Chapter 7
Structural Behavior of RAC

7.1 Introduction

Mechanical properties, long-term, durability aspects, and microstructure of recycled aggregate concrete were discussed in earlier chapters. In practice, there are many incidents in which the structures undergo impact loading, such as during an explosion, transportation structures subjected to vehicle crash impact, impact of ice load on marine and offshore structures, accidental falling loads on structural elements, protective structures under projectile or aircraft impact. The behavior of concrete beams subjected to impact load is different compared to the behavior under quasi-static loading. Due to short duration of loading, the strain rate of material is significantly higher than that under quasi-static loading conditions. Also, the failure behavior may be different from those under quasi-static loading conditions. To understand the behavior of RAC beams under impact load, a drop weight impact test was conducted by the authors on RAC beams. The behavior of beams made of recycled aggregate concrete prepared with different amount of recycled coarse aggregate under low-velocity impact is discussed in detail in this chapter. Further, the investigations made by different researchers on the flexural, shear, and axial behavior of reinforced concrete beams made with recycled aggregate are highlighted in this chapter.

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7.2 Impact Behavior

Many researchers have studied the impact behavior of plain, composite, and reinforced concrete beams subjected to low-velocity impact with natural coarse aggregates. Bentur et al. (1986) studied the behavior of plain and conventionally reinforced concrete beams under low-velocity drop weight impact load. The authors reported that in both the specimens, the peak load occurred within 1 ms after contact. In addition, it was reported that the energy estimated from the instrumented tup load did not agree with the calculated total energy. The authors also developed a method to calculate the bending load for failure of specimens under single impact. Banthia et al. (1987) investigated the impact behavior of normal strength, high-strength, and fiber-reinforced concrete beams subjected to low-velocity impact. It was reported that both normal and high-strength concretes are strain rate sensitive and the prediction of its behavior under impact load is not possible on the basis of static testing. The authors also reported that high-strength concrete had higher impact strength and more brittle than normal concrete. In addition, it was reported that the fiber-reinforced concrete is better than plain concrete in dynamic conditions due to its ductility and increased impact resistance. Wang et al. (1996) examined the influence of different types and volumes of fiber on the impact behavior of fiber-reinforced concrete (FRC) beams subjected to repeated drop of impacts. It was reported that the fracture energy of FRC with 0.5% steel fibers was more than that of polypropylene fibers. In addition, it was reported that the two different failure mechanisms exist in FRC with hooked steel fibers: One is a fiber-breaking failure mechanism which occurred when the fiber volume is below a critical value, and the second is a fiber "pull-out" mechanism which occurred when the fiber volume is above the critical value. Tang and Saadatmanesh (2003) investigated the behavior of conventionally reinforced beams strengthened with different types of composite laminates subjected to impact loads. From the experimental results, the authors concluded that the impact resistance of concrete beams significantly improved and the deflection and crack width reduced with the composite laminates. In addition, the authors concluded that the gain in strength depends on the type, thickness, weight, and material properties of the composite laminate. May et al. (2006) studied the influence of shape of impactor and type of interface on the behavior of reinforced concrete beams subjected to high-mass low-velocity drop weight impact loads. Two types of steel impactors were used: (1) spherical surface with a radius of 125 mm and a profile diameter of 90 mm and (2) a flat surface with a profile diameter of 100 mm. Similarly, two types of contact interfaces are used: One is a 12 mm thick plywood pad placed between the impactor and the beam at the impact zone, and the second is a direct contact of impactor with the beam. The authors also carried out a numerical study for the same. The authors have found good agreement between experimental and numerical results.

Rao et al. (2011) have conducted a detailed investigation on behavior of recycled aggregate concrete under drop weight impact load. In this study Ordinary Portland

Cement (OPC) of 43 Grade conforming to Bureau of Indian Standard Specifications (BIS) (1959, 1970, 1982, 1989, 1999) (IS: 8112-1989) with a specific gravity of 3.14 is used in this study. The locally available sand conforming to grading Zone II (IS: 383-1970) is used in both normal and recycled aggregate concretes. The natural coarse aggregates obtained from the locally available quarries with maximum size of 20 mm and satisfying the grading requirements of BIS (IS: 383-1970) are used in both normal and recycled aggregate concretes. The recycled coarse aggregate was obtained from old demolished RCC culvert near Kharagpur. Four concrete mixes, namely M-RAC0, M-RAC25, M-RAC50, and M-RAC100, are prepared using different proportions of recycled coarse aggregates and natural coarse aggregates. In the term M-RAC0, the letter M stands for the Mix, RAC represents the recycled aggregate concrete, and the number represents the percentage of recycled coarse aggregate. All concrete mixes are designed for M25 grade of concrete in accordance with the Bureau of Indian Standards (BIS) (IS: 10262-1982). In all the mixes, the free water–cement (w/c) ratio was kept constant at 0.43 and slump was maintained in the range of 50–60 mm by adding Sika Viscocrete R-550(l) superplasticizer. The details of the mixture proportioning are presented in Table 7.1.

The mechanical properties of RAC are conducted on standard test specimens of 100 mm cubes and 150 mm diameter × 300 mm height cylinders in accordance with BIS (IS: 516-1959; IS: 5816-1999) and American Society of Testing and Materials (ASTM C 469-02 (2002)), and the test results are presented in Table 7.2. Three recycled aggregate concrete beam specimens each for 0, 25, 50, and 100% recycled coarse aggregates are prepared. A total of 12 beam specimens of size 1.15 × 0.10 × 0.15 m are prepared for drop weight impact load test.

Table 7.1 Details of mixture proportions (kg per cubic meter of concrete) (Rao et al. 2011)

Mix designation	RCA (%)	Cement (kg)	Natural aggregates		RCA (kg)	Superplasticizer[a]
			Fine Aggregate (kg)	CA (kg)		
M-RAC0	0	401	574	1261	0	0.05
M-RAC25	25			930.75	310.25	0.05
M-RAC50	50			602	602	0.175
M-RAC100	100			0	1128	0.225

[a]Percentage by weight of cement

Table 7.2 Mechanical properties of RAC (Rao et al. 2011)

Mix designation	RCA (%)	Compressive strength (MPa)	Indirect tensile strength (MPa)	Modulus of elasticity (MPa)	Density (kg/m^3)
M-RAC0	0	49.45 (28.77[a])	2.67	3.120×10^4	2415.64
M-RAC25	25	45.75 (27.9[a])	2.30	2.675×10^4	2349.45
M-RAC50	50	42.5 (35.33[a])	2.19	2.671×10^4	2257.96
M-RAC100	100	40.8 (31.5[a])	2.05	2.640×10^4	2148.10

[a]Compressive strength at 7 days

7.2.1 *Instrumented Drop Hammer Impact Test Setup and Devices*

The in-house built drop hammer test setup shown in Fig. 7.1 is used in the present study to investigate the impact behavior of recycled aggregate concrete beams with different amount of recycled coarse aggregates.

The test setup consists of a fiber-reinforced plastic (FRP) guide tube which facilitates the aligned movement of drop weight hammers of different diameters required to be used for a particular test. The FRP guide tube was firmly fixed to the vertical posts, which are rigidly connected to the rigid steel frame, to avoid eccentricity. In the present study, a steel impactor of 50 mm diameter and 5 kg mass is suspended through the FRP guide tube passes over the frictionless pulley to induce the impact on beams. The impactor may be dropped from a maximum height of 1.5 m. To get a point contact between the impactor and the specimen, a spherical steel ball having a diameter of 15 mm was welded to the impactor at the bottom.

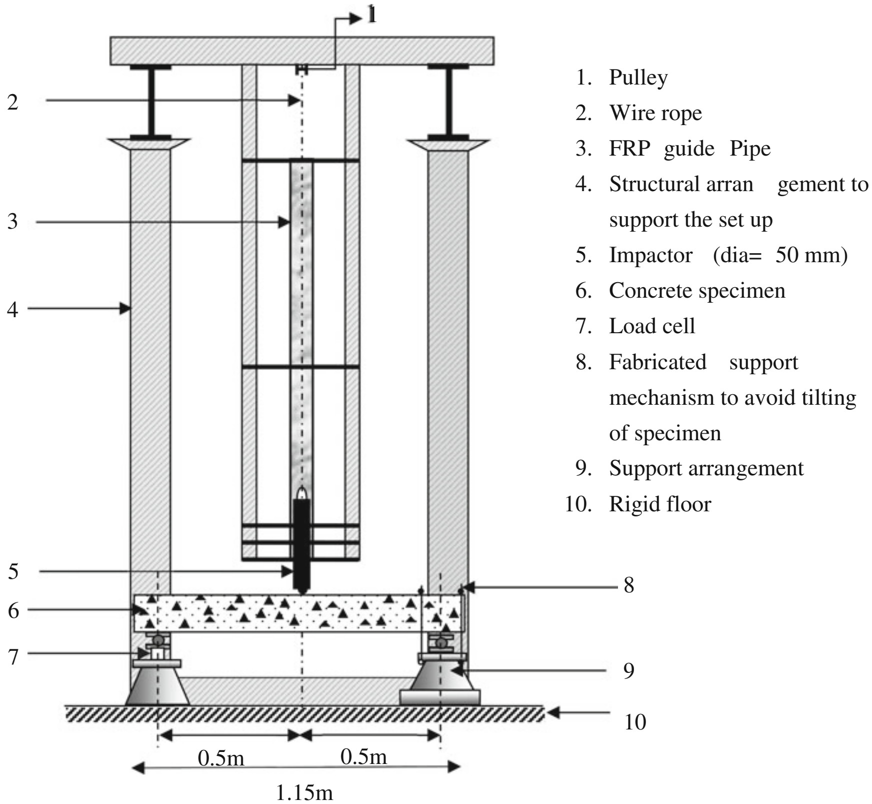

Fig. 7.1 Schematic diagram of drop hammer setup (Rao et al. 2011)

Fig. 7.2 Support arrangement (Rao et al. 2011)

A simply supported arrangement is made as shown in Fig. 7.1 for supporting the beam specimens. To prevent the slippage of the beam specimen after each impact, a bracing arrangement was made with steel angle sections as shown in Fig. 7.2.

Spectrum analyzer and accelerometers Vibration measurement system is used for measuring the acceleration, velocity, and displacement histories at different locations on the bottom surface and along the length of the beam. It is a six-channel pulse fast Fourier transform (FFT) and the constant percentage band (CPB) analyzer. In order to measure the acceleration, velocity, and displacement of the beams, four accelerometers were fixed at the bottom surface of the beams. The positions of the accelerometers (A1 to A4) are shown in Fig. 7.3. Accelerometers are DeltaTron type 4507 with a range of $\pm 700\ \mathrm{ms}^{-2}$ and working on the

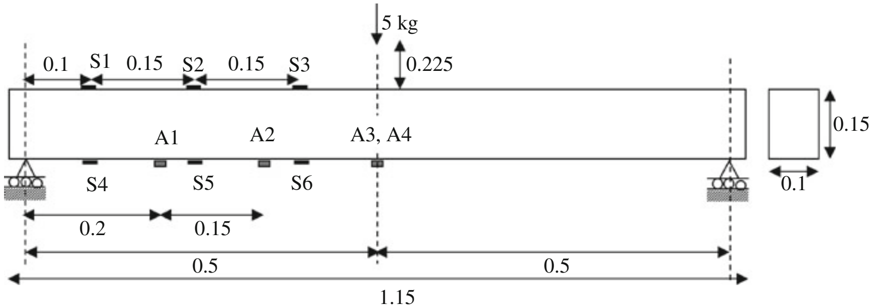

Fig. 7.3 Position of accelerometers and strain gauges on RAC beam (Rao et al. 2011). *Note*: All dimensions are in meters

piezoelectric principle. The accelerometers are connected to the six-channel pulse fast Fourier transform (FFT) analyzer. The acceleration data are captured at interval of 244 μs (Bruel & Kjaer Pulse user manual).

Data acquisition system (DAQ) and strain gauges An eight-channel NI SCXI 1000 chassis with 1520 universal strain module data acquisition system is used to record the strain data (NI SCXI 1520 user manual). The sampling can be recorded simultaneously at a minimum acquisition rate of 10^5 samples per second. BKCT-30 electrical strain gauges with ±350 Ω resistance (gauge length 30 mm and gauge factor 2.00 ± 0.02) are used to measure the strains at different locations along the length of the beams. A total of six strain gauges (S1–S6), three each on both top and bottom surfaces of the beams, were mounted, and their locations are shown in Fig. 7.3.

Load Cell A load cell (200 kg capacity) of cylindrical type is used to measure the support reaction. It has four inbuilt strain gauges. All strain gauges and load cell are connected to a DAQ, an eight-channel NI SCXI 1000 chassis with 1520 universal strain module. The strain data are acquired at a sampling rate of 10^5 records/s. The strain data acquisition is started simultaneously with the release of hammer from the required height.

7.2.2 Impact Test Results

The accelerometers and strain gauges were mounted on the completely dried beam specimens. The beams were then positioned on the supports with an effective span of 1.0 m. A weight of mass 50 N (5 kg) was set to drop from a height of 0.225 m above the top of the beam specimen and then released. This gives a tip velocity of 2.101 m/s at the time of impact. The hammer is dropped repeatedly from the same height till the failure occurred. During each impact, the acceleration, displacement, strain, and support reaction histories are recorded using suitable devices and the results are presented herein.

7.2.2.1 Accelerations

As discussed earlier due to the constraint of the acquisition rate in the instrument, the accelerations were acquired at 244 μs interval which is too small. This may lead to the missing of actual peak values of accelerations. However, the authors are basically interested to know the behavior of recycled aggregate concrete in contrast to the normal concrete with respect to accelerations, displacements, etc., under impact load. The variation of acceleration at midspan of the beam with recycled coarse aggregate having different percentages of RCA during the first impact is presented in Fig. 7.4.

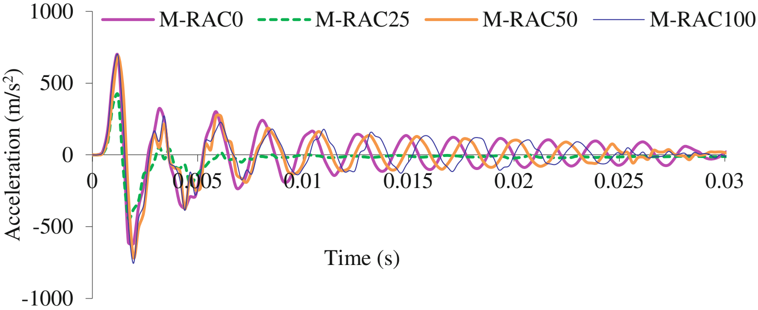

Fig. 7.4 Accelerations at midspan during the first drop of impact (Rao et al. 2011)

It is observed that in the first cycle of wave propagation the magnitude of acceleration is more in case of RAC with higher percentage of recycled coarse aggregate (50 and 100%) when compared to normal concrete. The peak value of acceleration in RAC with 100, 50, and 25% RCA is 756, 715, and 440 m/s^2, respectively, compared to an acceleration of 686 m/s^2 in normal concrete (M-RAC0). This indicates the acceleration depends on the mass (density) of the material: The higher the density, the lower is the acceleration. As discussed in previous section, the density of recycled coarse aggregates is 15% less than that of natural aggregates due to lower density of old mortar adhered to those and hence the density of RAC with 100% RCA is around 9 and 12% lower than the RAC with 25% RCA and normal concrete, respectively. After the first cycle of wave propagation, in the subsequent cycles of wave propagation the peak values of acceleration of RAC with 100% RCA are less than those of RAC with 25 and 50% RCA and normal concrete. This indicates that the frequency of recycled aggregate concrete beams with higher amount of recycled coarse aggregate is more than that of normal concrete. That is, the period of vibration is less in case of RAC.

The acceleration histories of normal and recycled aggregate concrete beams with 100, 50, and 25% recycled coarse aggregates at midspan for repeated drops of same height are presented in Figs. 7.5, 7.6, 7.7, and 7.8, respectively.

It is found that in both normal and recycled aggregate concrete beams the period of vibration decreases with the increase in drop number. This indicates the softening of the beam with the increase in drop number. That is, the stiffness of the beams reduces with the increase in drop number. It is also observed that the first peak values of accelerations increase with the increase in drop numbers in both normal and recycled aggregate concrete beams. In addition, it is observed that in normal concrete the acceleration diminished immediately after the peak and disappeared completely after 5 ms during the last drop when compared to the previous drops. This indicates that the beam failed immediately after impact. The same is observed physically at the time of testing. Whereas, in case of RAC with all percentages of recycled coarse aggregates, the frequency of vibration is more within the first 10 ms and thereafter the acceleration disappears completely during the last drop impact

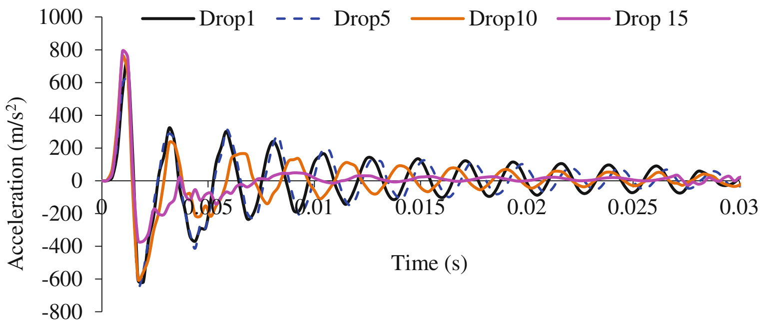

Fig. 7.5 Accelerations at midspan for repeated drops in normal concrete beam (M-RAC0)

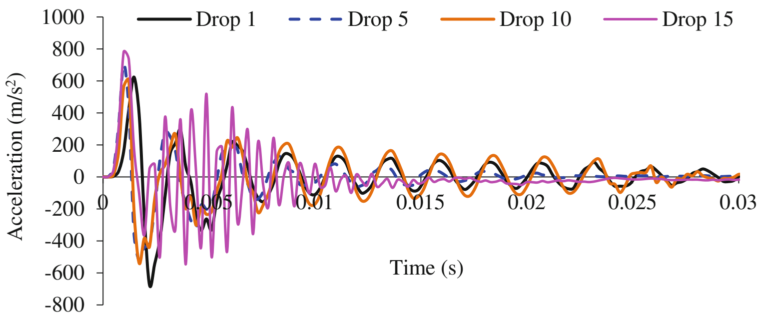

Fig. 7.6 Accelerations at midspan for repeated drop impacts in M-RAC100 beam (Rao et al. 2011)

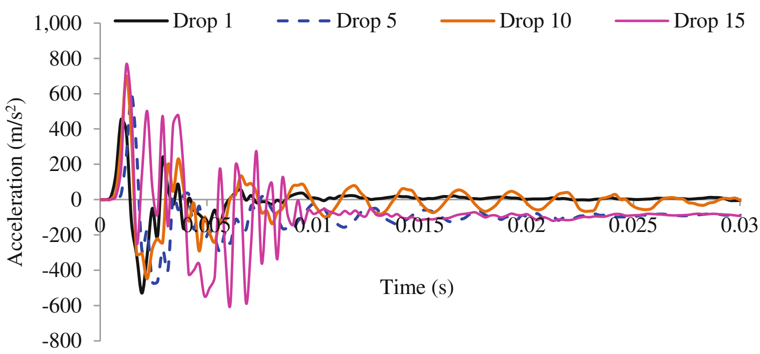

Fig. 7.7 Accelerations at midspan for repeated drop impacts in M-RAC50 beam (Rao et al. 2011)

compared to the previous drops. This indicates the reduction in stiffness of the material after certain number of drops. The recycled aggregate concrete is more vulnerable for stiffness reduction due to the presence of weaker interfaces and microcracks.

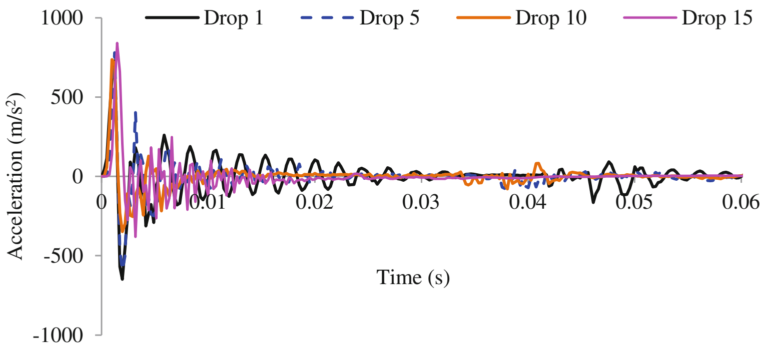

Fig. 7.8 Accelerations at midspan for repeated drop impacts in M-RAC25 beam (Rao et al. 2011)

Table 7.3 Average accelerations along the length (half span) during first and last drops of impact (Rao et al. 2011)

Mix designation	First drop			Last drop		
	500 mm	350 mm	200 mm	500 mm	350 mm	200 mm
M-RAC0 (3)	686	626	554	792	786	627
M-RAC25 (3)	568	548	341	731	657	543
M-RAC50 (3)	706	637	445	813	793	420
M-RAC100 (3)	733	707	462	814	832	576

Note The number within the parenthesis is the number of specimens tested

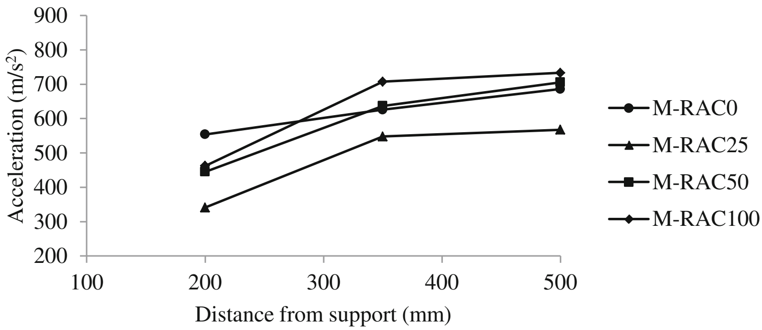

Fig. 7.9 Acceleration variation along length (half span of beam) during the first drop impact (Rao et al. 2011)

The variation in acceleration along the length (for half span of beam) for first and last drops in both normal and recycled aggregate concrete beams with all percentages of recycled coarse aggregate is presented in Table 7.3 and Figs. 7.9 and 7.10, respectively.

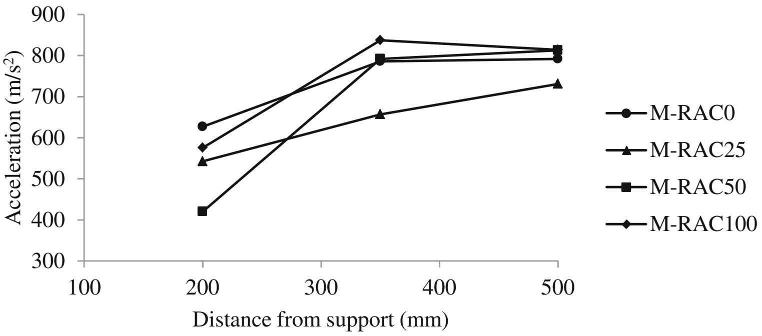

Fig. 7.10 Acceleration variation along length (half span of beam) during the last drop impact (Rao et al. 2011)

It is observed that the variation is similar in both normal and recycled aggregate concrete beams except in case of RAC with 100% recycled coarse aggregate. The acceleration decreases as the wave propagates toward the support. In case of RAC with 100% recycled coarse aggregate, the acceleration is more at 350 mm distance from support compared to 500 mm (middle) during the last drop of impact. This represents the crack initiated at a location away from the center (impact point). Figures 7.11, 7.12, 7.13, and 7.14 represent the variation in acceleration along half span of the beam for repeated drop impacts of same height for both normal and RAC beams with all percentages of recycled coarse aggregate. Each presented value is an average of three beams. It is observed that the magnitude of acceleration increases with the increase in number of drops at locations 350 mm and 500 mm from the support along the half span of the beam irrespective of recycled coarse aggregate percentage.

It is also observed that in case of RAC with 100% recycled coarse aggregate, the magnitude of acceleration at 350 mm distance from the support is more than that of acceleration at midspan after nine drops. The average accelerations at 350 mm

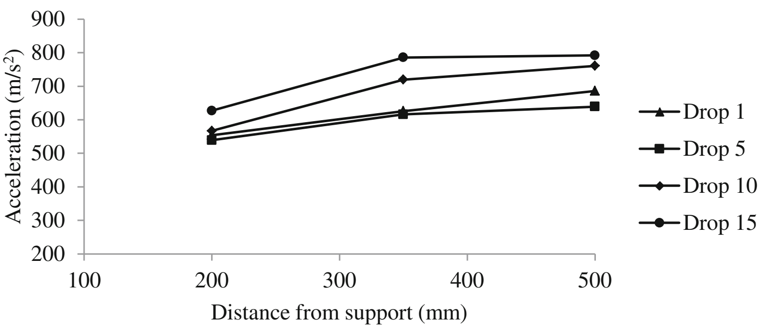

Fig. 7.11 Acceleration variation along length (half span of beam) for repeated drop impacts in normal concrete beam (Rao et al. 2011)

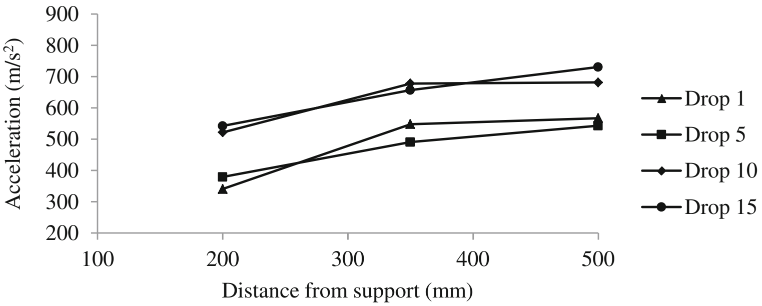

Fig. 7.12 Acceleration variation along length (half span of beam) for repeated drop impacts in M-RAC25 (Rao et al. 2011)

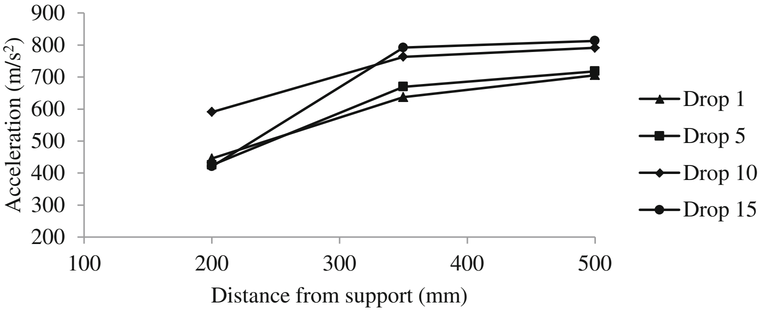

Fig. 7.13 Acceleration variation along length (half span of beam) for repeated drop impacts in M-RAC50 (Rao et al. 2011)

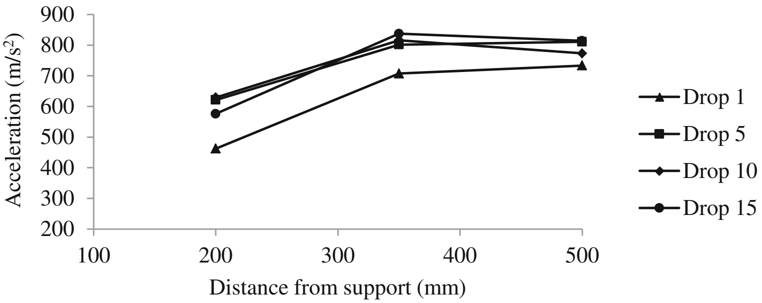

Fig. 7.14 Acceleration variation along length (half span of beam) for repeated drop impacts in M-RAC100 (Rao et al. 2011)

location are 837 and 814 m/s^2 during 10 and 15 drops of impacts, respectively, when compared to an acceleration of 816 and 773 m/s^2 at middle of the beam (500 mm location). This may be indicated that the failure initiated at a location away from the impact point instead of below the impact point.

7.2.2.2 Displacement

As discussed in previous section, the actual displacement peak values may be missed due to the small acquisition rate. However, the main focus of the experiment was to establish a comparative study between the recycled aggregate concrete and normal concrete. The displacement histories are measured from the acceleration histories at the middle of the beam on the lower side during each impact as discussed earlier. The maximum displacement histories among all repeated drop impacts for both normal and recycled aggregate concrete beams are presented in Fig. 7.15.

It is observed that the variation in displacement with time is similar for both normal and recycled aggregate concrete beams. The displacement mainly depends on the stiffness of the beam. It is observed that the maximum displacement is increased with the increase in percentage of recycled coarse aggregate. This is obvious that the stiffness of recycled aggregate concrete beams is lower than that of normal concrete beam. As discussed in Table 7.2, the modulus of elasticity of RAC with 100% RCA is 15.4% lower than that of normal concrete. It was observed under a uniaxial static loading that the strain is more at a given stress (load) in case of recycled aggregate concrete than that of normal concrete due to the presence of microcracks, weaker interfaces between recycled aggregate and old and new mortars and lower modulus of elasticity of recycled coarse aggregate. In addition, it is observed that there is an initial positive displacement occurred due to inertia force. The maximum displacement in recycled aggregate concrete at 25, 50, and 100% recycled coarse aggregates is 1.32, 1.63, and 1.795 mm corresponding to a displacement of 1.077 mm in normal concrete.

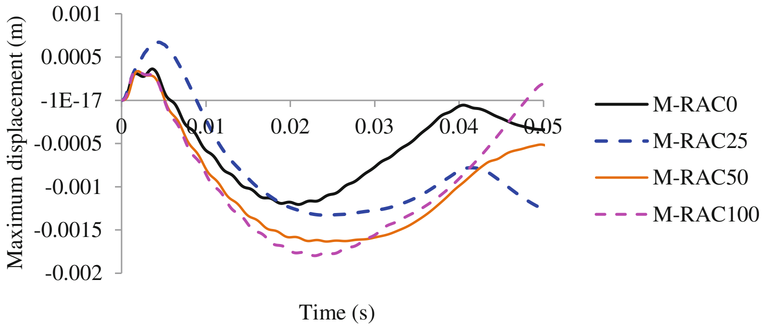

Fig. 7.15 Maximum displacement among all drops

7.2.2.3 Strains

The strain gauges are mounted on the top and bottom surfaces of half span of the beams to study the longitudinal distribution of strains. Three strain gauges each are mounted on top and bottom faces of the beam, and their positions are shown in Fig. 7.3. As the beams undergo impact, the nature of strains at a point oscillates from tension to compression or from compression to tension. Table 7.4 and Fig. 7.16 show the distribution of strains on both top and bottom faces of half span of the beam during the first drop of impact in both normal and recycled aggregate concrete beams. Each presented value in the graph is the average of three beams. In Fig. 7.16, the dotted line represents the tensile strains and solid line represents the compression strains.

It is observed that at all positions of strain gauges the strains are increased with the increase in percentage of recycled coarse aggregate. It is also observed that the strains on compression face are varying more linearly along the half span of the beams compared to those on tension face in both normal and recycled aggregate concrete beams. This indicates that the flexural crack may affect the tensile strains. In addition, in both normal and recycled aggregate concrete beams the magnitudes

Table 7.4 Average peak strains during the first drop of impact along the half span of beams

Location	Average peak strains			
Location (mm)	M-RAC 0	M-RAC 25	M-RAC 50	M-RAC 100
Top 400	−0.00016	−0.00016	−0.00017	−00000.00018
Top 250	−9.1E−05	−0.00011	−0.00011	−0.00013
Top 100	−7.3E−05	−3.2E−05	−4.9E−05	−7.9E−05
Bottom 400	0.00017	0.00017	0.000182	0.000208
Bottom 250	0.000113	0.000115	0.000136	0.000148
Bottom 100	6.8E−05	0.000058	6.5E−05	0.000104

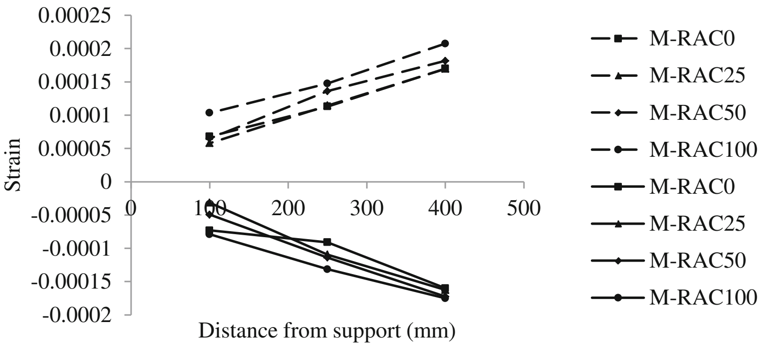

Fig. 7.16 Longitudinal distribution of strains for half span of the beam during the first drop impact

of strains on tension face at all positions of strain gauges are more than those on compression face. The magnitude of both compression and tensile strains at all locations is almost same in case of normal concrete and recycled aggregate concrete made with 25% RCA beams, whereas the magnitude of tensile and compression strains is much deviating in case of RAC with 50% RCA and 100% RCA from the normal concrete beams. The maximum tensile and compression strains in RAC with 50% RCA and 100% RCA are 0.000182, −0.00017 and 0.000208, −0.00018, respectively, compared to 0.00017, −0.00016 in normal concrete during the first drop of impact. This may be due to existence of microcracks in recycled coarse aggregate and weaker interfaces between aggregate and old mortar and new mortar.

The measured strains at different points along the half span of the beams in both normal and recycled aggregate concretes for repeated drops of impact are plotted in Figs. 7.17, 7.18, 7.19 and 7.20, respectively. The strains become erratic and cannot be measured properly once the specimen is cracked and fails in subsequent blows. The plots indicate the strain values prior to cracking only. The number of blows required to cause failure of the specimens varies depending on the percentage of

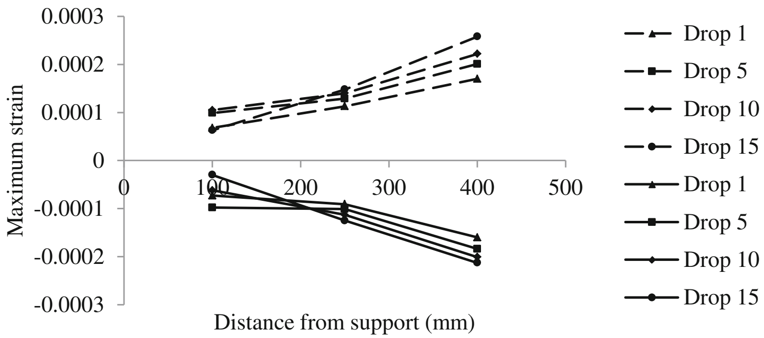

Fig. 7.17 Longitudinal distribution of strains for half span in normal concrete for repeated drops

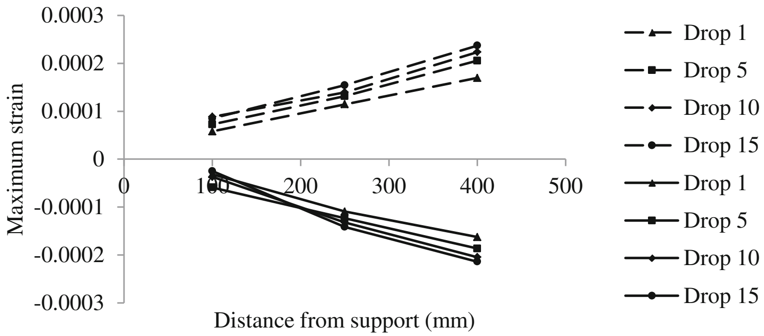

Fig. 7.18 Longitudinal distribution of strains for half span in M-RAC25 concrete for repeated drops

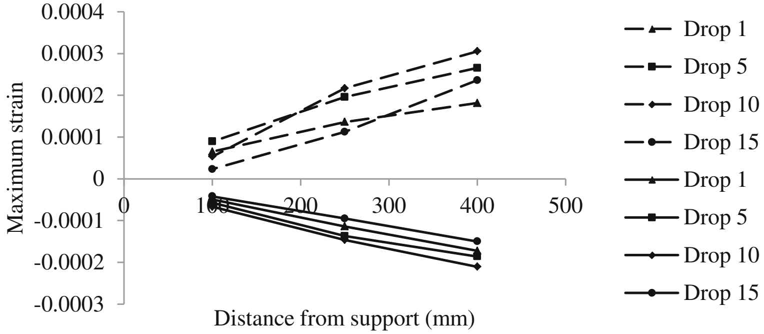

Fig. 7.19 Longitudinal distribution of strains for half span in M-RAC50 concrete for repeated drops

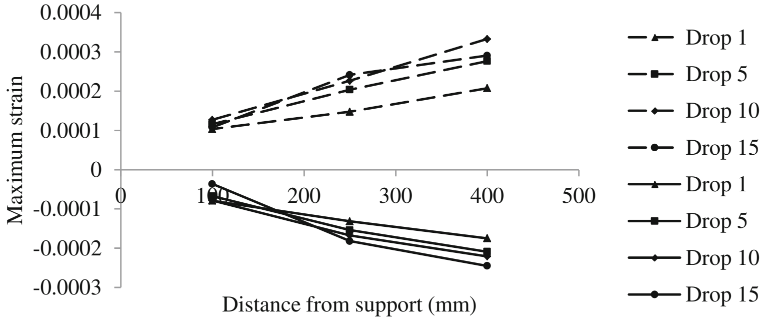

Fig. 7.20 Longitudinal distribution of strains for half span in M-RAC100 concrete for repeated drops

RCA. It is observed from the figures that the magnitude of strains on tension side is more than those on compression side at all positions of strain gauges in both normal and recycled aggregate concrete beams. It is also observed that both tension and compression strains are increased with the increase in drop number and the increment is more uniform with the increase in drop number in case of normal and RAC with 25% recycled coarse aggregate compared to RAC with higher percentage of recycled coarse aggregate (50 and 100%). In addition, nearer to impact point, the strain values on tension side have more deviation from the first drop to the subsequent drops. This indicates that the flexural crack influences the tensile strains and softening the beam with the repeated impacts. This may be due to the existence of microcracks and weaker interfaces between recycled aggregate and old and new cement mortars which may propagate during the repeated impacts. The maximum compression strains in RAC with 25, 50, and 100% RCA are −0.000214, −0.000.211, and −0.000250 and in those the maximum tensile strains are 0.000237, 0.000306, and 0.000333, respectively, compared to −0.000213, 0.000256 compression and tensile strains in normal concrete. This shows that 25% RCA on recycled aggregate concrete does not have significant influence on both maximum tension and compression strains during the repeated drops of impact.

7.2.2.4 Support Reactions

As discussed earlier, one of the supports on which the beam supported is arranged to measure the support reaction using a 200 kg load cell. The load cell is connected to the DAQ (NI SCXI 1000 chassis with 1520 strain module), and the data are recorded at 1/10000 s intervals in terms of strain. The load cell is calibrated with same DAQ under static loading, and then the strain output is converted into support reaction using the calibration chart. Figure 7.21 shows the support reaction histories for both normal and recycled aggregate concrete beams during the first drop of impact. The enlarged view of the peak values of support reaction is presented in Fig. 7.22.

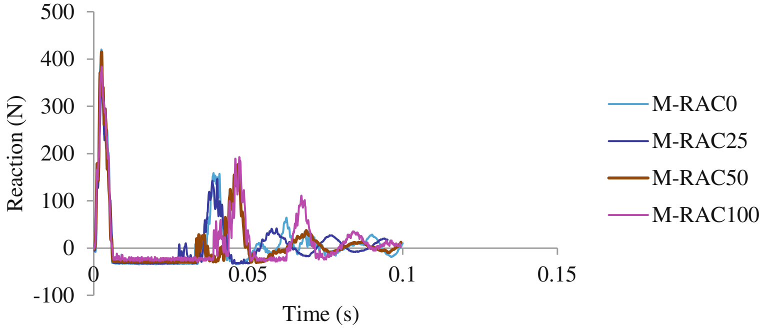

Fig. 7.21 Support reaction in both normal and recycled aggregate concretes during the first drop impact

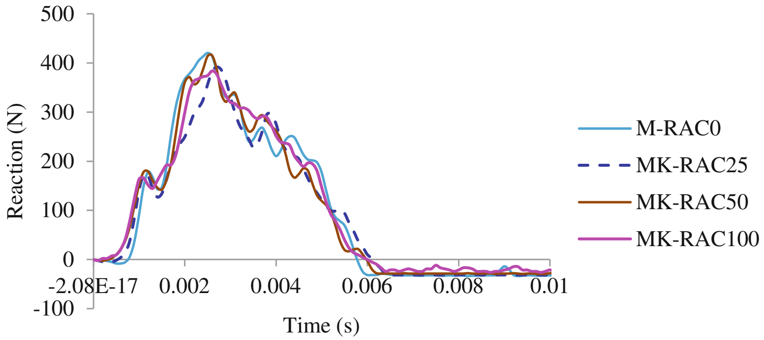

Fig. 7.22 Enlarged view of peak support reactions in normal and recycled aggregate concretes during the first drop impact

The reaction obtained from the load cell is the combined effect of direct impact caused by impactor and the inertia force produced by the vibration of the member. The reaction developed before the peak value in figures is due to the effect of direct impact induced by impactor and after the peak it is due to inertia force caused by vibration of the beam. It is observed that during the first drop of impact, the magnitude of reaction in case of normal concrete is more than that of recycled aggregate concrete at all percentages of recycled coarse aggregate. This indicates that the impact resistance depends on the stiffness of the member. It is also observed from the figures that the time taken to travel the longitudinal stress wave from center to the support is less in case of normal concrete compared to RAC with 100% recycled coarse aggregate. This may be due to the presence of weaker interfaces between recycled aggregate and old and new mortars, high porous nature of recycled coarse aggregates. In addition, the first small peaks observed in Fig. 7.22 may be due to the slipping of plates from the load cell at the time of impact. In Fig. 7.21, there are some new peaks, which are due to second drop of the hammer after the hammer bounced back. The variation in support reaction from the first drop of impact to the failure drop for both normal and recycled aggregate concretes is presented in Fig. 7.23.

It is observed that in both normal and recycled aggregate concrete beams, the support reaction marginally increases with the increase in drop number up to a certain number of drops and thereafter it reduces with further increase in drop number. It was observed during experimentation that the beam fails immediately on impact once the crack is initiated. However, possibly as the tested beam specimens are stronger in comparison with the impactor, the beam did not show any sign of distress even up to 10th blow and that is the reason there is increase in the reaction values. In addition, it is observed that the maximum reaction of concrete with natural aggregate is more than that of RAC with all percentages of RCA. This indicates that the stiffness of the member influences the impact and inertia forces: The larger the stiffness, higher the impact and inertia forces.

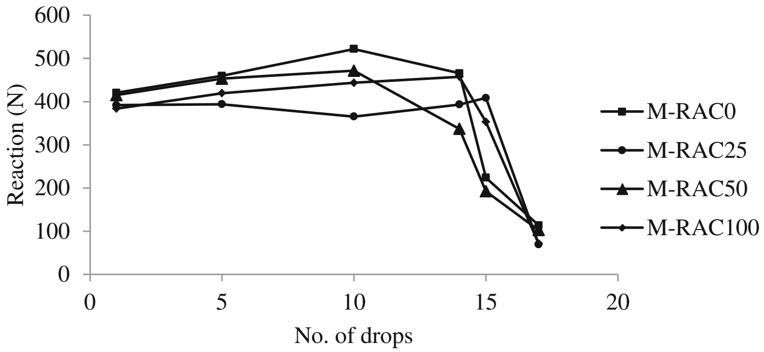

Fig. 7.23 Variation in support reaction with number of drops

Table 7.5 Maximum average values of support reaction

Mix	% of RCA	Maximum average support reaction (N)
M-RAC0	0	521.60
M-RAC25	25	492.13
M-RAC50	50	499.93
M-RAC100	100	469.22

Table 7.5 shows the average maximum values of support reaction among all the drops for both normal and recycled aggregate concrete beams. It is observed that the average maximum value of support reaction decreases with the increase in percentage of recycled coarse aggregate.

At 25, 50, and 100% recycled coarse aggregates, the average support reactions are 492, 499, and 469 N, respectively, compared to 521 N in case of normal concrete. The reduction in support reaction is in the order of 4–10% in case of RAC with 25–100% RCA compared to normal concrete. This may be due to lower stiffness of RAC. As discussed in the previous sections, the compressive strength and modulus of elasticity of RAC with 100% RCA are 15.4% lower than that of normal concrete and the impact value of recycled coarse aggregate is also less than that of natural aggregates.

7.2.2.5 Failure Pattern

The crack pattern and failure surfaces of beam specimens for both normal and recycled aggregate concretes are presented in Figs. 7.24 and 7.25, respectively. It is observed that both normal concrete and RAC made with all percentages of RCA are failed between 15 and 17 drops. In addition, it is observed that the cracks initiated at the bottom surface, vertically at or near the impact point in both normal and recycled aggregate concrete beams except in RAC with 100% recycled coarse aggregate. All beams are failed in the immediate next one or two drops after the initiation of crack. This may be due to brittleness of the material. In case of RAC with 100% recycled coarse aggregate, the crack initiated away from the impact point. Figure 7.25 shows the fractured surfaces of both normal and recycled aggregate concrete specimens. It shows that the failure path or surface is more tortuous in case of normal concrete and RAC with 25% recycled coarse aggregate.

This indicates that the failure is through the interface between aggregate and cement mortar and this is common in case of normal concrete as it is the weakest portion in normal concrete. In case of recycled aggregate concrete with higher percentage of recycled coarse aggregate (50 and 100%), the fractured surface is more even. This indicates that the failure is through the aggregate in addition to the weaker interfaces between aggregate and old and new mortars. A similar failure pattern is observed in case of split tensile test.

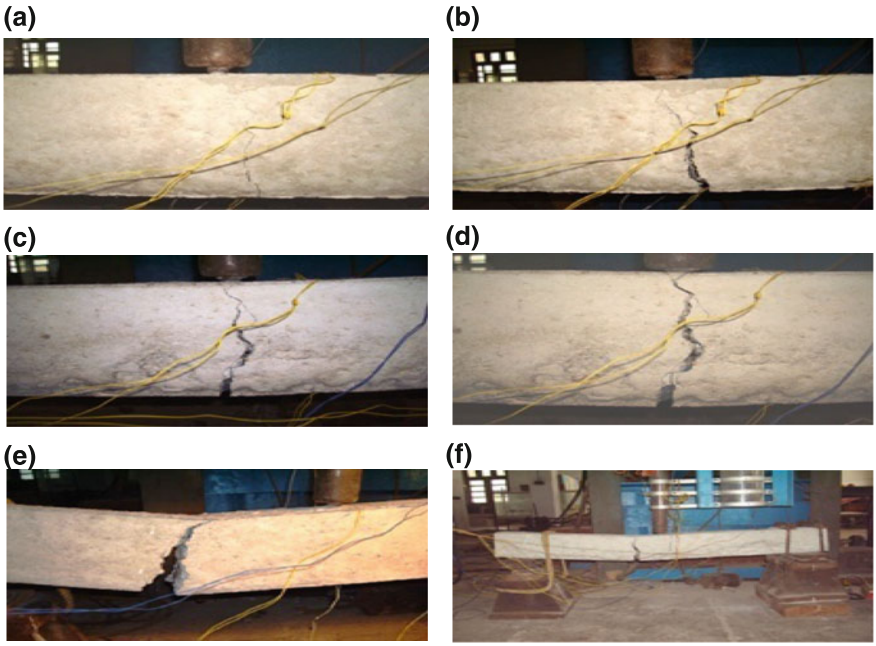

Fig. 7.24 Crack pattern of both normal and recycled aggregate concrete beams **a** and **b** normal concrete, **c** M-RAC25, **d** M-RAC50, **e** and **f** M-RAC100

7.3 Flexural Behavior of RAC

Ajdukiewicz and Kliszczewicz (2007) conducted a series of RCC beams made with six types of recycled aggregates obtained from crushed prefabricated concrete elements on flexural behavior under static loading. The concrete mixes of low, medium, and high strength were considered. Further two types of reinforcement were considered to obtain different shapes of failure, i.e., flexure and shear. All beams were tested under simply supported condition, and two equal loads were applied at 5 kN increment. It was found that the load-carrying capacity of beams with recycled aggregate concrete was 3.5% lower than those made with normal concrete in case of flexural failure and the capacity was bit greater when beams failed in shear. In addition, the deformations were large in beams made with recycled concrete compared to those made with normal concrete; however, this effect was controlled by the presence of reinforcement. It was further observed that at probable service load the deflections of beams made with RAC were approximately 18–100% greater than those made with natural concrete. At failure, the crack pattern and failure shapes were more or less similar to all the beams including

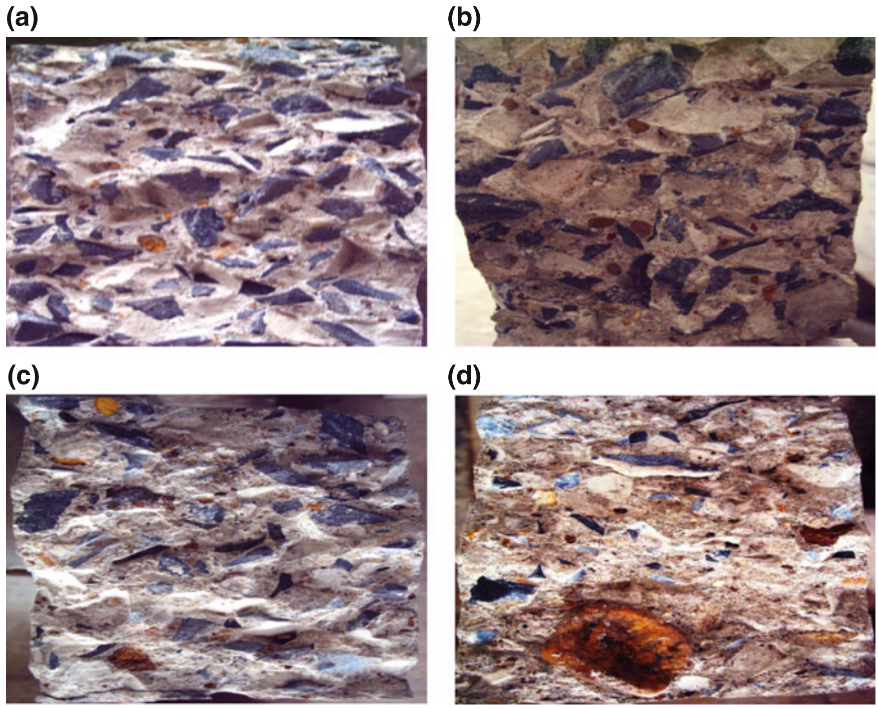

Fig. 7.25 Failure surfaces of **a** M-RAC0, **b** M-RAC25, **c** M-RAC50 and **d** M-RAC100

beams with normal concrete. In RAC beams, the first crack appeared at one step of loading ahead than in normal concrete beams. Initial cracks were developed along the stirrups in all the beams and as the load advanced, many more branched cracks of lesser width were found. This ensured the proper bond between reinforcement and concrete, and it was continued till the end of failure.

Sato et al. (2007) conducted studies on the flexural behavior of reinforced concrete beams made with recycled aggregate under static and sustained loadings. In their study, two types of recycled coarse aggregate and two types of recycled fine aggregate were obtained from normal concrete with w/c ratio 0.45 and 0.6, respectively. Another kind of recycled coarse and fine aggregate was obtained from real site, i.e., beams, columns, and slabs of old reinforced concrete (RC) buildings which were constructed during 1961 and 1967. A total of 37 RC beams were prepared to investigate the behavior of RC beams with the following factors, viz., w/c ratio of normal concrete from which the RCA obtained, usage of recycled coarse and/or fine aggregate, curing condition, w/c of recycled aggregate concrete and tension reinforcement ratio. The authors agreed with Ajdukiewicz and

Kliszczewicz (2007), that for a given w/c ratio, the deflections were large in case of beams with recycled concrete when compared to normal concrete. Further, not much significant difference in crack spacing was observed between recycled and normal concrete RC beams. In case of dry condition, the crack spacing was smaller when compared to wet condition. Further, it was found that the width of cracks in RC beams made with recycled concrete was larger than those made with normal concrete. However, these values were within the limits of Japan Society of Civil Engineers (JSCE) code. The authors also reported that the ultimate moment-carrying capacity of RC beams made with RAC was almost same as that of those made with normal concrete for a given w/c ratio and yielding of steel prior to the compression failure.

Arezoumandi et al. (2015) conducted a full-scale testing on flexural strength of reinforced concrete beams made with 100% recycled coarse aggregate as well as with conventional aggregate. In their study, two different longitudinal reinforcement ratios (0.47 and 0.64%) with shear reinforcement to avoid shear failure were considered. All beams are of rectangular section of size 300 mm × 460 mm with a span of 2.1 m (c/c distance of supports) of simply supported condition and subjected to a four point bending load. It was observed that the behavior of RC beams with conventional concrete and recycled aggregate concrete is similar with respect to crack morphology and crack progression. However, the cracks were closer in case of beams with recycled concrete compared to those made with conventional concrete. The failure was initiated by yielding of tension reinforcement in both the conventional concrete and recycled aggregate concrete RC beams. The load vs deflection of RC beams with both conventional concrete and recycled concrete is presented in Fig. 7.26. It was observed from the figure that all beams behaved as linearly elastic until the first flexural crack appeared, i.e., point A. With further increment in the load, it was observed that the tension steel yielded (point B). Upon further increment in the load, the concrete crushed in the compression zone and the beams were failed finally. It can also be seen from the figure that the cracking moment of beams with RCA was lower when compared to those made with conventional concrete. This may be attributed to the presence of two interfacial transition zones (ITZs) in beams with RCA (ITZ between original aggregate and adhered mortar and ITZ between adhered mortar and new mortar) as compared to only one interfacial transition zone, i.e., natural aggregate and mortar in conventional concrete beams. Figure 7.27 shows the load vs strain in longitudinal reinforcement in both conventional and recycled aggregate concrete beams. It can be seen that all the reinforcement gets yielded. Further, it can be seen that the stiffness of the beams with recycled concrete was lower than those made with conventional concrete. It could be ascribed to the lower modulus of elasticity of RAC compared with the conventional concrete. The crack pattern under flexural failure in both the RC beams made with conventional concrete and recycled concrete is shown in Fig. 7.28.

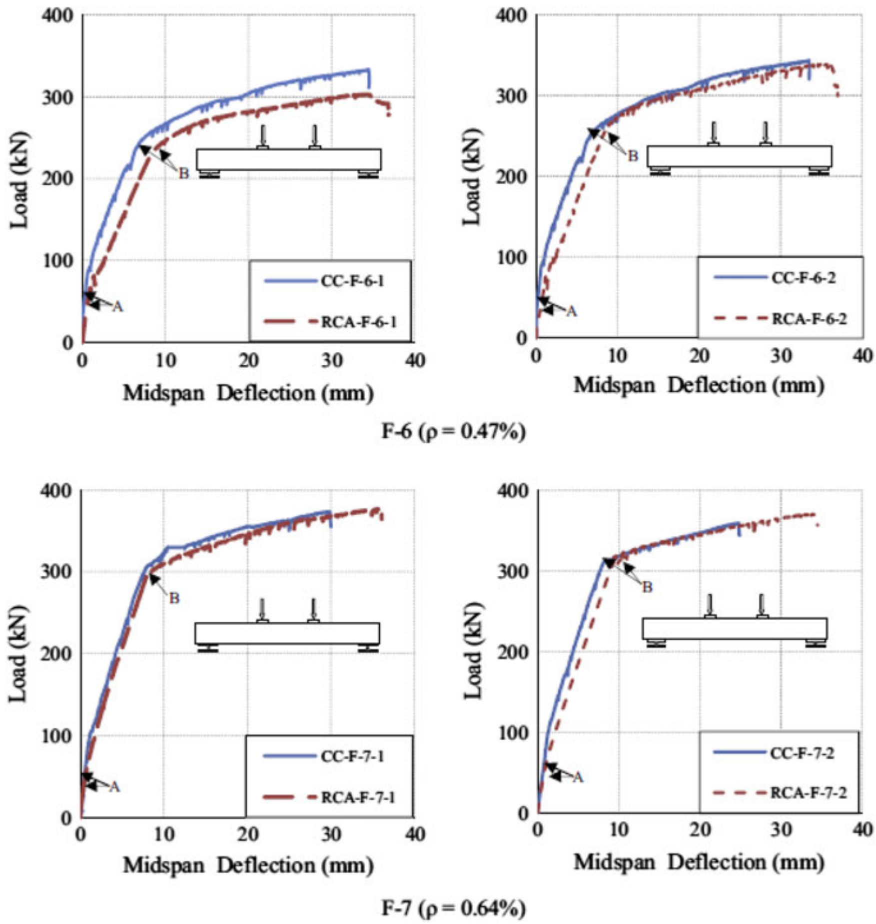

Fig. 7.26 Load versus deflection at midpoint for different longitudinal reinforcement ratios (F-6 means flexural beam with 2–19 mm diameters bars and F-7 means flexural beam with 2–22 mm diameter bears; 1, 2 represents beam1 and 2) (*Source* Arezoumandi et al. 2015)

Initially, the flexural cracks were developed in the maximum moment region and as the load increased the additional flexural cracks were developed in the region between supports and load points. With further increase in the load, most of the flexural cracks developed vertically and later on inclined flexure-shear cracks began to appear.

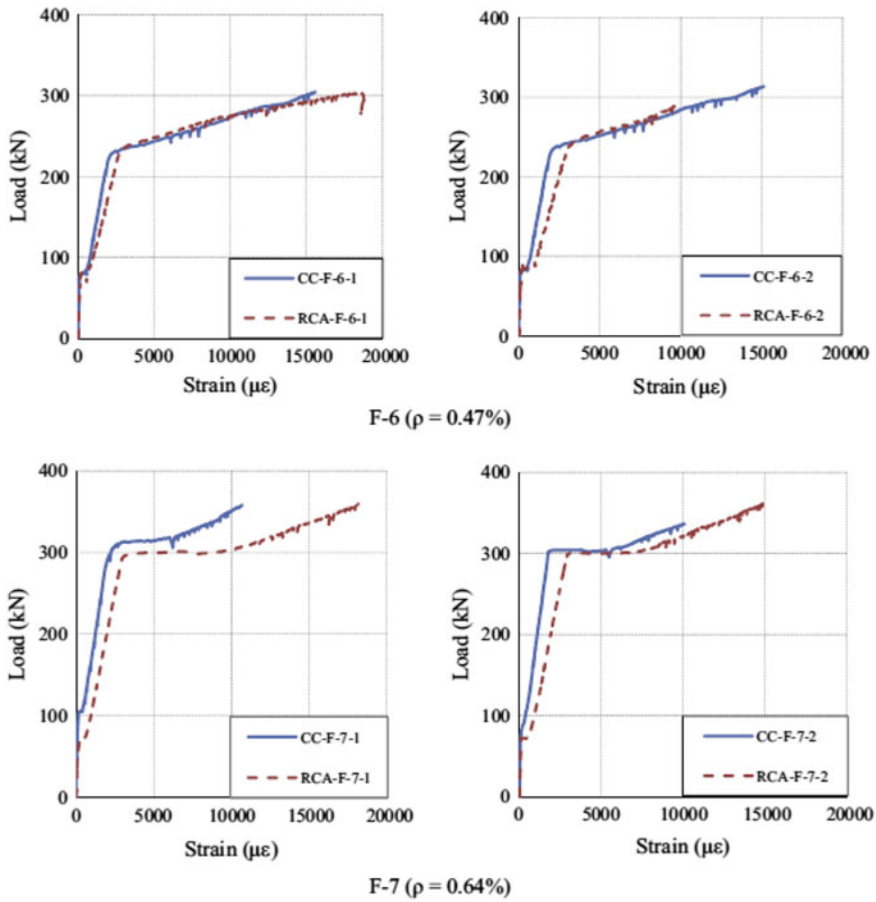

Fig. 7.27 Load versus strain in steel in both conventional concrete beams and recycled concrete beams with different percentage of longitudinal reinforcement (*Source* Arezoumandi et al. 2015)

7.4 Shear Behavior of RAC

Etxeberria et al. (2007) conducted investigations on shear behavior of recycled aggregate concrete without and with shear reinforcement. A total of twelve beam specimens with same compressive strength and same amount of longitudinal reinforcement, four concrete mixes of different percentages of recycled coarse aggregate (0, 25, 50, and 100%), and three different amounts of web reinforcements were considered in their investigation. All beams are simply supported with a span of 2.6 m and the cross sections of 200 × 350 mm and subjected to a two-point load (symmetric) system with shear span to depth ratio of 3.3. It was observed that in case of beams without shear reinforcement, the cracks were developed initially flexural and progressed at 45° (approximately) inclined toward the midsection and with

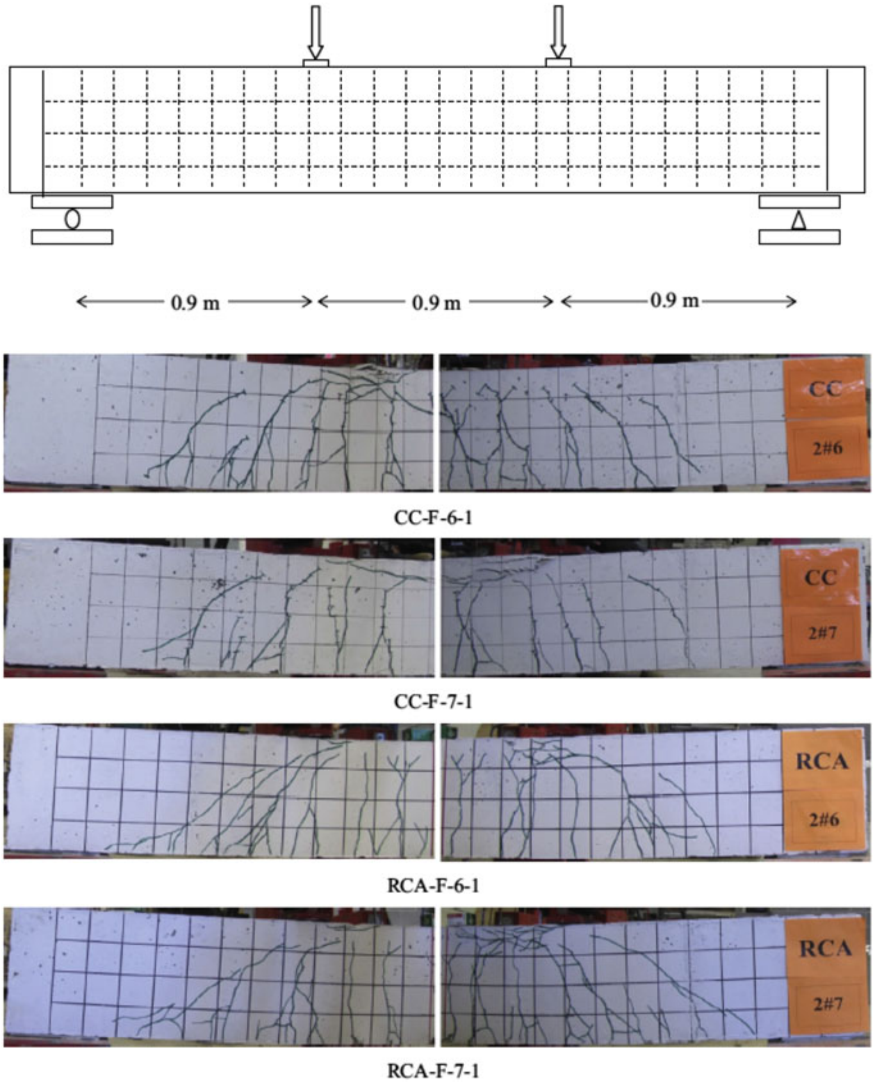

Fig. 7.28 Crack pattern of both conventional and recycled concrete beams at flexural failure (*Source* Arezoumandi et al. 2015)

an increase in the load a single inclined crack appeared joining the load point to the tip of the main initial crack, and the beam failed suddenly. In contrast, a more ductile response was observed in case of beams with shear reinforcements. After the development of initial shear crack, the shear reinforcement (stirrups) started functioning and thereafter series of shear cracks developed. It was further found that the shear strength of reinforced concrete beams without shear reinforcement made with recycled concrete depends on the content of RCA and at 25% RCA the effect was practically not significant. The cracking load was decreased with the recycled aggregate content in beams without shear reinforcement. This was probably due to the fact that the crack occurred at the weakest zone, i.e., at the interface between aggregate and old adhered cement mortar. In case of reinforced concrete beams with shear reinforcement, it was found that the effect of RCA content on ultimate shear strength was less significant; due to fact that, the compressive strength of RAC made with RCA was same as that of normal concrete by the addition of extra cement and low w/c ratio. It was finally concluded that 25% RCA can be used as a structural material, provided that all measures related to dosage, compressive strength, and durability aspects were adopted. Gonzalez-Fonteboa and Martinez-Abella (2007) studied the shear strength of RAC beams made with 50% RCA with different amounts of transverse reinforcement. The authors found that there was little difference in behavior of RAC beams in terms of deflections and ultimate load when compared to beams with normal concrete. In addition, the authors observed premature cracking and notable splitting cracks along the tension reinforcement in case of RAC beam. Gonzalez-Fonteboa et al. (2009) concluded that by the addition of silica fume, the notable splitting cracks which were observed along the longitudinal reinforcement in their previous study were palliated (Gonzalez-Fonteboa and Martinez-Abella 2007).

7.5 Other Structural Aspects

You-Fu and Lin-Hai (2006) examined the behavior of steel tubular columns filled with recycled aggregate concrete for different shapes of columns and for different load eccentricity ratios. It was concluded that both normal and recycled aggregate concrete-filled steel tubular columns behave in a similar manner and all were buckling failures. The load-carrying capacity of recycled aggregate concrete-filled steel tubular (RACFST) columns was slightly lower than that of normal concrete-filled steel tubular (CFST) columns. At 25% and 50% RCA, the load-carrying capacity of normal CFST columns had 1.7–9.1% and 1.4–13.5% higher than RACFST columns in circular and square shapes, respectively. This low strength of RACFST columns attributes to the lower strength of RAC than that of normal concrete. In a study, Xiao et al. (2006) discussed the seismic response of reinforced frames made with recycled aggregate concrete. It was reported that under low-frequency lateral loading, the failure pattern of frames is similar to all percentage of RCA and they failed at the end of the beams first and then at the columns' bottom. The ultimate load capacities of RAC frames were lower than that of normal concrete frames. However, this reduction was less than that of mechanical properties of RAC made with RCA. Finally, the authors concluded that frames made with properly mix designed RAC were suitable to resist an earthquake according to Chinese Standard GB 5011-2001.

7.6 Summary

The experimental results of behavior of recycled aggregate concrete beams under drop weight impact load are presented in this chapter. The behavior of RAC beams in terms of accelerations, displacement, strains, and support reaction histories under repeated drops of impact is discussed. The failure pattern of the recycled aggregate concrete beams under impact load is also highlighted. The behavior of reinforced concrete beams made with recycled aggregate concrete under flexure and shear reported by different researchers is discussed. The other structural aspects of the recycled aggregates are also described. Based on these studies, the following highlights are observed.

- At a given impact energy (energy imparted by the hammer per blow), the accelerations and midspan displacements of RAC beams are more than those of concrete with natural aggregates.
- The recycled aggregate concrete beams are more sensitive to the high strain rate of loading. Both tensile and compressive strains of RAC with high percentage of RCA (50 and 100) are significantly higher than those of normal concrete. However, inclusion of lower percentage (<25%) of RCA does not have much influence on strains during the repeated drops.
- Larger quantity of RCA (more than 25%) reduces the impact resistance of concrete. However, the lower percentage of RCA (<25%) in concrete has no significant influence on impact resistance.
- The load-carrying capacity of RAC beams and columns was lower than those of normal concrete beams when they are subjected to static flexural and compression loading. In addition, the deformations are larger in case of RAC than normal concrete. Nevertheless, the failure phenomenon was slower in case of RAC columns, as a result of greater ductility.
- With reference to shear strength of RAC beams with transverse shear reinforcement, 25% RCA does not show any significant effect on the strength and failure behavior.
- The modes of failure of recycled aggregate concrete-filled steel tubular columns (RACFST) and normal aggregate concrete-filled steel tubular columns (NACFST) are similar. However, ultimate load-carrying capacity of RACFST was little lower than that of NACFST.
- The frames made with properly mix designed RAC were suitable to resist an earthquake force according to the Chinese standards.

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