-RCA replacement ratio [46]. During the different experimental studies, the bulk density and apparent density of RCA were approximate 11% and 10% lower than that found for NA [42, 44, 62].

2.4 Water absorption

Water absorption is another property of aggregates that majorly defines concrete characteristics. RCA has higher water absorption than that NA. Therefore, water demand for RCA-concrete mixes is higher compared to the NA-concrete mix, which eventually affects the mix quality. As a result, the strength of concrete is compromised [63]. Generally, RCA has water absorption capacity around 3-8% and can range up to 15% in the worst case, compared to the NA having the same around 0.4-2% [57, 64, 65]. The higher water absorption capacity of RCA results from the porosity of old mortar adhered to RCA [49, 62]. Water absorption of smaller(10mm) RCA is found to be higher than that of larger(20mm) RCA because of the availability of greater surface area for the adhered mortar to be present [36]. In an experimental study, the porosity of larger and smaller RCA was 5.6% and 10.6% respectively with respect to NA with 0.8% and 1.8% respectively [48, 59]. Table 2.2 shows the observed water absorption capacity of RCA in different studies. It was concluded that porosity increases considerably with the increase in replacement ratio of RCA, and the total porosity to water is the variable that induces the greatest difference between the RCA and NA [64,66]. The rate of water absorption of

RCA has obviously been found higher than that in the NA because of its high porosity. In an experimental study, it was reported that NA and RCA attained 72 and 76% of their water absorption capacity, respectively, in the first 30 mins of the soaking period, and it reached 92 and 94% respectively, in the soaking period of 4 hours [38]. If the water absorption of larger (20mm) and smaller(10mm) RCA exceeds by 7 and 13% respectively, it is advised not to be used in the production of RCA-concrete [46]. The absorption capacity is one of the most significant properties distinguishing RCA from raw aggregates, and it can influence fresh and hardened concrete properties. Some researchers suggest a limit of 30% of RCA to maintain the standard requirements of 5% of absorption capacity of aggregates for structural concrete [67]. Water absorption of RCA is significantly affected by the strength of source concrete. C-RCA obtained from the source concrete with 28.3 MPa was found to be 30% higher than the C-RCA obtained from source concrete with a strength of 60.7 MPa [58].

Water absorption and desorption property of RCA are believed to act as an internal curing agent. RCA mixtures designed keeping the factor of internal curing at later age, resulted into similar or even better performance than NA-concrete [54]. Internal curing (IC) agent are those, which facilitates the availability of required water for hydration process inside the structure itself, in this process RCA is pre-saturated with amount of water it can absorb and then the same is used in low w/c concrete mix. With low w/c (less than 0.42), under-pressure is developed inside the sealed pore network of concrete as the water available of hydration is not adequate for full hydration. This under-pressure develops a suction pressure to withdraw water from the IC medium pores [54]. Pre-soaking of RCA has also been suggested to counter the problem of high water absorption capacity of RCA and the amount of water required to pre-soak the RCA was calculated according to SSD condition [28, 45, 68]. On the contrary, it has also been reported that during pre-soaking method water from IC medium pores breaches the bond and participates into the new cement matrix leading to a higher w/c in the transitional zone (ITZ) resulting into the weakening of strength [69]. To counter the high water absorption capacity of RCA in RCA-concrete, use of mineral admixture such as fly-ash proves efficient by reducing the volume of macro-pores [42, 45].

Table 2.2: Water Absorption of RCA from different studies

Author	Origin	Type of aggregates	Water absorption (%)	
			RCA	NA
Bairagi et al. (1993)	Laboratory Crushed	Coarse	3.95	0.99
Sagoe- Crentsil et al. (2001)	Commecially graded	Coarse	5.6	1
Gomez-Soberon (2002)	Laboratory Crushed	Coarse	5.82	0.876
			6.8	1.134
		Fine	8.16	1.49
Etxeberria et al. (2006)	Recycling plant	Coarse	4.44	0.8
Evanglista and Brito (2007)	Laboratory Crushed	Fine	13.1	0.8
Sato et al. (2007)	Laboratory prepared from two different w/c ratio old	Coarse	A: 6.13; B: 5.28	0.69
		Fine	A: 9.94; B: 11.02	2.63
Casuccio et al. (2008)	concrete: A = 0.45; B= 0.63 Laboratory prepared from two different w/c ratio old concrete: A = High strength; B= Normal strength	Coarse	A: 3.9; B: 3.8	0.5
Chakradhara Rao et al. (2011)	Laboratory recycled	Coarse	3.92	1.13
Yang and Han (2006)	Field recycled	Coarse	8.43	0.42
Xiao et al. (2006)	Field recycled	Coarse	9.25	0.4
Kou et al. (2007)	Laboratory recycled	Coarse	3.52 (20 mm), 4.25 (10 mm)	1.11 (20 mm), 1.12 (10 mm)

2.5 Mechanical properties of aggregate

RCA has reduced strength in comparison to NA, solely due to the presence adhered mortar on it. Los Angeles abrasion value, impact value and crushing value of RCA has lower value as compared to NA [38]. RCA obtained from lower strength old concrete shows higher values Los Angeles abrasion and vice –versa, it can be said that quality of adhered mortar majorly effects the LA abrasion value, i.e., the RCA obtained from higher strength old concrete possess higher resistance against mechanical actions than the RCA obtained from lower strength NA-concrete [61]. When the strength of concrete from which RCA is produced remain same, strength of RCA decreases with the reduction in size of aggregate. Smaller size aggregate has larger surface area helping higher coating of mortar in comparison to large size aggregate [48]. For 16-32 mm, 8-16 mm, and 4-8mm C-RCA derived from high strength NA-concrete, LA abrasion loss was 22.4%, 26.7% and 30.1% respectively, and for the similar size fractions of RCA obtained from low and medium strength NA-concrete it was 31.5% and 25.4%, 37.0% and 29.2%, 41.4% and 32.6% respectively [23]. Los Angeles loss percentage of 23.1% for C-RCA which was 47% higher than that found for original basalt aggregate (15.7%) [40]. Similarly, C-RCA has lower crushing value and 10% fines value [44, 62, 65].

According to ASTM C-33 [53]. standard “Standard Specification for Concrete Aggregates”, the aggregates will be valid to use in concrete production if the loss determined by the “Los Angeles Abrasion test” is less than 50%. Hence, in all the different cases it has been found that the Los Angeles abrasion percentage loss of the RCA is under the acceptable limit of 50% for application in structures, irrespective of its origin [46,63,66,70].

2.6 Enhancement treatments of RCA

To improve the properties of RCA two common methods of either removing or strengthening the adhered mortar, have been found in the literature review.

Different methods have been reported to reduce mortar content in RCA, such as pre-soaking in acid, heat grinding (thermal treatment), pre-soaking in water, mechanical grinding and sometime their combinations. In an experimental study, for pre-soaking treatment three types of acid was used; HCl, H_3PO_4 and H_2SO_4, which in turn enhanced the properties of RCA, consequently improving the performance of RCA-concrete [33]. In a different study, by using 3 levels of grinding method, adhered mortar content was reduced from 55% to 32.4% [25]. They also reported that grinding technique proved much better to remove adhered mortar than by using Los Angeles Abrasion method, as later method was able to reduce adhered mortar content from 55.7% to 45.5% only [25]. Mechanical grinding removes adhered mortar significantly and also improves the shape of aggregate. In a different study RCA were treated in a modified concrete mixer, in mixer RCA were placed and rotated for 5 hours at a speed of 10 rpm in the presence of water to discard foreign materials and infirm adhered mortar (similarly like in LA abrasion method) [54], using this simple treatment method RCA with 24% of adhered mortar was reduced to 9%. Strengthening of adhered mortar is another approach by which properties of RCA is improved. One of the method is polymer emulsion method, in which pores of RCA is filled by immersing it into polymer solution which seals the surface, which in turn enhances its physical and mechanical properties [71]. By using polymer emulsion the workability and durability of RCA-concrete improve, however, compressive strength reduces may be because of the diffusion of positive polymer groups into the cement paste makes it hydrophobic and inhibits the hydration of unhydrated cement. Treatment of

RCA with mineral admixtures such as silica fume, ground granulated blast furnace slag (GGBFS), fly ash, metakaoline has very much potential for enhancing its properties. On replacing cement by 10% silica fume, target strength was achieved with 100% RCA, ITZ of RCA-concrete was improved and its compressive strength increased upto 30% and 15% at the age of 7 and 28 days respectively [72]. Addition of fly ash or silica fume as fine aggregate replacement in RCA-concrete reduces the pore volume and accordingly, improves the pore structure, as a result of which compressive, tensile and bond strength also improves [45]. In [65], incorporated 25-35% class F fly ash as partial replacement of cement and reported the strength increment of 36.1% and 47.6% on 28 and 90 days. Different types of mineral admixtures such as fly ash (35%), silica fume (10%), metakaoline (15%) and GGBFS (55%) were used to study their influence on RCA-concrete and NA-concrete properties and it was reported that RCA-concrete performed better than NA-concrete with those admixtures, long-term and short term properties was enhanced with silica fume and GGBFS while GGBFS and fly ash presented improvement in long term properties [65]. Carbonation treatment to strengthen the adhered mortar of RCA is found to be the most efficient method and is also an environmentally friendly approach [73]. By using accelerated carbonation technique to treat RCA, its water absorption can be reduced upto 16.7%, 10% fine value increased upto 4%, crushing value reduced by 25.9%, this technique also enabled to increase the replacement level upto 60%, micro hardness of old mortar was found to be improved [74]. In a different study, it was reported that the physical properties of RCA were enhanced, apparent density increased by 4.7-5.6%, water absorption and crushing value decreased by 7.6-9.6% and 22.6-28.3% respectively [75]. Carbonation technique helps in increasing the density and hence, reducing the water absorption and crushing the value of RCA which eventually improves the workability and compressive strength of RCA-concrete, it also improves RCA-concrete performance against drying shrinkage [75]. Carbonation reaction results in the formation of calcium carbonate and silica gel which fill the pores of adhered mortar resulting into improved properties of RCA and hence enhancing the properties of RCA-concrete [71].

2.6.1 Fresh concrete properties of RCA-concrete

Fresh and hardened properties of RCA-concrete is highly dependent upon the characteristics of the RCA. Size and shape of RCA influence the amount of adhered mortar on it which correspondingly reflects its effect on the concrete mix [44, 76]. Properties of RCA-concrete majorly depends upon the source of RCA, RCA replacement ratio and their production process, initial water saturation and the mixing procedure adopted [11].

2.6.1.1 Mixture design

Due to relatively high absorption of RCA as compared to NA, extra water and hence higher starting slump may be necessary. This is particularly true for aggregates if they are dry before batching. Experience shows that RCA continue to absorb water after mixing in a batch plant. This can cause a loss of slump and workability after the mixing is complete. To offset this, RCA – like structural lightweight aggregate con be pre-wetted in stockpiles with a sprinkling system. The compressive strength, tensile strength, and modulus of elasticity of RCA-concretes, made with RCA which had been dry-mixed prior to production of concrete, to be considerably higher than the strengths and modulus of elasticity of corresponding concretes made with RCA which had not been dry-mixed prior to addition of water and cement. The effects observed after dry-mixing may be due to one or more of the following reasons: (1) the shape of coarse aggregates is improved by dry-mixing. (2) old mortar which is attached to the surface of RCA particles is removed by dry-mixing. (3) fine particles of old cement which are generated during dry-mixing of RCA accelerate the hydration of fresh cement similar to a chemical nucleating agent [23]. To improve the degraded physical properties of RCA, the strength and the mechanical behaviour of RCA-concrete, modified mixing processes are proposed. Two-stage mixing approach as shown in Fig. 2.1 was proposed to obtain comparable strength of RCA-concrete with that of NA-concrete [77]. In this process, the necessary amount of water was divided into 2 portions and was added into the mix separately [73]. The idea behind the two-stage mixing technique is to pre-wet the dry RCA in the first phase with the water required to saturate it and half of the effective water required for the mix design for about 3 to 5 minutes after which binders are added mixed for 2 more minutes, in the second phase, another half of effective water and superplasticizers are mixed for 5 more minutes to obtain a homogeneous consistency [69, 78]. In a different approach for double-mixing technique aggregates and binders are first pre-mixed after which water required are mixed, to achieve desired consistency mixing time was insistent on the water absorption velocity of RCA which was found to be about 12 minutes [79].

RCA-concrete produced using double mixing method showed higher strength (12.60%), reduced chloride penetration (22.7%) and carbonation depths (12.3%) of RCA-concrete, also by using this mixing approach it is possible to improve ITZ between old adhered mortar and new mortar of RCA-concrete [34]. The intent behind this approach is to strengthen the RCA by filling its pores with binders and to improve the interface bonding between RCA and new mortar [80]. Adhered mortar content on RCA not only degrades its properties against NA but also increases the mortar content in RCA-concrete (adhered mortar and new mortar) which in return, effect the overall performance of RCA-concrete negatively. To obtain the optimum mix design for RCA-concrete, several trial mixes is

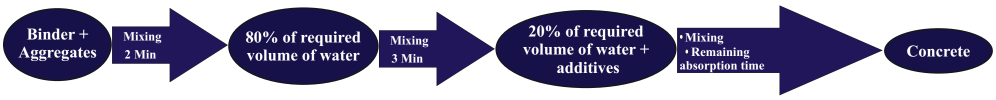

Figure 2.1: Two satges mixing approach

required as adjustment may require with respect to the quality of RCA. To reduce the numbers of experiment, [81] adopted Taguchi's approach with an L16 (215) orthogonal array and two-level factor using analysis of variance (ANOVA) and significance test with F-statistics [81].

[35] proposed a new method of mixture proportioning for concrete made with C-RCA. The new method was named as "equivalent mortar volume" in which the total mortar volume was kept constant. It has been reported that 100% RCA-concrete can have higher compressive strength with respect to the NA-concrete if its w/c is kept lower than the w/c of source concrete from which it is derived [63]. To achieve lower w/c, cement content should be increased as the water requirement by RCA is higher than NA [48]. RCA-concrete mix with 50% replacement by RCA require 6% more cement and for 100% replacement 8-9% more cement is required to achieve similar compressive strength as NA concrete mix [11]. [82] proposed a method of mix design for RCA-concrete from the available conventional methods. It has been suggested that the cement required was about 10% more in view of the inferior quality aggregate. In another study it was concluded that the proportion of cement increment suggested to maintain the w/c is not necessary, if the concept of w_{eff}/c is adopted [58, 79]. The main parameters that have most impact on the mechanical properties of RCA-concrete are effective water to cement ration (w_{eff}/c) and replacement ratio of RCA [83]. w_{eff} is the amount water required for

the reaction of binders i.e., the water required for the hydration of cement during mixing which can be calculated by deducting the amount of water absorbed by coarse and F-RCA from the total water provided in the mix [58, 78]. Investigation on the influence of two modes of mixing water (total water and effective water) in RCA showed that the using $w_{eff/c}$ resulted into more uniform slump and better compressive strength disrespect of replacement percentage than using total water to cement ratio cite [79].

- $w_{eff} = (w_m + w_{agg} + w_{ad} + w_{mc})$ - h_{abs}

Where, w_m = Added mixing water w_{agg} = water in aggregate due to absorption w_{ad} = water of the additive w_{mc} = water of the mixing component

- wt = constant total water volume = $w_m + w_{agg} + w_{ad} + w_{mc}$

The compressive strength depends linearly on the cement-to-water ratio, and Young's modulus and the splitting tensile strength can be expressed by a function of the compressive strength. Therefore, it is possible to design the mixture proportions of recycled concretes in the same way as conventional concrete cite [51]. Different types of mixing approach adopted in previous studies and their effect on resulting concrete is shown in Table 2.3.

2.6.1.2 Workability and fresh concrete density.

To achieve proper workability higher slump is required. Because of the higher water absorption capacity of RCA, RCA-concrete requires 10-20% more water to achieve similar slump as that of NA-concrete. RCA can absorb water even after mixing which causes drop in slump and workability, especially with the use of dry aggregates [32,61,63]. Workability of RCA-concrete is also affected by the surface texture and shape of RCA as it has more rougher surface and more irregular shape [65, 70, 84]. Slump of RCA-concrete decreases as the % of replacement RCA in it increases [36, 38, 69]. According to Buck T. Hansen (1986), concrete made with recycled coarse aggregates and natural sand needs 5% more water than conventional concrete in order to obtain the same workability. If the sand is also recycled, 15% more water is necessary to obtain the same workability. According to [85] concrete made with recycled coarse aggregates and natural sand needs 5% more water than conventional concrete in order to obtain the same workability. If recycled fine aggregate is also used, 15% more water is necessary to obtain the same workability.

Table 2.3: Mixing approach adopted in previous studies for enhancing the quality of concrete mix of RCA

Authors	Proposed methodology	Significance
Otsuki et al. (2003)	Double mixing method	Compressive strength increased up to 12.6% than normal mixing, Chloride penetration depth reduced to 22.7%, Carbonation depth was up to 12.3%.
Tam et al. (2005)	Two stage mixing approach	28-Days Compressive strength increased up to 21.19% at different percentage replacement, developed a stronger ITZ by filling the cracks and pores in RA.
Kong et al. (2010)	Three stage mixing approach	Triple mixing method is based on two stage mixing approach (TSMA). Compared with TSMA, the triple mixing approach could further improve the properties of the RCA, the micro-structure of ITZs and the RCA-concrete.

Continued on next page

Table 2.3 – continued from previous page

Authors	Proposed methodology	Significance
Corinaldesi et al. (2009)	Additions of fly ash or silica fume into concrete to replace fine aggregate	Improvement of pore structure by reducing the volume of pores, as a result mechanical performance such as compressive strength, tensile and bond strength could be improved .
Limbachiya et al. (2012)	10% silica fume was used as a partial replacement of Portland cement	Enhanced compressive strength and compactness, target strength could be achieved with 100% RA.
Kou et al. (2012)	Incorporation of 25-35% class F fly ash as well as partial replacement of cement	Strength gain was more in between 28–90 days, increase in strength was up to 19.4%, 36.1% and 47.6% from 28 to 90 days for concrete containing 0, 25, 35% fly ash respectively. For 100% RA, replacement of cement caused reduction in strength.

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Table 2.3 – continued from previous page

Authors	Proposed methodology	Significance
Katz (2004)	Pre-treating of RA with silica fume solution (10 wt%)	Compressive strength increased up to 30% and 15% at ages of 7 days and 28 days respectively, ITZ between RA and matrix could be improved.
Kou et al. (2011)	Incorporated different mineral admixtures such as fly ash (FA) (35%), silica fume (10%), meta kaolin (15%), GGBS (55%)	Silica fume and GGBS contributes to both short term and long term properties, FA and GGBS showed their beneficial effect on long term properties. Contributions of mineral admixtures to the performance improvement of RCA-concrete are higher than that to NA concrete.

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Table 2.3 – continued from previous page

Authors	Proposed methodology	Significance
G. Fathifazl et al. (2009)	"Equivalent Mortar Volume (EMV)" method	The total mortar volume in the RCA-concrete and in the companion natural-aggregate-concrete are made equal; this method yields recycled aggregate concrete showing fresh and hardened properties equivalent to that of concrete comprising NA.

To achieve the same slump, concrete made with RCA required about 10% more water than that made with NA due to its higher porosity [63]. The way of preparing RCA for concrete mixtures influences the concrete workability: workability of concrete with natural and RCA is almost the same if water saturated surface dry RCA is used. Also, if dried RCA is used and additional water quantity is added during mixing, the same workability can be achieved after a prescribed time. Additional water quantity depends on the time for which the same workability has to be achieved. It is determined as water quantity for which the RCA absorbs for the same period of time [32]. To control the workability of RCA-concrete mix different techniques have been adopted.

- Pre-saturation of RCA for 10 – 20 min [40].
- Using RCA in saturated surface dried (SSD) condition [65].
- Increase the superplasticizer amount [11].
- Increase the cement content in the concrete composition [57].

In order to achieve the same workability and performance of RCA-concretes to that of NA-concrete different superplasticizers has been successfully employed [46, 47, 65, 70]. Some superplasticizers that has been found in literature: Glenium, modified carboxylate based superplasticizer, Naphthalene based C313, Sika Viscocrete R-550 [36, 46, 47, 86]. New concrete will have a lower density because of the large amount of old mortar and cement paste adhering to RCA. The density of new concrete may be from 5-15% lower than that of control concretes made with conventional aggregate. The natural air content of RCA-concrete may be a little higher than that of corresponding concretes made with conventional aggregates. Bulk density of concrete made with RCA was found to be approximately 2150 kg/m^3 which is lower than that of fresh aggregate concrete (2400kg/m^3) [49]. Fresh concrete density and bulk density observed in previous studies are shown in Table 2.4. T.Hansen (1986) [23] concluded that the natural air content of RCA-concrete may be slightly higher than that of control concretes made with conventional concrete. But it is certainly possible to produce RCA-concrete in laboratory with no significant increase in air content compared with control mixed.

Table 2.4: Fresh concrete properties of RCA-concrete from different studies

Author	Type of aggregate (replacement amount)	Density (kg/m3)	Bulk Density (kg/m3)
Sagoe-Crentsil et al. (2001)	Coarse aggregate	2466	2890 (bulk)
	Coarse recycled	2335	2394 (bulk)
Gomez- Soberon (2002)	Natural (Coarse + Fine)	2130	2593.3 (average)
	Recycled concrete (Coarse + Fine)	2090	2236.7 (average)
Vieira et al. (2011)	Natural (coarse)	2413.5	2600
	Recycled concrete (Coarse, 20% v/v)	2392.3	2400
	Recycled concrete (Coarse, 50% v/v)	2355	NA
	Recycled concrete (Coarse, 100% v/v)	2299.8	NA
Etxeberria et al. (2007a)	Natural	2420	2670
	Recycled concrete (Coarse, 25% v/v)	2400	2430
	Recycled concrete (Coarse, 50% v/v)	2390	NA
	Recycled concrete (Coarse, 100% v/v)	2340	NA

2.6.2 Characteristics of hardened RCA-concrete

2.6.2.1 Compressive strength

RCA-concrete generally has been found to be weaker in strength than NA-concrete. Compressive strength of RCA-concrete decreases with an increase in the replacement ratio of RCA [87]. The relative strengths of 98 to 94% in compression were reported when the replacement % varied from 25 to 50% and for a replacement % of 100%, the value reduced to 86% [38]. 10 to 40% of decrement in strength has been observed if everything else except aggregate type is kept the same [23, 30]. On 100% replacement of NA by RCA, the compressive strength decreases by 25% [11], 10 to 25% [63], 13% to 17% [88], 19% [65] in comparison to NA-concrete; in some studies the reduction was even under 10% [87]. Replacement of NA by 25-30% C-RCA has been reported to have a very less detrimental effect on the strength of RCA-concrete [46, 57].

RCA-concrete with only C-RCA shows lesser variation in its strength, but on F-RCA, the variation becomes larger. The compressive strength of RCA-concrete made with both coarse and F-RCA is 85% of the strength of conventional concrete or more, while that of RCA-concrete made with C-RCA and natural sand is 95% of the strength of conventional concrete or more [23]. A higher reduction in compressive strength of RCA-concrete-concrete has been observed if the maximum size of aggregate decreases [58], due to the availability of a larger surface area for old adhered mortar [48]. In another finding, it is reported that F-RCA with 30% replacement can be utilized without affecting the performance of concrete [36].

The strength of old concrete governs the strength of adhered mortar, which affects the properties of RCA and concrete prepared from it [78]. The strength of RCA-concrete is related to the relative strength between new mortar and adhered mortar, which means that if the new mortar of RCA-concrete is stronger than adhered mortar, then old ITZ will govern its strength otherwise, new ITZ will govern its strength [34, 53]. Contrarily it has also been reported that the properties of old concrete have not so significant effect on RCA-concrete [31], also the w/c of old concrete as well as of new RCA-concrete control the compressive strength of later keeping other constituents identical. However, it has also been reported that RCA-concrete shows comparative values even higher than NA-concrete with 100% replacement of RCA obtained from higher strength old concrete [63,65,78,86,89]. In [63], it has been shown that concrete made with RCA has high bonding strength between the coarse aggregate and the surrounding paste. This is because of the angularity of the coarse aggregate and the residual cementation on the surface of the RCA. Similar results have been found by [86] stated that RCA could develop strength equal to greater than natural rocks. The effect of old concrete quality is not clear from the literature; some have reported a negative impact on the other hand, there are also some results reporting less significance. The quality of adhered mortar depends on the strength of the old concrete and the compressive strength of RCA-concrete can be obtained equivalent to that of NA-concrete regardless of replacement percentage, if the quality of RCA is produced from high-strength older concrete. It can be said that the performance of RCA-concrete depends more on the quality rather than quantity of RCA [32]. Industrially RCA show lower strength values than laboratory-controlled RCA [58], this can be explained as such, that industrially RCA may comprise more types of impurities, foreign material, and different quality types of source concrete. The strength gaining rate is relatively slow in case of all the RCA-concrete compared to NA-concrete between 7 days to 28 days curing period [88], but it is evident that the compressive strength of RCA-concrete has also been reported to continue to increase even after 28 days [58]. Up to 30% replacement of NA by RCA, RCA-concrete mix with higher compaction factor reported gaining higher early age strength [45]. Compressive strength development of RCA-concrete with the age of curing remains the same irrespective of the replacement ratio of RCA, also RCA-concrete mix with lower water to binder ratio shows a higher rate of gain of strength at any age against the mix with a higher water to binder ratio regardless the RCA replacement ratio [38]. By using mineral admixtures like fly ash, silica fume, and GGBFS, the performance of RCA-concrete can be improved. With fly ash (or silica fume) as fine aggregate replacement combined with acrylic-based superplasticizer, RCA-concrete of equivalent strength or even better than NA concrete can be produced [45]. Fly ash in RCA-concrete reduces the early gain in strength certainly due to the delayed pozzolanic activity [54], but the concrete mixtures prepared with fly ash have a greater improvement in strength between 28 and 90 days [65]. The 56-day compressive strength of 60.30 MPa was achieved on 100% replacement of NA by RCA, using 25% fly-ash and 5% micro-silica as replacement of cement [54]. Compressive strength comparison between concrete containing 50% RA (RCA 50), 50% fly ash (FA 50), sustainable concrete (SC, 50% RCA and 50% FA) and conventional concrete (CC) was done and the following relation was observed [90]:

RCA 50 (35.5 MPA) > FA 50 (32.4 MPa) > SC (30.8 MPa) > CC (29.0 MPa)

The use of alkali-activated slag cement in RCA-concrete results in better compressive strength than with OPC [56]. Physical and mechanical strength decrease associated with RCA could be mitigated with slag, and that adequate strengths could be achieved [84]. Slag cement showed better performance in improving the later age strength and also showed an increase in strength gain when a similar water-cement ratio was used [40]. Adhered mortar on RCA acts as a reservoir and facilitates the dissipation of water required and hence, increases the degree of hydration. Taking the higher water absorption capacity of RCA into account and using it as internal curing (IC) agent, the 28-day compressive strength of RCA-concrete has been reported to increase by 39%, and it was also found that RCA(field-recycled)-concrete exhibited higher compressive strength than RCA(treated)-concrete [54]. The compressive strength of the recycled concrete tends to improve, increasing FRA proportion for higher w/c. The effect of the fine material in this case can be more pronounced and compensate for the low cement content of the mixtures. Moreover, the F-RA presents high water absorption, a rougher texture, and a more irregular shape, which can contribute to improve the transition zone of the recycled concrete due to the increase in adhesion between matrix/aggregate [91].

2.6.2.2 Tensile and flexural strength

[61] demonstrated that there are no great differences in tensile strength of C-RCA and natural sand concrete with respect to NA-concrete. However, if F-RCA replaces the natural sand in the concrete using C-RCA then the tensile strength will reduce by 20% with respect to NA- concrete. For a given compressive strength of concrete, the split tensile and flexural strengths are lower for RCA-concrete than parent concrete [48]. The tensile of RCA-concrete is generally lower than that of NA-concrete, but the variation is less significant than the compressive strength of the same. The tensile splitting strength of RCA-concrete with 0.25, 0.50 and 1.0 replacement ratios reported being 94%, 90% and 60% of NA-concrete; similarly, for the flexural strength, it was 94%, 87%, and 74%. [38]. Similar drop in splitting and tensile strength is observed in different reports [46,84]. With increase in percentage replacement of RCA in RCA-concrete, the tensile and flexural strength decreases more [48,65]. The ratios of the flexural and the splitting strengths to

the compressive strength were in the ranges of 16–23% and 9– 13%, respectively [49]. Low strength RCA-concrete show higher loss in splitting tensile strength than high strength RCA-concrete [63].

The tensile-splitting strength of RCA-concrete upto 30% replacement level values obtained was acceptable [36]. RCA-concrete prepared with high strength RCA was reported to be equivalent to that of NA-concrete; however, with low and medium strength RCA, its strength depreciation is significant [78]. It has also been reported that the splitting tensile strength for commercially produced RCA-concrete and NA-concrete showed similar results [40]; this can be accredited to the reduced adhered mortar content on RCA. The flexural strength of Concrete made with RCA was found to be similar to concrete made with NA [26]. It was observed that there is not much difference in flexural strength of RCA-concrete at 100% replacement and NA-concrete (5.23 MPa for 0% and 4.97 for 100% replacement) [46].

By replacing 50% cement with slag, improvement in tensile strength of RCA-concrete was observed [84]. The tensile strength of the slag cement RCA-concrete has been reported to improve with curing, while the tensile strength of Portland cement RCA-concrete remains practically unchanged beyond 28 days for the duration of measurement [40]. Using RCA with alkali activate slag results in better splitting tensile strength and flexural strength than with OPC [56].

In an experimental investigation, it was concluded that the provisions of the code adopted in ACI 318 predict the flexural strength of reinforced NA and RA concrete beams with similar accuracy [92].

2.6.2.3 Modulus of elasticity

The modulus of elasticity of RCA-concrete is generally lower than the corresponding NA-concrete. The 10-12% reduction was observed in modulus of elasticity of RCA-concrete with 30% replacement of NA by RCA [87, 93] and reduction of 30-35% was observed with 100% replacement [44, 46, 87]. Old mortar adhered to RCA is weak in strength, porous in nature with lower stiffness, and has a lower density which correspondingly reduces the modulus of elasticity of RCA-concrete [78], as modulus of elasticity depends on the compressive strength and density of the material [36]. Modulus of elasticity of RCA-concrete has higher reduction as the size of RCA decreases [48]. RCA-concrete comprising 100%

C-RCA resulted in a reduction of 8.5-9.2% in comparison with NA-concrete, but with 100% F-RCA reduction (13.9-25.8%) was even higher [58]. This behavior was justified as the inclusion of F-RCA results in increase in its porous nature. The use of both coarse and F-RCA aggregate the modulus of elasticity of RCA-concrete. Increasing percentage replacement of RCA in concrete decreases its modulus of elasticity. Laboratory crushed RCA-concrete with C-RCA/F-RCA replacement of 25/25%, 50/% and 100/100% exhibited reduction of 5%, 14%, and 21% respectively against NA-concrete [38], whereas when field-recycled RCA has used the decrease in modulus of elasticity was reported to be 15%, 20% and 28% [58]. Stiffness reduction is more aggressive in RCA-concrete than its compressive strength [86], also stiffness of RCA-concrete decreases as the % replacement of RCA increases [32,36,70]. Quality of parent concrete from which RCA is derived considerably affect the modulus of elasticity of RCA-concrete. Fig. refr5 represents the variation of elastic modulus of high strength RCA-concrete (made with low strength (20MPa) and high strength(110MPa), % RCA) with similar strength reference NA-concrete, and it is clearly depicted that the elastic modulus of RCA-concrete made with low strength RCA is lower than that of same with high strength RCA. RCA-concrete produced with treated RCA results in increased modulus of elasticity compared to NA-concrete [54].

2.6.2.4 Durability of RCA-concrete

The durability of concrete can be described as the capability to resist the charge of different chemicals, weathering actions, and abrasion while maintaining its desired engineering properties.

2.6.2.5 Water absorption and permeability

Permeability of RCA-concrete is generally higher, around 2 to 5 times than that of NA-concrete. Permeability of RCA-concrete is dependent upon the quantity of RCA, and increases with the increase in replacement percentage. It also depends on the porosity of new and old mortar; if RCA is derived from less porous old concrete then the permeability depends on the new mortar [32].

RCA-concrete with 100% replacement resulted 21% higher water permeability than NA-concrete [60]. RCA-concrete has an average of 25% higher water absorption than the NA-concrete; the residual mortar attached to RCA resulted in this behavior [40]. In an experimental study to assess the engineering behavior of RCA-concrete, water absorption of RCA-concrete was found to be 0.6 times higher than in NA-concrete [68]. RCA-concrete with 30% RCA did not show any kind of detrimental effect on air-permeability [26]. In other studies, it was reported that with upto 20% replacement, RCA-concrete showed minimum water absorption and total pore volume [59]. The higher permeability of RCA-concrete can be rectified by using lower water/cement ratio or by using mineral admixtures such as fly ash, silica fumes, and GGBFS. The pore structure of RCA-concrete can be amended by reducing the volume of macro-pores with the use of fly ash [45]. It was observed during the experimental investigation that the total volume percentage of pore spaces (voids) and water absorption increases proportionately with the increase of % replacement in RCA-concrete. The correlation between the density and porosity of concrete was established as shown in Equation (2.1) [66]:

$$\rho^c_{app} \frac{gr}{cm^3} = 0.034 \times (81 - \eta^c_v(\%)) \tag{2.1}$$

The porosity of RCA-concrete increases with an increase in the replacement ratio. For 30% and 100% replacement porosity of RCA-concrete increases by 16 and 40% compared to NA [87]. The porosity growth in RCA-concrete can be accredited to the aspect of increment in the total paste volume as the replacement ratio of RCA increases [66]. The relationship between the concrete porosity and the porosity of aggregates and the volume of the paste was established as [66]. The density is decreased with the increase in coarse aggregates replacement ratio. This is mainly due to the lightweight and more porous nature of old cement mortar that is adhered to the RCA. The reduction in density of RCA-concrete is in the range of 4–10% when compared to normal aggregate concrete [46]. Table Density, Voids, Water absorption, and Chloride penetration of concretes for different coarse aggregate replacement ratios (CRR) [46]. Use of mineral admixtures like fly ash and silica fume to improve the durability properties significantly [54].

2.6.2.6 Carbonation

Between RCA-concrete and NA-concrete when w/c is kept similar, RCA-concrete exhibits higher carbonation than NA-concrete [34, 40]. The carbonation depth in RCA-concrete has generally been found to be 1.3 to 2.5 times that in the NA-concrete [49]. Contrarily, it has also been reported that the carbonation depth decreased when the RCA replacement percentage increases, even with 100% RCA replacement carbonation depth was found to be lower in RCA-concrete than NA-concrete [59]. RCA-concrete has a high alkaline reserve due to the presence of old mortar adhered to RCA, which comprises unhydrated cement and calcium hydroxide particles. The high alkalinity of RCA-concrete defends the concrete surface against carbonation mechanism [45]. High water-permeability and low resistance to chloride diffusion are two major durability concerns for RCA-concrete [64]. Chloride penetration depth has been found to increase as the replacement % of RCA increases. The difference observed between NA-concrete and RCA-concrete at 100% replacement was 0.7 mm (14%) [46]. But during another study on the Influence of the chloride diffusion, RCA-concrete with 100% C-RCA was reported to have no negative influence [26]. The use of mineral admixtures like fly ash, silica fume, and GGBFS can prove beneficiary for improving the durability properties of RCA. Fly ash has been found very effective in the reduction of carbonation and chloride ion penetration depth. The service life of a structure with RCA-concrete is also improved as the use of mineral admixtures increases the initiation period for corrosion of reinforcement [45]. Chloride diffusion coefficient can be improved by incorporating slag in the RCA-concrete mix [84]. Using RCA with alkali activate slag results in better performance under different exposure conditions like chloride, sulphate or magnesium sulphate than OPC with NA [56].

2.7 Micro structural Property

The micro-structure of RCA-concrete is more complex as compared to NA-concrete because of the presence two ITZ's, the first is between the RCA and new mortar, and the second is between the RCA (new ITZ) and the old adhered mortar (old ITZ) [80]. The presence of old ITZ acts as a weak link as it is already weak in nature because of the presence of minute pores in the old mortar, and cracks developed in the aggregate due to the crushing process. Adhered mortar on RCA increases its porosity and water absorption, which in turn decreases its strength [64]. By using Scanning electron microscopy (SEM) the porosity in RCA-concrete was found to be around 20% with respect to porosity in NA-concrete having a porosity range of 15.22% - 16.7%, which clearly indicates that the ITZ of RCA-concrete is loose and porous than the ITZ of NA-concrete [88] reported the micro-structure of RCA-concrete to be porous with loose particles coated on its surface which resulted into numerous tiny pores, micro-cracks and fissures. The micro hardness of ITZ in RCA-concrete was found to be lower than ITZ of NA-concrete, indicating the higher percentage of porosity. During an experimental study, it was reported that the quality of adhered mortar on RCA has more influence on the characteristics of ITZ than its quantity [34]. Interfacial bonding between aggregate and cement paste i.e. ITZ (Interfacial transition zone) governs the strength of concrete as it is the weakest link. And as a matter of fact, in RCA-concrete there exist two ITZs (one between RCA and old mortar and the second between old and new mortar); therefore, RCA results in lower strength concrete than NA. Microstructural analysis of RCA-concrete using SEM technique shows that in normal strength, RCA-concrete failure starts in the new ITZ, whereas cracks propagate initially from the old ITZ in high strength RCA-concrete. This shows that high strength RCA-concrete is very susceptible to the characteristic of RCA. By using EDX analysis of RCA-concrete, it was reported that the amount of C-S-H hydration product in normal strength RCA-concrete is found to be lower in old ITZ than in their new ITZ, whereas the same is found to be higher in the new ITZ of high strength RCA-concrete [78]. The weak ITZ of RCA-concrete can be strengthened by using certain mineral admixtures like nano-silica, fly ash, metakaoline, slag and hence, properties of recycled concrete can be enhanced [68, 84]. Scanning electron microscopy (SEM) on the micro-structure of ITZ in RCA and RCA mortar revealed that carbonation treatment not only improved the original ITZ in RCA but also increased the newly formed ITZ in the RCA mortar [75].

2.8 Codal provision in other countries

Developed countries like the UK, USA, France, Germany, Denmark, Japan and Netherlands have succeeded in developing economically feasible technologies for recycling up to 80 – 90% of C&D wastes. EN1260 was expanded to include RCA in the EN Standard for aggregate for concrete. In UK BS 8500-2:200628 considers two types of RCA: recycled concrete aggregate (RCA) and recycled aggregate (RA). Code stipulates that RCA must be composed of 83.5% of concrete and masonry content not more than 5%. It allows 20% replacement of coarse aggregate up to the strength of 50 MPa. 100% replacement is allowed for strength under 20 MPa. There is no provision for F-RCA. In Germany, guidelines for the use of recycled mineral materials are given in DIN 4226 – Aggregate for concrete and DIN 4226 – 100 – RCA for concrete and mortar; DIN 1045 permits up to 26% RCA in structural concrete of cube strength 37.5 MPa in dry or low humidity climate. In Norway, the allowed proportion of RA of type II (aggregate containing greater than 99% concrete and rock) is up to 30% in case of concrete of cube strength 30 MPa exposed to mild climate and 20% for cube strength of 65 MPa exposed to the moderately aggressive climate. In the case of type I (aggregate containing greater than 95% concrete rock masonry and bricks) allowed proportion is limited % for cube strength of 30 MPa under mild exposure. Fine aggregate from recycled concrete can be used up to 5% in case of type I and 10% in case of type II, for concrete of cube strength of 30 MPa for mild exposure. In Australia, HB 155:2002 describes two types of RCA, namely, Type I A which predominantly contains recycled concrete, and type 1B which contains bricks up to 30%. HB 155:20027 defines two grades of RCA-concrete i.e. Grade 1 RCA-concrete with % substitution of type 1A RCA with a maximum strength limit of 40 MPa. Grade 2 RCA-concrete with 100% substation of type 1A/1B RCA with maximum specified strength of 25 MPa. In the USA, ASTM C94/C94M-11655 allows replacement up to 20-25% by weight of coarse aggregate (high grade concrete) for structural application, and % replacement is allowed for concrete cube strength up to 25 MPa. In South Korea, Korean Standard KSF 2573 allows up to 30% replacement of only coarse aggregate for concrete strength of 27 MPa and under, 30% replacement of coarse aggregate and fine aggregate for concrete strength of 21 MPa and under. Limiting values for RCA: Coarse aggregate should have oven dry density greater than 2.5 g/cm^3 and water absorption less than 3%, fine aggregate should have oven dry density greater than 2.2 g/cm^3 and water absorption less 5%. In Japan, JISC (Japan Industrial Standard Committee) stabilized requirements for RCA in 2007.

2.9 IS code

Construction agencies like CPWD say that Indian laws permit the use of only naturally sourced building material. Before 2016, the IS: 323-1970 Indian standard specification related to aggregates for concrete, laid down by the Bureau of Indian Standards (BIS), stipulated that concrete can be made only with naturally accessed materials. Construction agencies cite this rule to avoid using recycled C&D waste. Identification of C&D waste as potential construction material happened after the revision of IS 383 in 2016. As per IS 383:2016, after processing of C&D waste two types of aggregate are recovered which are named as RCA (RA) and Recycled Concrete Aggregate (RCA). RA is a mixture of all: concrete blocks, bricks, tiles, stone etc., and RCA is the product of concrete waste IS 383. Indian standards has allowed 100% use of coarse-RA in lean concrete and have advised not to use fine-RA; for both C-RCA and F-RCA upper limit for use in plain concrete, reinforced concrete and lean concrete is 25%, 20% (upto M25) and 100% respectively IS 383 Similarly, other countries have also established certain upper limit for the use of RA and RCA in concrete for different usage.

The composition of C&D waste generally depends upon the construction and structure type. Like if a flyover or any superstructure like a bridge or dam is demolished, then major constituents of C&D waste will be concrete and steel; on the other hand, if any residential is demolished then various types of waste may be present like soil, masonry, wood, glass, tiles, metals etc. in addition with concrete waste.

2.10 Research gap

Previous studies are largely focused on the use of C-RCA in the production of concrete with little focus on recycled fines. There is very less study on the use of both coarse as well as F-RCA together in the concrete. In this study, both coarse and F-RCA was varied from 0 to 100% with interval of 30%. Both coarse and F-RCA was varied individually as well as simultaneously.‘ Lot of laboratory treatment methods are available in the literature that does improve the properties of RCA close to NA, but most of them demands extra cost and are also not viable for industrial scale. Like carbonation treatment, coating with polymers, chemical treatment, microwave treatment methods, rapid analysis method etc. In this study, mechanical and thermo-mechanical treatment method was used to study its adhered mortar reduction capacity, focusing on its use on industrial scale. Most of the studies are majorly focused on either reducing the adhered mortar or on strengthening it. But by using either of the treatment methods, properties of RCA-concrete can be improved if the single sourced RCA was used in it. In this study, both adhered mortar removal as well as strengthening it was used for enhancing the properties of RCA.

2.11 Summary

This chapter has outlined the major developments on the utilization of RCA (both coarse and fine) for the production of structural concrete. Although the researchers have witnessed a great advancement for the use of C-RCA and F-RCA in place of C-NA and F-NA respectively in the new concrete, there are still some lacunae that need to be addressed further. Extensive research has been conducted on evaluating the potential of RCA derived from different quality of old concrete as a replacement of NA. Apart from quantity of RCA, its quality also impacts the performance of new concrete. Concrete containing large amount of RCA shows reduced value in fresh and hardened properties. Incorporation F-RCA has large negative impact on properties of concrete than the use of C-RCA. When both C-RCA and F-RCA is used simultaneously in place C-NA and F-NA the concrete properties degrades further. Various treatment methods used for improving the physical and mechanical properties of C-RCA is discussed in detail. Various techniques is also discussed for the production of concrete mix of RCA equivalent to that of NA-concrete. Many of the methods mentioned above are currently at the experimental stage, to maximize the use of C-RCA as well as F-RCA in concrete production. The methodologies discussed in this chapter are promising to elevate the percentage replacement of RCA in concrete but still producing concrete with 100% C-RCA as well as 100% F-RCA without compromising strength needs further research.