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Properties of recycled aggregate and recycled aggregate concrete: effect of parent concrete

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Abstract

In the present investigation, an attempt was made to study the influence of the strength of parent concrete on the properties of recycled aggregates and recycled aggregate concrete. In this study, four grades of normal concrete mixes: M20, M25, M30, and M40 were considered as parent concrete to produce the recycled coarse aggregates and recycled aggregate concrete. Four recycled coarse aggregates viz. RCA20, RCA25, RCA30 and RCA40 were derived from M20, M25, M30, and M40 parent concretes, respectively. Two grades of recycled aggregate concretes viz. MR20 and MR30, each with two sets of RCA were also produced. MR20 was designed with RCA20 and RCA25 and similarly MR30 with RCA30 and RCA40. The properties such as compressive strength, split tensile strength, flexural strength and ultrasonic pulse velocity were studied. The experimental results indicate that the compressive strength of recycled aggregate concrete made with RCA obtained from the same grade of parent concrete is lower than the normal concrete, whereas the RAC made with RCA obtained from higher grade of parent concrete is quite comparable. The energy absorption of RAC under flexural load is more than the controlled concrete.

Keywords Recycled coarse aggregate (RCA) · Recycled aggregate concrete (RAC) · Ultrasonic pulse velocity (UPV) · Split tensile strength · Flexural strength · Energy absorption

Introduction

In the recent times, the extensive increase in the rate of population, urbanization and industrialization made remarkable growth in the infrastructural development, particularly in the field of construction. Hence, there is a lot of demand for new structures, which requires billions of tons of concrete. Further, it plays an important role in countries economy development due to its large volume utilization. Since the coarse aggregate contribute around 60–75% of the total volume of concrete, as it uses approximately 20 billion tons of coarse aggregate in every year (Behera et al. 2014). Mehta and Meryman (2009) stated that approximately 20 billion metric tons of concrete per annum is utilized in construction in the present scenario. However, the research group of Fredonia has forecasted that the global consumption of aggregate used in construction may exceed 26 billion tons by 2012 (Sonawane and Pimplikar 2013). It was anticipated that in the next two to three decades the aggregate demand will be two-fold if the rate of consumption increases with the same pace (Oikonomou 2005). On one side, the natural resources are significantly affected due to extensive usage of aggregate in the construction sector. Further, this affects the sustainable development of the society. On the other hand, most of the countries are facing the problem in handling the solid waste, since there is a huge amount of waste contributed from the construction and demolition of structures. In India, as per the Central Pollution Control Board (CPCB) studies, the solid waste generation is about 48 million tons per annum of which 25% is from the construction industry only. Therefore, the use of recycled coarse aggregate from the construction and demolition waste (C&DW) as an alternative material (aggregates) for making new concrete, acquires the importance to save the natural resources and reduce the need of waste disposal.

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Indeed, the construction demolition waste deposition has an impact on environment and contributes significantly to the landfill saturation. The maximum possible utilization of the C&DW as an aggregate in concrete is very effective and anticipating technique towards the sustainable development in the construction sector.

In the recent times, many attempts have been made to replace the natural coarse aggregate (NCA) partially or fully with the recycled coarse aggregate in concrete (Frondistou-Yannas 1977; Hansen and Narud 1983; Bairagi et al. 1993; Limbachiya et al. 2000; Ajdukiewicz and Kliszczewicz 2002; Poon et al. 2004; Rao et al. 2006; Rahal 2007; Etxeberria et al. 2007; Yang et al. 2008; Kou and Poon 2008; Padmini et al. 2009; Chakradhara Rao et al. 2011). In general, the properties of concrete like compressive strength, tensile strength and modulus of elasticity reduces with increase in the percentage replacement of natural coarse aggregate by recycled coarse aggregate. However, the properties of concrete does not affect significantly if the replacement of NCA by RCA is limited to 30% (Chakradhara Rao et al. 2011; Elhakam et al. 2012). A few of the researchers tried to improve the properties of RAC using secondary cementitious materials such as fly ash, silica fume, metakaolin, ground-granulated blast slag (Elhakam et al. 2012; Kou et al. 2011; Kou and Poon 2013). Further, attempts have been made to improve the quality of recycled coarse aggregate and hence the properties of RAC by various treatment techniques (Katz 2004; Tam et al. 2005a, b; Tam et al. 2007; Tam and Tam 2008; Li et al. 2009). It was found that the properties could be improved significantly due to the improvement in the interfacial transition zones between recycled aggregates and cement mortar. Very few studies are made on the influence of the quality of parent concrete on the properties of recycled aggregate concrete. Padmini et al. (2009) examined the influence of parent concrete made with different maximum sizes of coarse aggregate (10, 20 and 40 mm) of different strength as recycled coarse aggregate on strength of RAC. It was concluded that the RAC needs lower w/c ratio than the parent concrete from which the recycled coarse aggregate derived, to achieve a particular compressive strength and the difference in strength between RAC and parent concrete increased with higher strength. This means the presence of adhered mortar does not have significant effect on lower strength of RAC. In addition, the authors concluded that for a given target mean strength, with an increase in maximum size of RCA the strength achieved was increased. Kou and Poon (2015) concluded in their studies that the mechanical properties of high-performance recycled aggregate concrete (65 MPa) made with RCA obtained from lower strength (30 and 45 MPa) parent concrete lowered significantly when compared to those of natural aggregate concrete. Whereas, the same RAC (65 MPa) made with RCA obtained from higher strength (80 and 100 MPa) parent concrete, these properties are comparable and even slightly more than those of concrete prepared with 100% natural coarse aggregate.

In light of the above scenario, the present paper explores the properties of two grades (20 and 30 MPa) of recycled aggregate concretes prepared with RCA obtained from four different strengths (20, 25, 30 and 40 MPa) of normal concrete.

Experimental programme

Materials

Since the Ordinary Portland Cement (OPC) is not available in this locality, Portland Pozzolana Cement (PPC) conforming to the requirements of BIS (IS: 8112–1989) is used in the present study. The specific gravity of cement is 3.15 and the compressive strength at 3, 7 and 28 days of curing are 15.7, 22.7 and 36.8 MPa, respectively. The locally available natural sand as fine aggregate (FA) and 20 mm maximum size natural coarse aggregate (NCA) available from the local quarries conforming to the grading requirements of IS: 383 (1970) are used.

Recycled coarse aggregate

Four types of recycled coarse aggregates viz: RCA20, RCA25, RCA30, and RCA40 are considered in this study. These recycled coarse aggregates are obtained from M20, M25, M30 and M40 grades of the original concrete, respectively. The tested specimens of each grade of original concrete are crushed to a maximum size of 20 mm aggregate through the laboratory jaw crusher to obtain the recycled coarse aggregate. The aggregates of size which passes through 20 mm and retained on 4.75 mm sieve size are selected as recycled coarse aggregate (RCA) in the present study. The physical and mechanical properties of these recycled coarse aggregate are studied and are presented in Table 1. In the Table RCA20 indicates the recycled coarse aggregate obtained from M20 normal (original) concrete. Similarly RCA25, RCA30, and RCA40 represent the recycled coarse aggregate obtained from M25, M30 and M40 normal concretes, respectively.

Details of normal concrete mixes

Normal concrete mixes of grades M20, M25, M30 and M40 are designed as per the guidelines of BIS (IS: 20262—2009) using fully natural coarse aggregates. The details of the mixes are listed in Table 2. The variation in

Table 1 Physical and mechanical properties of RCA and NCA

Properties	NCA	RCA20	RCA25	RCA30	RCA40	FA	BIS code limits
Bulk density (kg/m^3)	1556	1381	1375	1370	1364	1565	
Specific gravity	2.6	2.41	2.41	2.39	2.29	2.62	
Water absorption (%)	0.9	3.0	3.3	3.62	4.85		
Impact value (%)	12.24	15.5	16.34	17.35	19.14		Should not exceed 30%
Elongation Index (%)	33.95	24.02	25.16	25.61	31.43		Should not exceed 40%
Flakiness Index (%)	24.81	18.67	19.60	21.88	22.30		Should not exceed 40%

Table 2 Details of normal and recycled aggregate concrete mixes (quantities are per cubic meter of concrete)

Mix designation	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	w/c
M20	387.5	568.726	1175.8	0.48
M25	420	530	1155	0.46
M30	450	514	1119	0.43
M40	492.5	594.97	1069.4	0.38
MR20RCA20	387.5	568.7	1047.82	0.48
MR20RCA25	387.5	568.7	1100.80	0.48
MR30RCA30	450	514	1093.05	0.43
MR30RCA40	450	514	1070.65	0.43

cement content in the table is due to the difference in grade (strength) of concrete.

Recycled aggregate concrete mixes

Two grades of recycled aggregate concretes MR20 and MR30, each with two types of RCA obtained different strength of original concrete are examined. MR20 is prepared with RCA20 and RCA25 separately and these are designated as MR20RCA20 and MR20RCA25, respectively. Similarly, MR30 is prepared with RCA30 and RCA40 separately and are designated as MR30RCA30 and MR30RCA40, respectively. All the mixes are designed as per the guidelines of BIS (IS: 20262—2009) for normal concrete. The details of the recycled aggregate concrete mixes are presented in vide Table 2.

Specimen casting and testing of concrete

The details of properties of concrete mixes, age at test and specimen size along with standard test method are presented in Table 3.

Results and discussion

Physical and mechanical properties of recycled coarse aggregate

The particle size distribution of both natural and recycled coarse aggregates is presented in Fig. 1. It reveals that the gradation of both natural and recycled coarse aggregates is almost similar trend. Further, it shows that the recycled coarse aggregates are relatively finer than the natural coarse aggregate. This is mainly due to the adherence of old mortar in RCA, which produces the finer particles during the crushing process of aggregate.

Using the guidelines given in BIS (IS 2386 (Part I, III and IV)), the physical and mechanical properties of fine aggregate, natural and recycled coarse aggregates are determined and are listed in vide Table 1. It reveals that the bulk density, specific gravity of all RCA is lower than those of the natural coarse aggregate and the water absorption is higher than that of the natural coarse aggregate. This attributes the adherence of the old cement mortar to aggregate in RCA which is light and porous in nature. Further, it reveals that the density and specific gravity of

Table 3 Details of property, test age, specimen sizes and test method

Property	Age at test (days)	Specimen size and shape	No. of specimens	Standard test method
Compressive strength	3, 7, 28	150 × 150 × 150 mm cubes	9	IS 516
Split tensile strength	28	150 mm dia × 300 mm height cylinders	3	IS 5816
Flexural strength	28	100 mm × 100 mm × 500 mm Prisms	3	IS 516
Ultrasonic pulse velocity (UPV)	28	150 × 150 × 150 mm Cubes	3	IS 13311

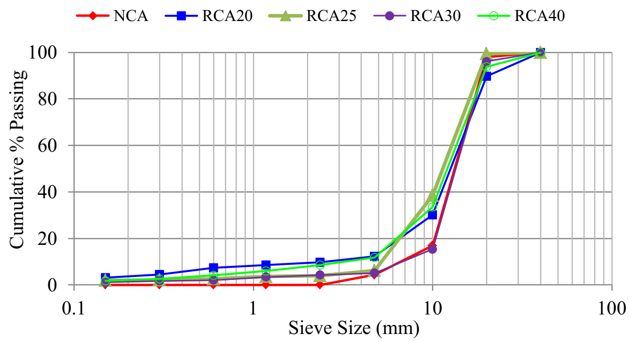

Fig. 1 Particle size distribution of both natural and recycled coarse aggregate obtained from different strengths of normal concrete

RCA40 which is obtained from higher strength of original (normal) concrete (M40) are slightly lower than those (RCA20) of obtained from lower strength parent concrete (M20) i.e., the specific gravity and density of RCA are slightly decreased with the increase in the strength of original concrete. Due to relatively strong bond between the aggregate and the mortar in higher strength parent concrete compared to lower strength parent concrete, the quantity of attached mortar content to the aggregate increases with strength of parent concrete. Therefore, the presence of relatively lower density of higher quantity of old mortar decreases the density and specific gravity of RCA obtained from higher strength parent concrete. The water absorption of RCA40 obtained from the higher strength of original concrete (M40) is higher than that of RCA20 obtained from the lower strength of normal concrete (M20). This could be possible due to the presence of relatively higher quantity of cement mortar in RCA in higher strength of original concrete compared to RCA in lower strength of original concrete. The adhered mortar is relatively high porous in nature as compared to the freshly crushed granite aggregate, which increases the water absorption of RCA. Similar results were reported by Padmini et al. (2009) in the literature. The authors reported that the water absorption of RCA obtained from compressive strength of 37, 50 and 58 MPa concrete are 3.65, 4.1 and 4.86, respectively. The flakiness and elongation indices of all RCA are relatively better than those of the natural coarse aggregate. This may be due to the appropriate care and method of crushing adopted i.e., jaw crushing in the production of RCA. The impact value of all RCA is higher than that of natural coarse aggregate. Further, there is a slight increase in the impact value of RCA with the increase in the strength of original concrete. Since the aggregate obtained from higher strength of original concrete has relatively higher quantity of adhered mortar compared to the aggregate obtained from lower strength of original concrete, which produce more percentage of powder formation during the impact.

Properties of concrete

The details of the mixes of both normal concrete and recycled aggregate concrete are presented in vide Table 2. The properties like compressive strength, split tensile strength, flexural strength and ultrasonic pulse velocity of concrete are studied. The compressive strength is studied at 3, 7 and 28 days of curing, whereas the other properties are studied only at 28 days of curing.

Compressive strength

The development of compressive strength of different grades of normal concrete w.r.t. different curing periods is presented in Fig. 2. It is observed that for all the grades, the compressive strength attained at 3 and 7 days curing period is ranging from 47 to 51% and 65 to 70%, respectively, those of 28 days compressive strength. In general, the strength of normal concrete at 7 days curing period is approximately 60–70% of that of 28 days compressive strength.

The variation in compressive strength of normal concrete (M20) and recycled aggregate concrete MR20 made with RCA20 and RCA25 are presented in Fig. 3. It is observed that at 3, 7 and 28 days curing periods, the

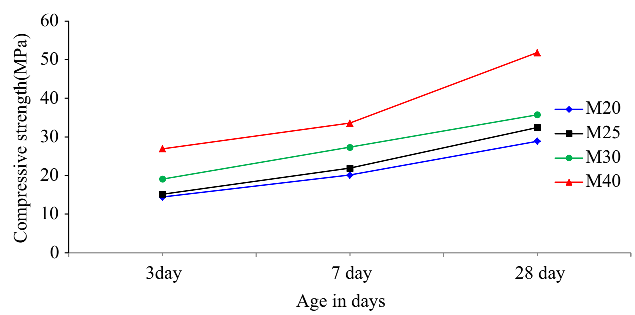

Fig. 2 Development of compressive strength of normal concrete of different grades with curing periods

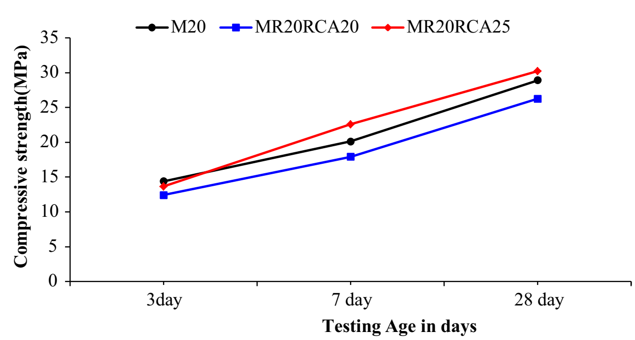

Fig. 3 Compressive strength variation in normal concrete (M20) and RAC (MR20) made with RCA20 and RCA25

compressive strength of MR20RCA20 is lower by 13.8, 10.8, and 9.1%, respectively, than those of corresponding normal concrete M20. Whereas, a change in trend is observed for 7 and 28 days curing period in case of MR20RCA25 and it is slightly improved than its parent concrete (M20) compressive strength. The increase in compressive strength of MR20RCA25 are 12.2 and 4.6%, respectively, at 7 and 28 days curing periods than those of normal concrete M20. But, at 3 days, a slight reduction in compressive strength of MR20RCA25 is observed when compared to its corresponding normal concrete M20. The compressive strength development in normal concrete (M30) and recycled aggregate concrete MR30 prepared with RCA30 and RCA40 are presented in Fig. 4. The development of compressive strength in recycled aggregate concrete prepared with different strengths of parent concrete aggregate i.e., RCA30 and RCA40 are almost similar trend as it is in normal concrete (M30) with respect to different testing periods.

It is observed that at 3, 7 and 28 days testing periods, the compressive strength of RAC made with RCA obtained from the same grade of normal concrete aggregate i.e., MR30RCA30 is lower by 21.85, 10.84, and 16.3%, respectively, than those of the normal concrete M30. Whereas an improvement in compressive strength is found for the same grade of RAC (MR30) when it is made with RCA obtained from higher strength of parent concrete i.e., MR30RCA40 at 28 days curing period. For MR30RCA40, the compressive strength at 28 days curing period is 38.22 MPa which is 6.9% higher than that of the normal concrete (M30). Therefore, from Figs. 3 and 4, the test results of recycled aggregate concrete reveal that the compressive strength of the recycled aggregate concrete made with RCA obtained from same grade of parent concrete is always lower than that of the parent concrete at all the curing periods. Whereas in RAC made with RCA produced from relatively higher strength parent concrete, the compressive strength at 28 days testing is slightly higher than that of the normal concrete. That means the RAC made with relatively higher strength of parent concrete aggregate may produce similar strength as the normal concrete of the same grade. The improvement in compressive strength may be due to the higher original strength of cement mortar adhered to aggregate in RCA25 and RCA40 compared to RCA20 and RCA30, respectively, and hence the old interfacial transition zones in MR20RCA25 and MR30RCA40 are relatively stronger than those of the MR20RCA20 and MR30RCA30, respectively. A similar result is reported in the literature. Kou and Poon (2015) reported in the literature that the compressive strength of high-performance concrete made with recycled aggregate obtained from 80 and 100 MPa normal concrete satisfied the designed strength of 65 MPa and it was similar to or even slightly higher than that of the concrete with natural coarse aggregate.

Split tensile and flexural strengths

The test results of split tensile strength of normal concretes of grade M20, M25, M30 and M40 are 2.59, 3.78, 4.0 and 4.15 MPa, respectively, after 28 days of curing. Similarly, the flexural strength of M20, M25, M30 and M40 grade concretes are 5.12, 5.2, 6.46 and 8.67 MPa, respectively. These results indicate that the split tensile strength and flexural strength are approximately 8.5–12 and 16–19%, respectively, of their corresponding compressive strengths. In general, the tensile strength of concrete made with natural coarse aggregate is in the range of 10–15% of that of compressive strength.

The split tensile strength of recycled aggregate concrete prepared with RCA obtained from different strengths of parent concrete is presented in Fig. 5. The ratio (percentage) of split tensile strength (*fct*) to compressive strength (*fcs*) of RAC are presented in Fig. 6.

Fig. 5 shows that irrespective of the strength of parent concrete, the split tensile strength of RAC is lower than those of the normal concrete at 28 days of testing. Possibly,

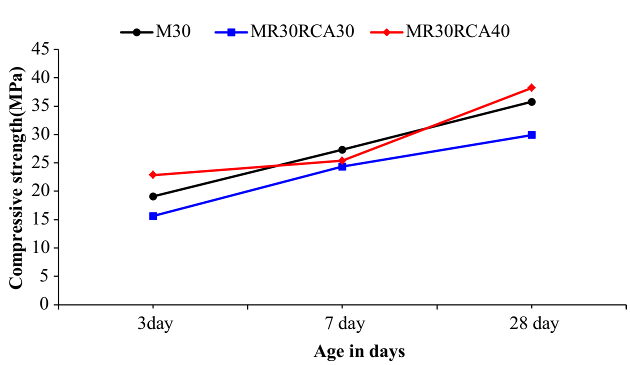

Fig. 4 Development of compressive strength of normal concrete (M30) and RAC (MR30) made with RCA30 and RCA40 with different curing periods

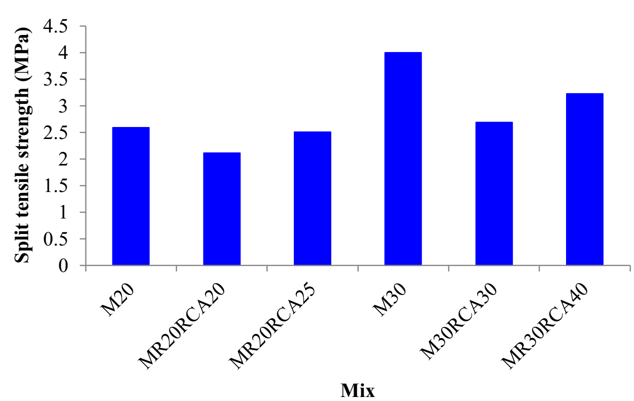

Fig. 5 Split tensile strength of normal concrete and recycled aggregate concrete mixes

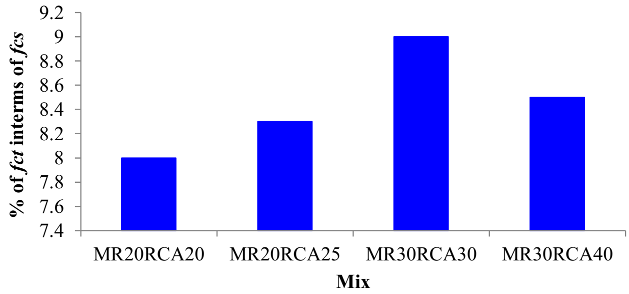

Fig. 6 Ratio of split tensile strength (*fct*) to compressive strength (*fcs*) of RAC

this may be due to the presence of weaker old interfacial transition zones and more number of microcracks in RCA, which may lead to the failure under tension. However, further investigations on the size and number of microcracks in RCA and at the old and new interfacial transition zones of concrete through scanning electron microscope (SEM) are required to strengthen above observation. The physical observation of the fractured surfaces reveals that the failure in RAC is mainly through the recycled aggregate rather than the new interface. The split tensile strength of MR20RCA20 and MR20RCA25 are 2.11 and 2.51 MPa, respectively, against 2.59 MPa of normal concrete (M20). Similarly, in MR30RCA30 and MR30RCA40, the split tensile strengths are 2.69 and 3.26 MPa, respectively, against a value of 4 MPa in normal concrete. These results reveals that the RCA obtained from the higher strength of parent concrete improves the split tensile strength of recycled aggregate concrete of lower strength. This improvement may be due to the presence of relatively strong old interfacial transition zones in higher strength parent concrete aggregate comparatively lower strength parent concrete aggregate and also an improvement in the bond between RCA and new cement mortar. However, further investigation on microstructure of old and new ITZ through SEM may be needed to enhance the above conclusion. From Fig. 6, it is observed that irrespective of the strength of parent concrete, the split tensile strength of RAC is approximately 8–9% of their corresponding compressive strength.

Figure 7 shows the variation of the load displacement curve of normal concrete (M20) and RAC made with RCA derived from 20 and 25 MPa parent concretes under flexure. Similarly, the variation of load with displacement under flexure for M30 normal concrete and RAC prepared with RCA obtained from 30 and 40 MPa is presented in Fig. 8. It is observed from the Figs. that irrespective of the strength of the parent concrete, the peak load of RAC is lower than those of the corresponding normal concrete. This is apparently because of poor mechanical properties of recycled coarse aggregate. However, with the increased

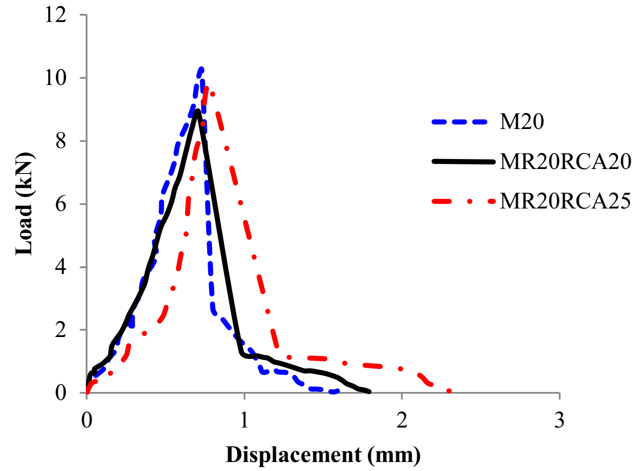

Fig. 7 Behaviour of normal concrete (M20) and RAC made with RCA20 and RCA25 under flexural load

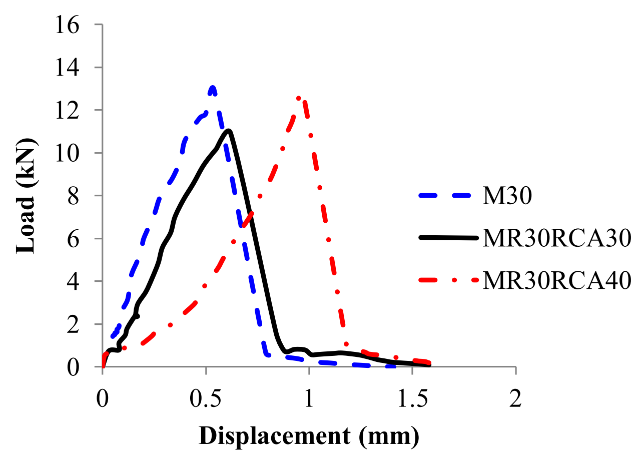

Fig. 8 Behaviour of normal concrete (M30) and RAC made with RCA30 and RCA45 under flexural load

strength of parent concrete, the peak load of RAC is increased. Further, it reveals that the displacement at peak load in RAC is more than those of the corresponding normal concrete, which may be due to the lower modulus of recycled coarse aggregate and the presence of weaker interfaces between new and old cement mortars and between old mortar and aggregate. Therefore, the area under the load displacement curves of RAC are relatively more when compared to their corresponding controlled concretes. Hence, the energy absorption capacities of RAC made with RCA are more than the normal concrete under flexure. The energy absorption capacity of MR20RCA20 and MR20RCA25 are 4.72 and 5.60 N mm, respectively, against 4.32 N mm of their controlled concrete. Similarly, in MR30RCA30 and MR30RCA40, the energy absorption capacity is 5.64 and 5.94 N mm, respectively, against 5.60 N mm of its controlled concrete.

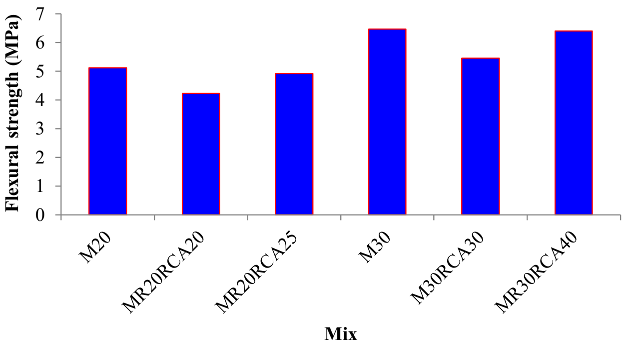

Fig. 9 Flexural strength of normal concrete and recycled aggregate concrete mixes

Figure 9 presents the test results of flexural strength of controlled concretes and recycled aggregate concretes made with different strength of the parent concrete aggregate.

It reveals that irrespective of the strength of parent concrete, the flexural strength of RAC are lower than those of the normal concrete. However, there is an improvement in flexural strength of RAC with higher strength parent concrete aggregate. The flexural strength of MR20RCA20 and MR30RCA30 are lower by 17.5 and 15.6%, respectively, than their corresponding normal concretes M20 and M30. But the flexural strength of RAC designed with RCA25 and RCA40 are significantly improved and they are almost close to their corresponding normal concretes i.e., M20 and M30, respectively. These improvements may be due to the improved new interfacial transition zones between RCA and new cement mortar. Further, the aggregate obtained from the higher strength parent concrete is having a relatively stronger bond between it and the old cement mortar.

Ultrasonic pulse velocity (UPV)

The ultrasonic pulse velocity test results of concrete are presented in Fig. 10. It is observed from the figs. that the

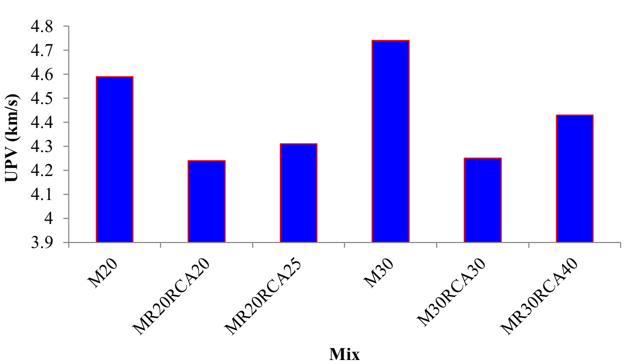

Fig. 10 Ultrasonic pulse velocity test results of normal concrete and recycled aggregate concrete mixes

UPV of recycled aggregate concrete prepared with RCA from both lower and higher strength parent concrete are lower than those of corresponding normal concretes. The recycled aggregates consists of strong natural coarse aggregates adhered with more porous cement mortar, which lowers the density of RCA. Further, during crushing of the normal concrete-tested samples, the recycled aggregate is subjected to more microcracks and the travelling time of UPV in a solid media depends on the density and elastic properties of the material. As discussed in "Physical and mechanical properties of recycled coarse aggregate", the density of RCA is lower than natural aggregate, which increases the travel time of the ultrasonic waves. Hence, the UPV of RAC is relatively lower when compared to those of normal concretes. Ravindrarajah et al. (1988) reported similar result in the literature. The UPV of all RAC mixes ranges from 4.24 to 4.43 km/s against 4.59 to 4.74 km/s of their corresponding normal concretes. This shows the uniformity of concrete mixes. According to IS: 13311-1992 (Part 1), the quality of concrete graded as excellent and good when the pulse velocity is more than 4.5 and 3.5 to 4.5 km/s, respectively.

Further, it is observed that the UPV of RAC is slightly improved with the RCA obtained from higher strength parent concrete compared to RCA obtained from the same strength of parent concrete. The bond between the aggregate and the cement mortar matrix is relatively improved with the increase in strength of concrete due to lower w/c ratio and higher quantity of cement content, thereby the number and size of microcracks may be reduced at the interfacial transition zone. Hence, in case of higher strength parent concrete, there may be relatively lesser number of microcracks and improved interfacial transition zones between RCA and new cement mortar due to the presence of relatively rich mortar.

Closing remarks

The present paper discussed the influence of recycled coarse aggregate obtained from different strengths of parent concrete on properties of recycled aggregate concrete. Based on the test results the following closing remarks can be drawn.

- The bulk density and specific gravity of RCA obtained from higher strength parent concrete are relatively lower and water absorption is slightly higher than those obtained from the lower strength of the parent concrete. Possibly, this could be due to the adherence of relatively large amount of light porous old cement mortar to the recycled aggregate obtained from higher strength parent concrete compared to the lower strength parent concrete.

- The compressive strength of recycled aggregate concrete made with RCA obtained from same grade of the parent concrete is always lower than that of parent concrete at all curing periods. However, the RAC made with RCA produced from higher strength parent concrete, the compressive strength at 28 days of curing is slightly higher than that of the normal concrete. That means the RAC made with higher strength parent concrete aggregate may produce similar strength as the normal concrete of same grade.
- The split tensile strengths of RAC are also improved with the use of RCA derived from higher strength of the parent concrete. However, these are always lower than those of normal concrete.
- The peak load of RAC produced with RCA from higher strength parent concrete is almost close to their corresponding normal concretes under flexure. Further, the energy absorption of RAC under flexure is more than the controlled concrete.
- The ultrasonic pulse velocity of RAC prepared with RCA derived from higher strength parent concrete is just 6% lower than those of corresponding normal concrete.

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