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Micro-concrete composites for strengthening of RC frame made of recycled aggregate concrete

Comingstarful Marthong*, Risukka N. Pyrbot[a], Stevenly L. Tron[a], Lam-I D. Mawroh[a], Md. Sakil A. Choudhury[a] and Ganesh S. Bharti[a]

Department of Civil Engineering, National Institute of Technology Meghalaya, Shillong-793003, India

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Abstract. In this paper, to access the suitability of recycled aggregate for structural applications, concrete strength i.e., compressive, tensile and flexural strength were evaluated and compared with those specimens made of natural aggregates. Test results indicated that 30 to 42% of the mentioned strength decreases. To study the performance of frame structures made of recycled aggregate concrete (RAC) two reinforced RAC frames were prepared and tested under monotonic loading. The joint regions of one of the RAC frame were casted with micro-concrete. A reference specimen was also prepared using natural aggregate concrete (NAC) and subjected to a similar loading condition. The RAC frame resulted in a brittle mode of failure as compared to NAC frame. However, the presence of a micro-concrete at the joint region of an RAC frame improved the damage tolerance and load resisting capacity. Seismic parameter such as energy dissipation, ductility and stiffness also improves. Conclusively, strengthening of joint region using micro-concrete is found to have a significant contribution in improving the seismic performance of an RAC frame.

Keywords: RAC frame; recycled aggregate; mechanical strength; micro-concrete; monotonic loading; seismic performance

1. Introduction

Recycling of demolished concrete waste is beneficial from the viewpoint of environmental preservation and effective utilization of resources. The processed concrete waste (recycled aggregates) either fine or coarse has been used as a replacement of the natural aggregate for a number of years. Behera *et al.* (2014), Pellegrino and Faleschini (2016) extensively reviewed and summarized the past achievement on using recycled aggregate (RA) for concrete productions. It was reported that the mechanical and durability performances of recycled coarse aggregate (RCA) concrete are generally inferior to conventional concrete. Various researchers (Hancen 1992, Limbachiya *et al.* 2004, Rao *et al.* 2011, Xiao *et al.* 2012) showed that reduction in the mechanical strength is not much prominent, when RCA replacement is up to 30%. Further, results reported by Padmini *et al.* (2009), Tabsh and Abdelfatah (2009), Brito *et al.* (2016) showed that RCA concrete exhibited a similar behavior, which can be adequately used in concrete technology application. However, the behavior of RCA concrete towards mechanical action depends upon the type of demolished structure, the age of the structures, the level of RCA replacement, water cement ratio (w/c) and the moisture condition of RCA (Ajdukiewicz and Kliszczewicz 2002). Literature revealed that most studies on utilization of RCA in concrete production have been limited to mechanical strength evaluation (Shayan *et al.* 2002, Xiao *et al.* 2005, Kwan *et al.* 2012, Abdollahzadeh *et al.* 2016, Ashish and Saini 2018, Hamad *et al.* 2018, Tripura *et al.* 2018). For confident utilization of RCA in the construction industry, their structural behavior ought to be investigated. Some past studies concerning the structural behavior of beams (Han *et al.* 2001), columns (Chao *et al.* 2010) and beam-column joints (Corinaldesi and Moriconi 2006, Corinaldesi *et al.* 2011, Gonzalez and Moriconi 2014, Faleschini *et al.* 2017, Marthong 2018), RC frame structure (Xiao *et al.* 2006, Brito *et al.* (2016) manufactured from RCA were reported. Most of their findings on their structural behavior are positive. However, due to the brittle behavior of RCA, the load carrying capacity of most of the RCA specimens got reduced. This perhaps was the reason that RCA concrete was not prominently adopted in structural elements casting.

In all RC framed structures, the beam-column joints play an important role in the overall response of the frame structures under strong influence of seismic attack. Further, these elements are the most vulnerable to seismic loads for several causes and particularly in case of exterior joints (torsional effects due to their position in the frames) (Faleschini *et al.* 2017). To enhance the seismic capacity of the frame structures, steel fibres reinforced concrete (SFRC) has been incorporated in the beam-column joint region (Shakya *et al.* 2012, Ghani and Hamid 2013, Oinam *et al.* 2014, Dhaval *et al.* 2015, Qureshi and Muhammad 2018). Test results revealed that SFRC enhanced the flexural capacity, shear strength, ductility and energy dissipation capacity. However, used of SFRC mixtures encounter

*Corresponding author, Associate Professor
E-mail: commarthong@nitm.ac.in
[a]Former Under Graduate Students

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Table 1 Physical properties of NCA and RCA

Mix	Apparent density (kg.m^3)	Bulk density (kg/m^3)	Grading (mm)	Elongated particle content (%)	Water absorption (%)	Crush index (%)
NCA	2830	1560	5-16	5	0.97	5.81
RCA	1700	1190	5-16	10	5.20	12.23

difficulties when fibre content is increases, such as lack of workability, homogeneity and balling phenomenon in fresh SFRC. While a significant amount of research has been done on improving the seismic performance of RC frames using SFRC at the beam-column joint region, a limited research has been focussed on utilizing special materials like High Performance Fibre Reinforced Cementitious Composites (HPFRCC) or Engineered Cementitious Composites (ECC) (Qudah and Maalej 2014, Said and Razak 2016) and Slurry Infiltrated Fibrous Concrete (SIFCON) (Balai and Thrugnanam 2016) and micro-concrete (Marthong *et al.* 2013) to improve the seismic behaviours of an RC frame. Micro-concrete is another type of high strength concrete, which is based on Portland cements, graded aggregates, fillers and additives which impart controlled expansion characteristics in plastic state. The polymer modified micro concrete is normally supplied as a ready to use dry powder that requires only addition of clean water at the site in order to produce a free-flowing non-shrink repair micro concrete. It has been successfully used in repairing and strengthening of RC elements like beam, column, beam-column connections etc., where access is restricted and compaction is not possible.

Due to various negative aspects possessed by recycled aggregate for concrete productions, the seismic performance of frame structures made of RCA may be lower than those of conventional concrete. Like SFRC, HPFRCC and SIFCON, the micro-concrete which has 28 days compressive strength of 55 N/mm^2 and processes various advantages like improving the early compressive, tensile and flexural strength as well as in reducing the brittle nature of specimen. This high strength material can be used to improve the seismic capacity of the RCA concrete frame. Therefore, the main objectives of this study is to investigate the structural behavior of an RC frame prepared with RCA concrete and incorporating micro-concrete within the joint region and partly in both column and beams, which is the D-region as defined by ACI 318-08 (2008).

2. Experimental program

2.1 Materials

Ordinary Portland Cement (OPC) of 43 grades conforming to IS: 8112 (1989) was considered. The maximum size of NCAs was 16 mm. River sand was used as fine aggregate (FA) (0-4.75 mm size). The RCAs (5-16 mm size) were obtained from the demolished reinforced cement concrete (RCC) roof slab of 20 years old. The large pieces of the roof slab were transported to the laboratory and broken into pieces of aggregates smaller than 20 mm in size and sieved through a 16 mm sieve. The aggregates greater than 16 mm in size were further broken down to a maximum size of 16 mm. All aggregates used in this study have been tested as per relevant codes (IS 2386 a, b, 1963) and the physical properties are presented in Table 1 and the particle size gradation is shown in Fig. 1. The high strength concrete used is a polymer modified concrete (powder) which is based on Portland cements, graded aggregates, fillers and additives which impart controlled expansion characteristics in plastic state. It is commercially supplied as a ready to use dry powder that requires only addition of clean water at the site to produce a free-flowing non-shrink repair micro concrete. It is suitable for various structural strengthening measures such as encasement build-ups, jacketing, etc. where access is restricted and vibration of the placed material is difficult or impossible. The micro concrete was modified by the addition of 5 mm to 12 mm aggregates as per manufacturer instructions. The properties of micro concrete obtained from the data sheet supplied by the manufacturer are presented in Table 2.

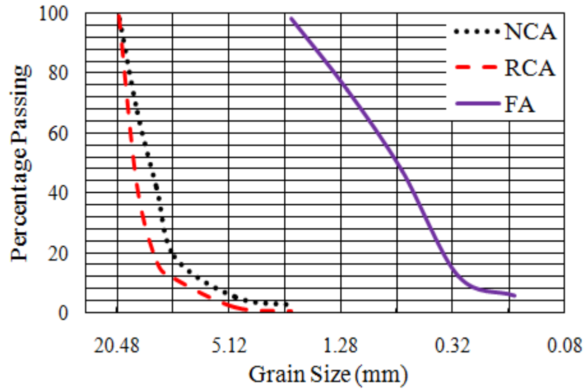


Fig. 1 Particle size gradation

Table 2 Properties of micro concrete

Powder: Coarse aggregate (By weight)	1:0.75			
Water: Powder (By weight)	0.16			
Compressive Strength (MPa)	1 Day	3 Days	7 Days	28 Days
	15	35	45	55
Workability	Flowable			

2.2 Concrete mixture proportions

Table 3 represents the specimens and test parameters for characterizing the mechanical properties of concrete. Mix M-0 and M-100 were prepared using 100% of NCA and 100% of RCA respectively. All concrete mixes were prepared with the same w/c of 0.5 and the same degree of workability (slump value of 60 mm) evaluated according to IS 1199 (1959). The concrete mixes were designed for a characteristic cube compressive strength of 25 N/mm^2 which resulted in a target mean cube compressive strength of 31.6 MPa as per IS 10262 (2009). The concrete mixes were produced with 372 kg/m^3 of cement, 733 kg/m^3 of fine aggregate and 1087 kg/m^3 of coarse aggregate for a w/c of

Table 3 Specimen used for evaluating the mechanical properties of concrete

Mixes	Cube (mm)	Cylindrical (mm)	Prism (mm)	Total mixture
M-0	150×150×150	100Ø ×200	500×125×125	100% NCA
M-100	150×150×150	100Ø ×200	500×125×125	100% RCA
Test parameter	Compressive strength	Split tensile strength	Flexural strength	

0.5. To achieve a better workability, 0.85% of super plasticizer by volume of water was used in the mixing of M-100. In each sample three specimens were casted. Specimens from the mould were removed after 24 hours of casting and were kept in a water tank for 28 days curing before testing.

2.3 Selection and description of RC frame

In this study, a typical full scale residential building with floor to floor height of 3.0 meters and a beam with effective span of 3.6 meters were considered. The full scale RC frame is then scaled down to 1/3rd for experimental investigation. The detailing of the frame is shown in Figure 2. The frame has been designed following the standard code of practice of IS 13920-2016 and IS 456-2000. A cross section of 100 mm×100 mm and 135 mm×100 mm for column and beam elements respectively were considered. High yield strength deformed (HYSD) bars of 8 mm diameter (Fe 500) were used as main bars in both column and beam. Following the code provision of IS 13920 (2016) lateral ties of 6 mm diameter mild steel bars (Fe 250) at 25 mm c/c spacing were used in the special confinement zone of the column, while the remaining part was increased to 50 mm c/c. Similarly, the shear reinforcement in beam were of 6 mm diameter bars having spacing of 25 mm c/c near the beam-column joint for a length of 225 mm and a spacing of 40 mm c/c in the remaining part. The yield stress (MPa) and ultimate stress (MPa) for HYSD bars tested as per code provisions of IS 432(1982) and IS 1608 (1995) were found out to be 530 MPa and 620 MPa, while the same for Fe 250 were 285 MPa and 450 MPa respectively. The detailed description of the specimens is given in Table 4.

2.4 Casting of RC frames

Three identical RC frames were casted. The specimens were designated as specimen S1, S2 and S3. Specimen S1 was treated as the reference specimen which was casted using ordinary concrete (i.e., 100% NCA). Keeping the geometric dimensions, grade of concrete and steel, the amount and detailing of reinforcing bars similar as that of specimen S1, the other specimens S2 and S3 were casted using 100% of RCA concrete. However, the joint region of specimen S3 was casted totally with micro-concrete as per guideline of ACI-318 (2008). As per manufacturer guidelines the micro-concrete was modified by mixing with 5 mm to 12 mm silt-free aggregate in the ratio 1:0.75 (micro-concrete: coarse aggregate (by weight)). A water-

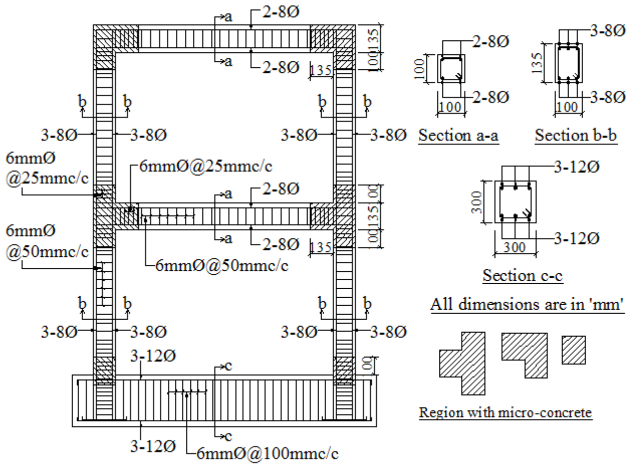


Fig. 2 Reinforcement detailing of RC frame

Table 4 Description of RC frame

Beam			Column		
Span (mm)	Section (mm)	Longitudnal Reinforcement	Length (mm)	Section (mm)	Longitudnal Reinforcement
1200	100×135	2-8Ø -top 2-8Ø -bottom	1000	100×100	3-8Ø -top bar 3-8Ø -bottom bar

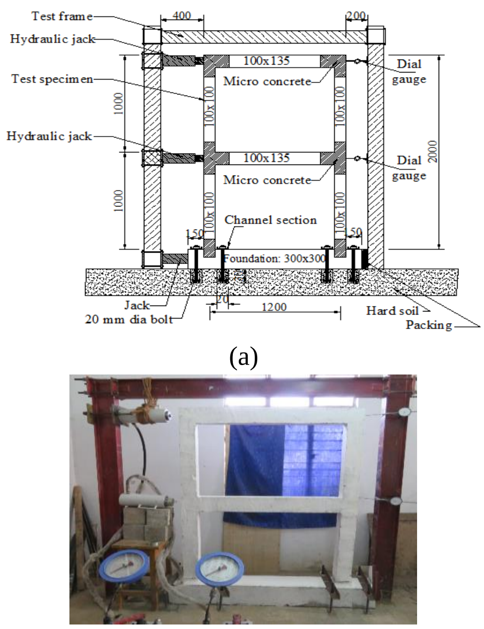
(a) Specimen S1&S2 (b) Specimen S3

Fig. 3 Casting of RC frame

powder ratio of 0.16 was used for mixing the micro-concrete mixture. The specimens were then cured for 28 days after which they were tested. Fig. 3 shows the casting of the frame.

2.5 Test set-up and instrumentation

Schematic diagram of the test set-up and the actual testing arrangement is shown in Fig. 4. The test set-up consists of a loading frame of capacity 400 kN and a hydraulic jack of 100 kN capacity. The load was applied manually through the hydraulic jack mounted on the side of the frame. The foundation of the RC frame were held tightly in position with the help of hydraulic jacks and also with the help of mild steel plates which helped in clamping the foundation to the ground. Holes were punched into the mild steel plates which were fitted into the bolts (firmly established in the ground by concreting) with the help of nuts of appropriate size. Two dial gauges of 100 mm measuring range were used to measure the lateral displacement corresponding to the applied load.



(a)

(b)

Fig. 4 Testing of RC frame (a) Test set-up (b) Actual testing arrangement

2.6 Loading sequence

As shown in Fig. 4 the frame specimens were subjected to monotonic lateral loading at the side of the top beam. A hydraulic jack of capacity 100 kN was attached to the side of the loading frame and was used for applying the necessary lateral load to the specimens. A dial gauge was attached to the loading frame opposite to the hydraulic jack to measure the displacement undergone by the specimens corresponding to a particular load. A maximum displacement of 100 mm was applied in all the specimens.

3. Behavior of recycled aggregate concrete: results and discussion

At a *w/c* of 0.5, the slump measured as per IS 1199 (1959) for M-0 was 60 mm, while for M-100 was 30 mm respectively. The high absorption of free water from the mixture during mixing process causes high water demand of the mix with increasing RCA contents. This shows that RCA concrete resulted in a significant effect on the workability of concrete. Same level of workability as those of mix M-0 could be achieved by adding super plasticizer of 0.85% by volume of water. The concrete specimen as presented in Table 5 was used for evaluating the mechanical properties. Test parameters included are compressive strength, splitting tensile strength and flexural strength. Concrete cubes and prismatic specimens were tested for compressive strength and flexural strength as per IS: 519 (1959), while a cylindrical specimen was tested for splitting tensile strength in accordance to IS: 5816 (1999). The test results presented in Table 5 shows that all test parameters decreases in the range of 30-42% with mix of RCA concrete.

Table 5 Results of compressive, tensile and flexural strength of concrete specimens

Mix	Compressive strength (MPa)	Reduction in compressive strength (%)	Splitting tensile strength (MPa)	Reduction in splitting tensile strength (%)	Flexural strength (MPa)	Reduction in flexural strength (%)
M-0	41.56	-	3.67	-	2.28	-
M-100	27.75	33.23	2.18	40.60	1.32	42.11

Table 6 Capacity comparison of RC frame specimens

Sl.No.	Test parameters	S1	S2	S3
1	Average load capacity, kN	39.50	32.50	38.00
	Reduction with respect to S1 (%)	-	17.72	3.80
2	Energy dissipation, kN-mm	1304.00	825.00	1179.80
	Reduction with respect to S1 (%)	-	36.73	9.52
3	Ductility	2	1.26	1.85
	Reduction with respect to S1 (%)	-	37.00	7.50

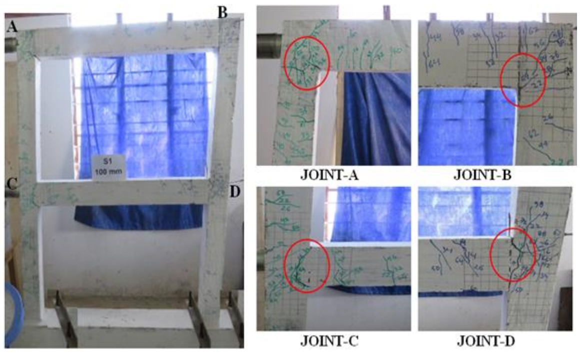


Fig. 5 Failure modes of specimen S1

4. Behavior of RC frame: results and discussion

4.1 Failure mode of specimens

Figs. 5 to 7 represent the failure pattern of the specimens. It is observed that the initial crack formation in all the specimens is mainly developed at the joint interface of beam and column. With further application of lateral load, a number of cracks were observed at the joint region and also the initial cracks widened more and more. The faster growth of cracks for specimen S2 which spreads away from the joint region reveals a brittle mode of failure as compared to specimen S1 and S3. Also as observed during experimentation, specimen S2 lost its resistance after cracking whereas specimen S3 could sustain a portion of its resistance after cracking and able to resist more loads and produced a better ductility in the frame. The presence of a micro-concrete at the joint region of frame S3 makes the joint stronger and hence delayed the crack formations as compared to specimen S2 and S1. Thus, Fig. 7 showed the minimum number of cracks at the joint region. Wider cracks occurred only at the beam portion which is the desirable failure mode of frame structures.

The load capacity were noted for displacements starting from 1mm up to 100 mm at an increment of 1mm and the crack formations were noted for each set of displacements.

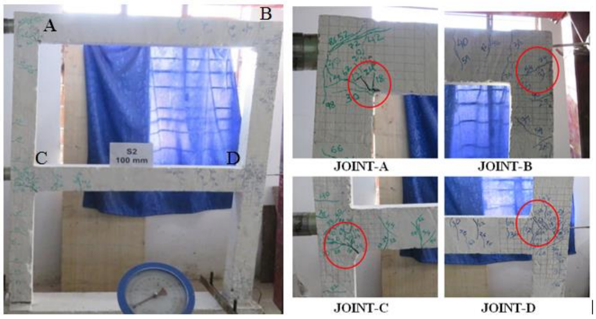


Fig. 6 Failure modes of specimen S2

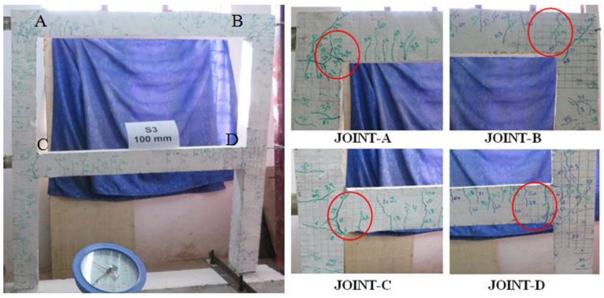


Fig. 7 Failure modes of specimen S3

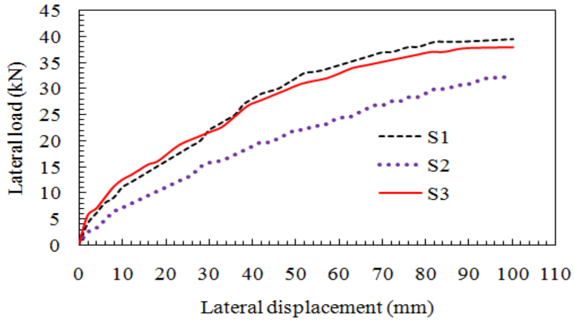


Fig. 8 Load versus displacement curve of the frame

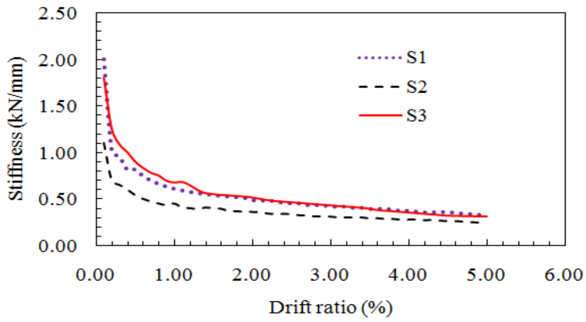


Fig. 9 Stiffness degradation of the specimens

Fig. 8 shows the load versus displacement curve. It can be observed that with increase in displacement, specimen S1 presented the highest load carrying capacity followed by specimen S3 and least with specimen S2. The higher load carrying capacity presented by specimen S3 at each displacement level in comparison to specimen S2 show an excellent contribution of micro-concrete in a RCA concrete frame which is well comparable to specimen S1. As presented in Table 6 the addition of micro-concrete in an RCA concrete frame cause a strength reduction of only 4% in comparison to specimen S2 of 18%.

4.2 Evaluation of stiffness of the frames

Stiffness is an indicator of the response of a specimen and extent of strength degradation during loading. It is calculated as the slope of the line joining the peak capacity at a given displacement. The slope of this straight line is the stiffness of the specimens corresponding to that particular displacement amplitude according to Naeim and Kelly (1999). The stiffness is formulated as

$$K = \frac{F - f}{D - d} \tag{1}$$

where, F is the maximum load of a particular specimen in the positive cycle, f is the maximum load of a particular specimen in the negative cycle, D is the displacement corresponding to the maximum load of a particular specimen in the positive cycle and d is the displacement corresponding to the maximum load of a particular specimen in the negative cycle. The present study adopted a monotonic increasing load and hence, the value of f and d are taken as zero. The drift angle is defined as the ratio of beam tip displacement to the length of the beam measured from the joint to the position of the dial gauge. The drift obtained by horizontal displacement of the beam ends are equivalent to the inter storey drift angle of a frame structure subjected to lateral loads. Drift ratio is calculated as

$$\text{Drift ratio (\%)} \ = \frac{\Delta}{H} x100 \tag{2}$$

Where, Δ and H are the applied displacement and the storey height of the frame measured from the top level of foundation to the top beam of the frame respectively.

The performance of the specimen S3 due to the presence of micro-concrete at the joint region may be evaluated by comparing stiffness versus displacement with those of specimens S1 and S2. These plots are shown in Fig. 9. Comparing these plots, similar degradations trends could be observed in all the specimens. Stiffness of the frames was gradually reduced during loading. This occurred due to bond failure, minute cracks formed in the frame. Stiffness was getting reduced higher for specimen S2. The initial stiffness of specimen S1, S2 and S3 are 2.0 kN/mm, 1.1 kN/mm and 1.8 kN/mm respectively. Thus, the presence of micro-concrete at the joint region led to an increase in initial stiffness of the frame at about 39% as compared to specimen S2. Further, it is also observed that the degradation in stiffness for specimen S3 is little slow with increase in lateral movement as compared to the specimen S2 which is well comparable to the specimen S1. This behavior may be attributed to the ductile properties imparted by the micro-concrete present at the joint region which controlled the early cracking of the joint region. The lower degradation is a desirable property in earthquake like situations. It was observed during the past earthquake that most of the RC structures failed due to sudden loss of stiffness with increasing lateral movement (Sezen *et al.* 2000). Therefore, from these comparisons it can be

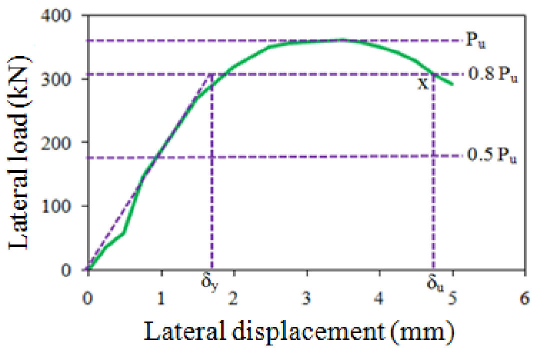


Fig. 10 Procedures for ductility calculation

concluded that the presence of micro-concrete at the joint region of the RC frame made with RCA improved the performance during seismic action.

4.3 Evaluation of energy dissipation capacity

The ability of a structural member to resist the fracture when subjected to static or to dynamic or impact loads depends to a large extent on its capacity to dissipate its energy. Hadi (2007) reported that the energy absorbed by a column before failure is correlated to the ductility of the column. This energy can be computed based on the area under the load versus displacement curve presented in Fig. 8 as implemented in several previous studies by Hadi (2006), Hadi (2007), Shannag and Ziyyad (2007). The computed energies are tabulated in Table 3. RCA specimens (S2) without micro concrete at the joint region presented the lowest energy dissipation capacity. The increase in energy dissipation of specimen S3 showed that micro-concrete has a tremendous potential use in the joint region of the RC frame. The inclusion of micro-concrete at the joint region of an RC frame made of RCA concrete lead to an increase of energy dissipation to about 1.4 times (Table 6) with respect to S2. The increase in stiffness due to presence of micro-concrete at the joint region attracted more load corresponding to any drift angle for specimens S3, which prevent the initial crack propagations. Thus, the total area enclosed by the plot of load versus displacement was more for specimen S3 as compared to S2. This was perhaps the reason for improvement in energy dissipation. It may be noted that the energy dissipating capacity of specimen S3 as presented in Table 6 is well comparable to specimen S1 (-10%) while for specimen S2 is 37% which demonstrated the benefit of using recycled aggregate concrete in an RC frame when micro-concrete is present at the joint region.

4.4 Evaluation of ductility of the frames

Ductility is basically the ability of a structure to accommodate deformations well beyond the elastic limit. It is the capacity to dissipate energy in hysteretic loops and to sustain large deformations. As the loads versus displacement curves for tested specimens do not have a distinct yield point, ductility capacity was determined using an idealized approximation procedure proposed by Shannag *et al.* (2005) which has been explained in Fig. 10. As shown in the figure, the yield displacement is calculated as the point of intersection between two straight lines drawn in the envelope curve. The first line was obtained by extending the line joining the origin and 50% of ultimate load capacity point of the curve, while the second line was obtained by drawing a horizontal line through the 80% of ultimate load capacity point. In the figure, δy represent the yield displacement. Horizontal lines drawn through the 80% of ultimate load capacity point intersect the curve at far end at points *x*. The abscissa of this point denoted by δu was taken as maximum displacement. The displacement ductility (μ) was calculated as the ratio of maximum displacement (δu) to the yield displacement (δy). The calculated values listed in Table 6 clearly show a higher ductility was achieved in case of specimen S1. However, the presence of micro-concrete in specimen S3 contributed more ductility than the specimen S2. The presence of micro-concrete at the joint region postponed the crack development towards the beam and column region and finally it was led to higher ductility, which is well comparable to the control specimen S1 (-8%).

5. Conclusions

In conclusion, by comparing the results obtained from the two concrete mixtures, it can be noted that when recycled coarse aggregate is used instead of natural coarse aggregate for concrete production, about 30-42 percent of mechanical strength (compressive, tensile and flexural strength) decreases. In addition, the results obtained through a monotonic loading test of an RC frame made of either RCA or NCA were evaluated by means of parameters such as cracking patterns, stiffness degradation, energy dissipation and ductility. The faster growth of cracks which spreads away from the joint region reveals a brittle mode of failure for a frame made of RCA concrete. In the other hand when the joint region of an RCA frame is incorporated with a micro-concrete the frame showed adequate structural behavior and exhibited a higher energy dissipation capacity and ductility and lower degradation of stiffness, which is a desirable property in earthquake like situations. Therefore, it can be concluded that the strengthening of joint region using micro-concrete is found to have a significant contribution in improving the seismic performance of RCA frame structures.

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