Mechanical properties of recycled aggregate concrete treated by variation in mixing approaches

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Abstract
Increased demand for natural aggregates (NA) due to infrastructural development has necessitated the use of alternative aggregates in the field of construction. One such option is the utilization of construction and demolition wastes, preferably named as recycled coarse aggregates (RCA) to produce a sustainable recycled aggregate concrete (RAC). Perhaps, the quality of RCA is usually poor due to the presence of adhered mortar on its surface affecting the strength and durability properties of RAC. Consequently, it is essential to improve the behavior of recycled aggregate concrete. In order to improve the recycled concrete aggregate, four different processing techniques such as two-stage mixing approach (TSMA), mortar mixing approach (MMA), sand enveloped mixing approach (SEMA) and double mixing approach (DMA) were used to improve the quality of RAC. This paper aims at providing a comparative study on the suitability of different mixing approaches and their influence over the fresh and hardened properties of recycled aggregate concrete. The performance behaviour of RAC was evaluated at 7, 14, 28 and 90 days with various percentage replacements of RCA at w/c ratios of 0.45 and 0.5. Experimental results indicate that the strength of concrete made of 100% RCA was equivalent to the target strength at 90 days. Also, among the various mixing processing techniques, MMA shows better fresh and hardened properties of concrete at different curing ages. Micro-structural investigations through SEM were performed to investigate the modification in the ITZ of the RAC through MMA approach.

Keywords: recycled coarse aggregate; recycled aggregate concrete; mixing approach; adhered mortar; processing techniques.

Introduction

Industrialization and urbanization had emerged at its peak due to an increased population and they resulted in depletion of natural resources. Perhaps, it leads to a shortage of natural resources and the generation of a huge amount of solid wastes. Approximately 20 to 40 billion tons of natural resources were being procured and used as raw materials by the construction industries every year(Vivian et al. 2018). European Aggregate Association estimated that nearly 400 tonnes of aggregates were required to build an individual residential house and 3000 tonnes as base course for a single kilometre of highway (UEPG 2015). Also, the technological advancement necessitated the production of concrete close to 25 billion tonnes per year (Cement sustainability initiative, WBCSD, 2020) and nearly one-third of it end up as wastes. Upon scarcity, the necessity on aggregates had reached at its peak in the field of construction. Researchers have been pioneered in finding an alternative material to be used as aggregates in concrete. Attempts have been made to procure the construction and demolition (C&D) waste and reuse in the concrete as RCA. Utilization of RCA as a partial or complete replacement to natural coarse aggregates (NCA) developed a new era in concrete termed as “recycled aggregate concrete (RAC)”.

RAC is a sustainable material prepared by mixing RCA from demolished buildings with ordinary potland cement at different proportions. But RAC is mainly used for non-structural applications like sub-base of roadways, filling works in roads and construction etc, rather than in structural members like beams, columns etc. This is due to the higher porosity of RCA and weaker interfacial transition zone (ITZ) of RAC resulting from the presence of adhered mortar on the surface of RCA. Moreover, no proper guidelines were specified on the utilization of RCA in concrete for its structural applications. In India, the RCA were categorized based on three grades limiting its utilization less than 50% by weight of concrete. Also, no proper mix specifications to evaluate the fresh and hardened properties of RAC were established (RILEM 273-RAC).

The physical characteristics of RCA such as the presence of adhered mortar, density, abrasion, crushing index, method of crushing, surface texture, and also the other characteristics like mixing approach, ITZ, aggregate size are the factors which govern the strength of RAC (Akbarnezhad et al. 2013, Abrahams et al. 2018, Ho et al. 2013, Huda et al. 2014, Ozbakkaloglu et al. 2018, Matias et al. 2013, Sarhat et al. 2013, Saravanakumar et al. 2016). All other factors, except the mixing approach and aggregate preparation has a direct relationship with the quality of parent concrete as the source and quality of RCA decides the strength of RAC (Abrahams et al. 2018, and Huda et al. 2014). In previous researches, RAC prepared by normal mixing approach (NMA) shows up to 35% reduction in strength compared to normal aggregate concrete (NAC) (Abdulla 2015, Akbarnezhad et al. 2013). Concerning to the levels of replacement, up to 50% replacement of RCA, the strength of RAC and NAC will be similar, beyond which it causes a decrease in the strength of RAC (RILEM 273-RAC, Ho et al. 2013, Ozbakkaloglu et al. 2018).

To improve the quality of RAC and its percentage of utilization, researches were performed to modify the conventional mixing approach by DMA, triple mixing approach (TMA), MMA, TSMA, SEMA and sand enveloped portland cement approach (SEPA) (Liang et al. 2013, Kong et al. 2010, Uniyal et al. 2014, Tam et al. 2006, Li et al. 2012). However, study on TSMA (Tam et al. 2006, Tam et al. 2007 and Tam et al. 2008) does not provide any conformity over the performance of RAC upon 100% utilization of RCA. Another study by (Liang et al. 2013) through TSMA, SEMA and MMA concluded that RCA can be utilized completely but the influence of mixing approaches on the long term strength of RAC was not performed. Further more studies in treating the RCA by chemicals such as HCl, H_2SO_4, mechanical methods like heating, scrubbing and abrasion etc. tend to remove the adhered mortar on the surface of RCA (Ismail et al. 2013, Revathi et al. 2015, Saravanakumar et al. 2015, Xuan et al. 2016, Kothari et al. 2016). But the viability on complete removal of adhered mortar on RCA that could enhance the performance of RAC was not yet confirmed. Conversely, the processing techniques of RAC through mixing approaches tend to coat the surface of RCA with mortar or sand mixture rather than a partial removal of the adhered mortar on its surface. Considering all such aspects of previous research, this study involves the behaviour of RAC by variation in w/c ratio of 0.45 and 0.5 with different percentage replacements of RCA from 0% to 100%.

Research significance

The entire research study was performed in three phases. The first phase involves the fresh property study on RAC. In this study, RAC with 100% of RCA were prepared by NMA, TSMA, MMA and DMA for both w/c ratios and the workability of RAC was studied. The second phase of the study was performed to satisfy two purposes. The first was to optimize the RCA for it effective utilization in concrete by NMA. The second was to study the effect of RCA in improving the strength of RAC upon prolonged curing. For this, RCA was replaced by 0%, 20%, 40%, 60%, 80% and 100% by weight of NCA. The strength of RAC with different levels of replacement was studied for its strength at 7, 14, 28, 56 and 90 days. The third phase of the study was performed to investigate the influence of TSMA, SEMA, MMA and DMA on the mechanical properties of RAC for the optimal w/c ratio of the concrete mixture. For this, the RAC with 0%, 50% and 100% replacement of RCA was prepared by all mixing approaches. The mechanical properties like compressive strength, flexural strength was studied at 7, 28 and 90 days and elastic Modulus was studied at 28 and 90 days.

Materials and methods

Materials

Ordinary portland cement of 43 grades, natural river sand passing through 2.36mm sieve according to IS 2386 – 1963 (Part 1 & 3) was used as fine aggregate (NFA), crushed rock aggregates of 10 mm and 20 mm, C&D wastes retrieved from the concrete beams and columns of 10 years old demolished building at the institute were used as coarse aggregate in this study. The collected RCA were crushed by jaw crusher of varying sizes of 20 mm and 10 mm to achieve better particle packing. It was then washed in water to remove finer dust particles, saturated in water for 24 hours and air dried for 3 hours to achieve saturated surface dry density (SSD). The physical properties of NCA and RCA were tested according to IS 2386 (1989) and results were given in Table 1. From the table it is found that RCA have higher water absorption, lower specific gravity and density. The water absorption of RCA was found to be 1.8 times higher than the BIS limits (<3%) and this is due to the presence of adhered mortar on the surface of RCA. BS 8500-2:2006 specifies the maximum limit on the presence of impurities in RCA as 16.5%, however the RCA used in the study contains only less than 8% of impurities. Nevertheless, water absorption is the only parameter found to be exceeding the BIS limits and so SSD was maintained for both NCA and RCA before its utilization in the mixture of concrete.

Table 1. Physical property of NCA and RCA. (Self – Elaboration).

Type of coarse aggregate	Grading (mm)	Specific gravity	Water absorption (%)	Apparent density (kg/m^3)	Bulk density (kg/m^3)
NCA	10~20	2.68	0.67	2734	1427
RCA	10~20	2.55	5.41	2671	1258

Mix design

In this study, the quantity of materials for the concrete mixture was prepared for 0.45 w/c and 0.5 w/c ratios to achieve target strength of 38.25 MPa and 28.25 MPa at 28 days for M30 and M20 grade concrete in accordance with IS 10262:2009. A total of 14 concrete mixes were designed wherein 7 concrete mixes were intended to optimize the RCA and remaining 7 concrete mixes to study the influence of mixing approaches by various replacement percentages at both w/c ratios. One category of the study on RAC which were prepared by replacing NCA by 0%, 20%, 40%, 50%, 60%, 80% and 100% of RCA by its weight were labelled as RCA-a-x-(1-5), with 'a' representing the w/c ratio of 0.5, 'x' representing the replacement percentages of RCA and 1-5 representing the type of mixing approaches. The numerical notations '1' represents the NMA, '2' represents the TSMA, '3' represents the SEMA and '4' represents the MMA and '5' represents the 'DMA'. The other was on RAC which were prepared by replacing NCA by 0%, 20%, 40%, 50%, 60%, 80% and 100% of RCA by its weight were labelled as RCA-b-y-(1-5), with 'b' representing the w/c ratio of 0.45, 'y' representing the replacement percentages of RCA and 1 to 5 represents the type of mixing approach. As the water absorption capacity of RCA is higher, RCA and NCA were pre-saturated to achieve SSD throughout the study. All the quantities of ingredients of concrete were determined with fixed w/c ratio of 0.5 and 0.45 for NAC and RAC. The mix proportions for different concrete mixtures are given in Table 2 and 3.

Table 2. Mix proportions of RAC (NMA). (Self – Elaboration).

Mix	(kg/m^3)				
	Cement	NFA	NCA	RCA	Water
RCA -0.5-00-1	372	829	1015	0	186
RCA-0.5-20-1	372	829	812	203	186
RCA -0.5-40-1	372	829	609	406	186
RCA -0.5-50-1	372	829	507.5	507.5	186
RCA -0.5-60-1	372	829	406	609	186
RCA -0.5-80-1	372	829	203	812	186
RCA -0.5-100-1	372	829	0	1015	186
RCA -0.45-00-1	413	799	1029	0	186
RCA-0.45-20-1	413	799	823.2	205.8	186
RCA -0.45-40-1	413	799	617.4	411.6	186
RCA -0.45-50-1	413	799	514.5	514.5	186
RCA -0.45-60-1	413	799	411.6	617.4	186
RCA -0.45-80-1	413	799	205.8	823.2	186
RCA -0.45-100-1	413	799	0	1029	186

Table 3. Mix proportions of RAC (TSMA, SEMA, MMA and DMA). (Self – Elaboration).

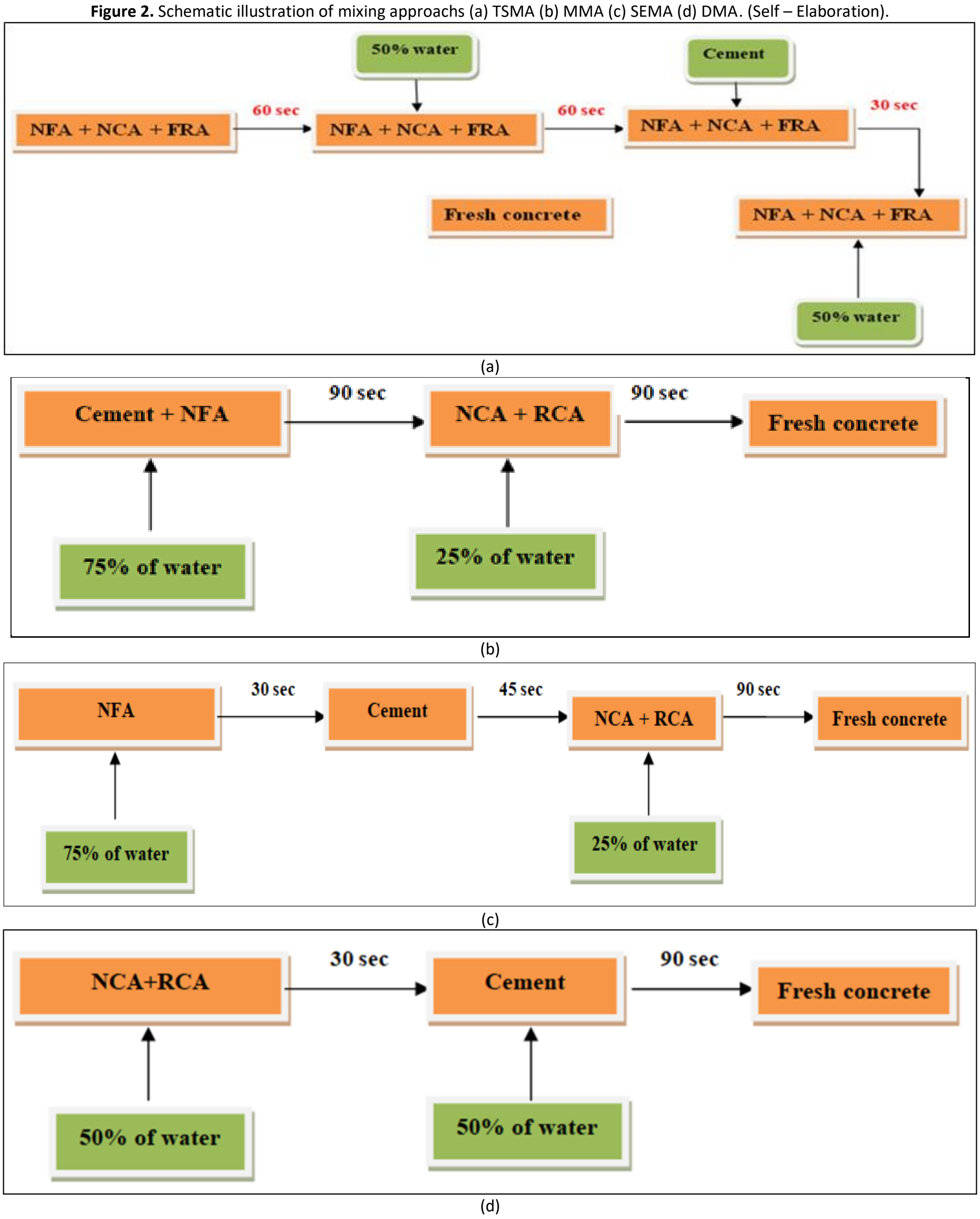
Mix	(kg/m^3)				
	Cement	NFA	NCA	RCA	Water
RCA -0.45-00-2	413	799	1029	0	186
RCA-0.45-50-2	413	799	514.5	514.5	186
RCA -0.45-100-2	413	799	0	1029	186
RCA -0.45-00-3	413	799	1029	0	186
RCA-0.45-50-3	413	799	514.5	514.5	186
RCA -0.45-100-3	413	799	0	1029	186
RCA -0.45-00-4	413	799	1029	0	186
RCA-0.45-50-4	413	799	514.5	514.5	186
RCA -0.45-100-4	413	799	0	1029	186
RCA -0.45-00-5	413	799	1029	0	186
RCA-0.45-50-5	413	799	514.5	514.5	186
RCA -0.45-100-5	413	799	0	1029	186

Methodology

The concrete mixtures were prepared by NMA, TSMA, MMA, SEMA and DMA to investigate the effect of RCA on the mechanical properties of RAC in laboratory under controlled conditions (Figure 1). In NMA, cement, fine aggregate, NCA and RCA were mixed together for 30 sec followed by the addition of water and further mixed for 90 sec. In TSMA, fine aggregate, NCA and RCA were mixed for 60 sec. Then 50% of water was added and the mixture was mixed for 60 sec. Upon, cement was added in the mixture and mixed for 30 sec and the rest 50% of water was added and the entire mixture was mixed for 120 sec (Tam et al. 2005). In MMA, fine aggregate, cement and 75% of water were mixed for 90 sec. Then NCA and RCA were added in the mixture with remaining water and mixed for 90 sec (Tam 2008, Liang et al. 2015). In SEMA, fine aggregate and 75% of water were mixed for 30 sec followed by the addition of cement and mixed for 45 sec. Finally NCA and RCA and the remaining water was added and mixed for 90 sec (Liang et al. 2015). In DMA, NCA and RCA with 50% of water were mixed for 30 sec, followed by the addition of cement and mixed for 90sec (Kong et al. 2010). For each mix, three cube moulds of 150 mm, three cylindrical moulds of 150 mm x 300 mm and prism moulds of 500 mm x 100 mm x 100 mm were prepared to investigate the mechanical properties. The concrete mixtures prepared in accordance with the mix were poured in the moulds in three layers, compacted by a table vibrator for about 120 sec and demoulded after 24 hours. It is then cured at 20 ºC (relative humidity >80%) for 7, 14, 28, 56 and 90 days and tested as per codal provisions. Figure 2 shows the schematic illustration of NMA, TSMA, SEMA and DMA approaches.

Figure 1. Preparation of specimens. (Self – Elaboration).

Figure 2. Schematic illustration of mixing approachs (a) TSMA (b) MMA (c) SEMA (d) DMA. (Self – Elaboration).



Testing of specimens

The mechanical properties of RAC were evaluated by compressive strength test, flexural strength test and elastic modulus test for different concrete mixtures cured at various ages. The experimental set up for the evaluating the mechanical properties of RAC was shown in the Figure 3. Compressive strength were measured using UTM with a capacity of 1000 kN in accordance with ASTM C39 and elastic modulus of concrete specimens were measured using UTM with a capacity of 1000 kN in accordance with ASTM C469. Flexural strength to determine the modulus of rupture was performed in accordance with ASTM C293. For compressive strength and flexural strength, the specimens were loaded as shown till it fails to evaluate their mechanical properties. For elastic modulus, specimens were loaded under UTM at a rate of 10 kg/cm^2/s and the corresponding stress and strain were measuring using LVDT attached as shown (Figure 3). For all mix combinations, an average of three specimens was tested to evaluate the behaviour of RAC.

Figure 3. Testing of specimens (a) Compressive strength (b) Flexural strength (c) Elastic modulus. (Self – Elaboration).

(a) (b) (c)

Analysis of results

The test results of compressive strength, flexural strength and elastic modulus of RAC were determined for all mix combinations at different curing ages. Table 4 and table 5 shows the hardened properties of RAC for all mix combinations.

Effect of mixing approaches on the workability of RAC

The workability of fresh concrete mixes at both w/c ratio of 0.45 and 0.5 by various mixing approaches were tested by performing a slump cone test as per ASTM C143 and results were shown in figure 4. The maximum slump of 145 mm was achieved at w/c ratio of 0.5 by SEMA approach. As evident from the results, workability of RAC decreases upon increase in the percentage of RCA by NMA. The workability of concrete mixtures by TSMA approach was found higher compared to those by NMA. The slump of RAC was found to be lesser than NAC at both w/c ratios of 0.45 and 0.5, even though after SSD in RCA before mixing. This attribute to the rough texture of RCA and its higher water demand compared to NCA (Liang et al. 2013, Revathi et al. 2014, Tam et al. 2005, and Ozbakkalogu et al. 2018). The higher slump value of fresh concrete mix by SEMA and MMA may attribute to the formation of non-porous mortar film over the surface of RCA, which reduces its water absorption thereby enhancing the workability.

Figure 4. Workability of concrete mixes by various mixing approaches. (Self – Elaboration).

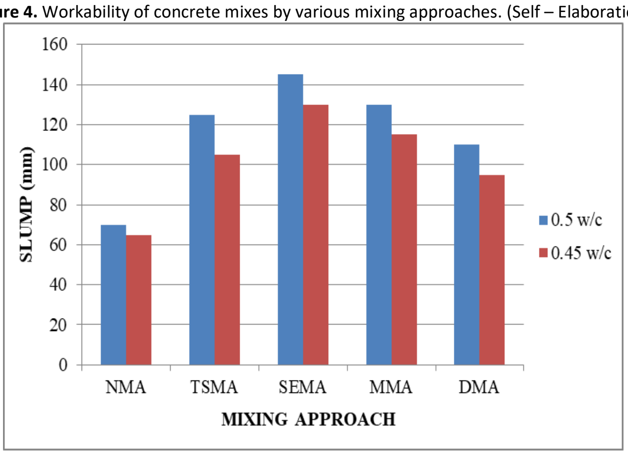


Table 4. Compressive strength of RAC (NMA). (Self – Elaboration).

Mix	Compressive strength (MPa)				
	7 days	14 days	28 days	56 days	90 days
RCA -0.5-00-1	21.83	30.21	32.65	38.01	38.74
RCA-0.5-20-1	21.51	29.30	32.56	38.73	39.68
RCA -0.5-40-1	22.14	30.07	33.42	39.88	41.65
RCA -0.5-50-1	28.02	30.61	34.02	41.87	42.35
RCA -0.5-60-1	20.37	27.09	30.11	33.84	36.12
RCA -0.5-80-1	19.15	25.60	28.45	31.92	32.52
RCA -0.5-100-1	17.14	23.74	26.38	28.96	30.41
RCA -0.45-00-1	26.74	35.29	39.22	46.08	47.15
RCA-0.45-20-1	25.84	35.68	39.65	47.50	48.77
RCA -0.45-40-1	26.73	36.72	40.81	49.05	51.37
RCA -0.45-50-1	27.11	37.58	41.76	51.67	52.33
RCA -0.45-60-1	26.91	36.97	41.08	46.24	49.51
RCA -0.45-80-1	25.80	34.89	38.72	43.77	44.65
RCA -0.45-100-1	24.11	32.61	34.35	39.87	41.83

Table 5. Compressive strength of RAC (TSMA, MMA, SEMA, DMA). (Self – Elaboration).

Mix	Compressive strength (MPa)			Flexural strength (MPa)			Elastic Modulus*10^3	
	7 days	28 days	90 days	7 days	28 days	90 days	28 days	90 days
RCA -0.45-00-2	27.38	39.38	47.40	3.54	4.27	4.65	31.46	34.23
RCA-0.45-50-2	32.35	47.23	55.76	3.81	4.68	5.17	34.20	37.36
RCA -0.45-100-2	26.77	37.90	54.16	3.48	4.12	4.97	30.81	36.67
RCA -0.45-00-3	28.14	40.32	48.17	3.65	4.33	4.58	31.94	34.70
RCA-0.45-50-3	33.83	49.73	61.16	4.02	4.81	5.34	35.59	39.24
RCA -0.45-100-3	27.11	38.44	55.91	3.49	4.28	5.19	31.22	37.86
RCA -0.45-00-4	28.76	41.21	49.33	3.59	4.36	4.87	32.15	35.17
RCA-0.45-50-4	34.26	50.58	63.57	4.07	4.90	5.51	35.98	39.65
RCA -0.45-100-4	28.05	39.10	57.05	3.63	4.37	5.27	31.25	37.73
RCA -0.45-00-5	26.91	38.25	46.77	3.63	4.09	4.41	30.92	34.19
RCA-0.45-50-5	32.07	47.01	55.28	3.80	4.62	5.24	34.28	37.25
RCA-0.45-100-5	26.66	37.19	54.07	3.43	4.05	4. 91	30.48	36.61

Improvement in the strength of RAC upon replacement of RCA

Compressive strength of RAC by NMA at both w/c ratios for various ages of curing is given in the Table 4. From the results, it is clear that optimal replacement for RCA in concrete is 50%. The RAC records maximum compressive strength of 52.33 MPa for RCA-0.45-50-1 which is ample for structural applications. Furthermore on complete utilization of RCA, the strength reduces by 23.43% for w/c ratio of 0.5 and 12.72% for w/c ratio of 0.45 at 28 days compared to NAC. Whereas at 56 days, the strength reduces by 10.22% for w/c ratio of 0.5 and 9.78% for w/c ratio of 0.45, and for 90 days, the strength reduces by 6.94% for w/c ratio of 0.5 and 6.74% for w/c ratio of 0.45. Conversely, it could be observed that the target strength for M20 (30.41 MPa) and M30 (41.83 MPa) grade concrete was attained upon complete utilization of RCA at 90 days. Upon 50% replacement of RCA, the strength was found to be increased by 4.29% at 28 days, 4.75% at 56 days and 1.65% at 90 days for w/c ratio of 0.5. Similarly, for 50% replacement of RCA, the strength was found to be increased by 2.27% at 28 days, 5.07% at 56 days and 1.83% at 90 days for w/c ratio of 0.45 mixes. Beyond 50% replacement of RCA, the strength was found to be decreasing irrespective of the ages of curing.

Improvement in the strength of RAC upon influence of mixing approaches

RAC mixes with w/c ratio of 0.45 were prepared through various mixing approaches and the improvement in strength of RAC was analyzed as it measures the maximum strength compared to w/c ratio of 0.5 (Table 4). Figure 5 shows the compressive strength of RAC at 28 days by various mixing approaches. Improvements in the strength of RAC by TSMA, MMA, SEMA and DMA compared to NMA at w/c ratio of 0.45 for various ages of curing are shown in the figure 6. It could be observed the maximum improvement in strength of about 26.68% was recorded by MMA at 90 days. For a NAC, the strength improvement of RAC was around 2-10% at 7 days, 0.4-10.20% at 28 days and 0.53-10.56% at 90 days. Whereas for RAC with 50% of RCA the strength improvement was around 5.34-17.68% and with 100% of RCA, the strength improvement was around 22.77%-26.68% at 90 days. The improvement in the strength of RAC was high for all mixing approaches at 90 days compared to 28 days and that implies even at higher replacement of RCA, increase in the curing period will eventually increase the strength of the RAC.

Figure 5. Compressive strength of RAC by various mixing approaches at 28 days. (Self – Elaboration).

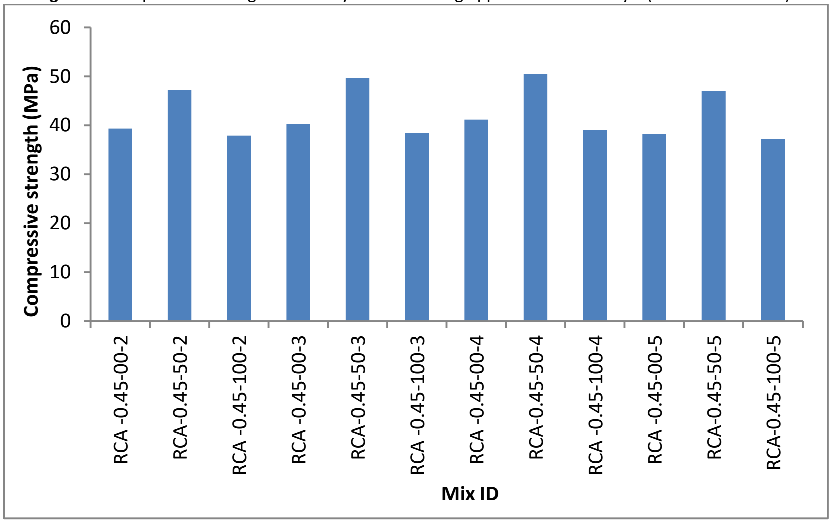
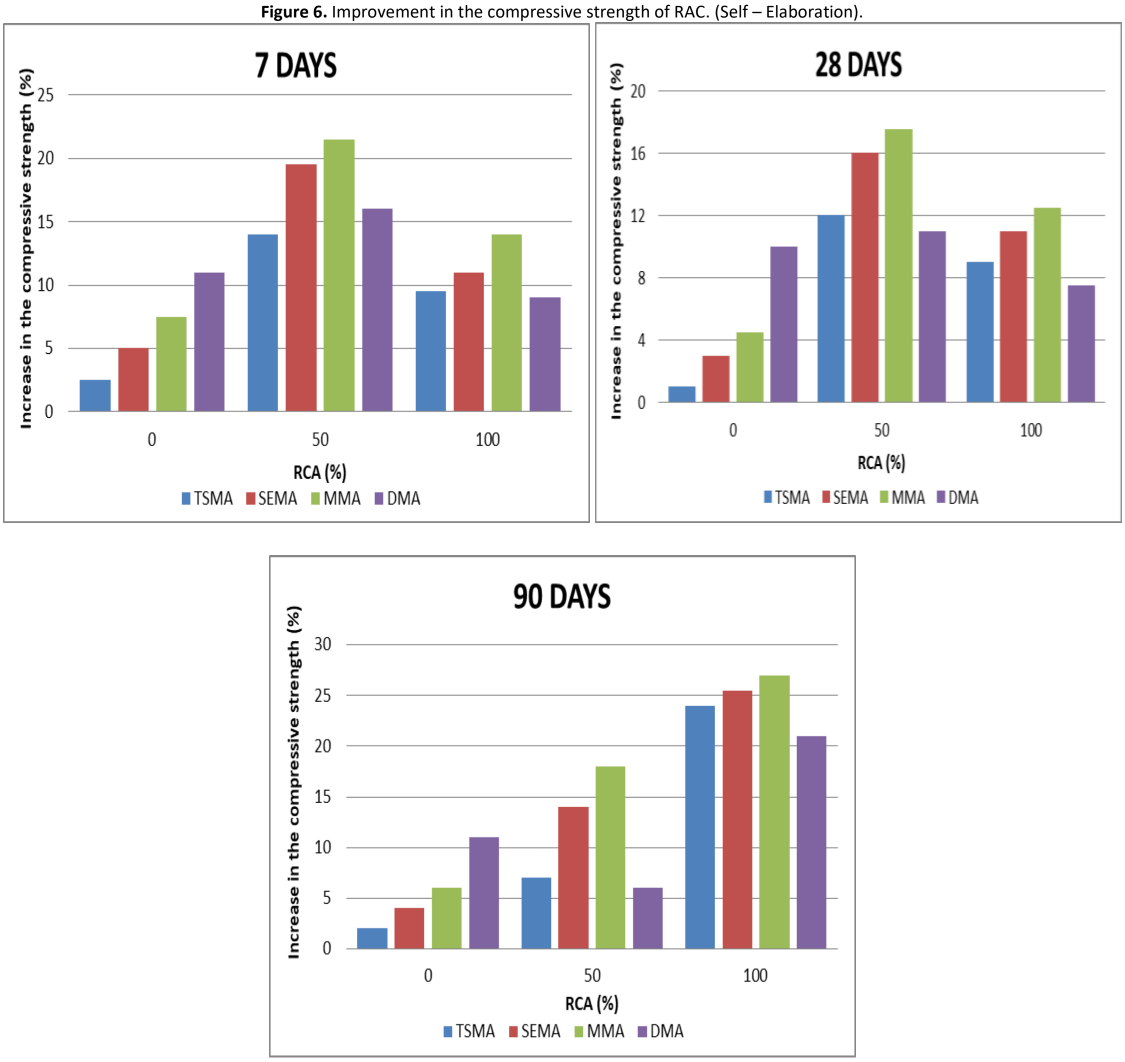


Figure 6. Improvement in the compressive strength of RAC. (Self – Elaboration).



Compressive strength

From the results (Table 4&5), the variation in the mechanical properties of RAC upon replacement of RCA was observed (Zhou et al. 2017, Surya et al. 2013, Kong et al. 2010). The strength of RAC increases with increase in the percentage of RCA till 50%, eventually a decline in the strength of RAC was observed beyond it at early ages. This is due to the porous nature of RCA as a result of adhered mortar on its surface that weakens the ITZ of RAC (Ho et al. 2013, Ryu 2002, Otsuki et al. 2003, Neville 1995, Jalilifar et al. 2020). As we know, NAC is a three-phase structure comprising of aggregates, cement mortar and ITZ. Conversely, in the case of RAC, the structure is composed of four phases namely aggregates, cement mortar and two ITZ (one between aggregate and cement mortar and other between old adhered mortar on RCA and new cement mortar).

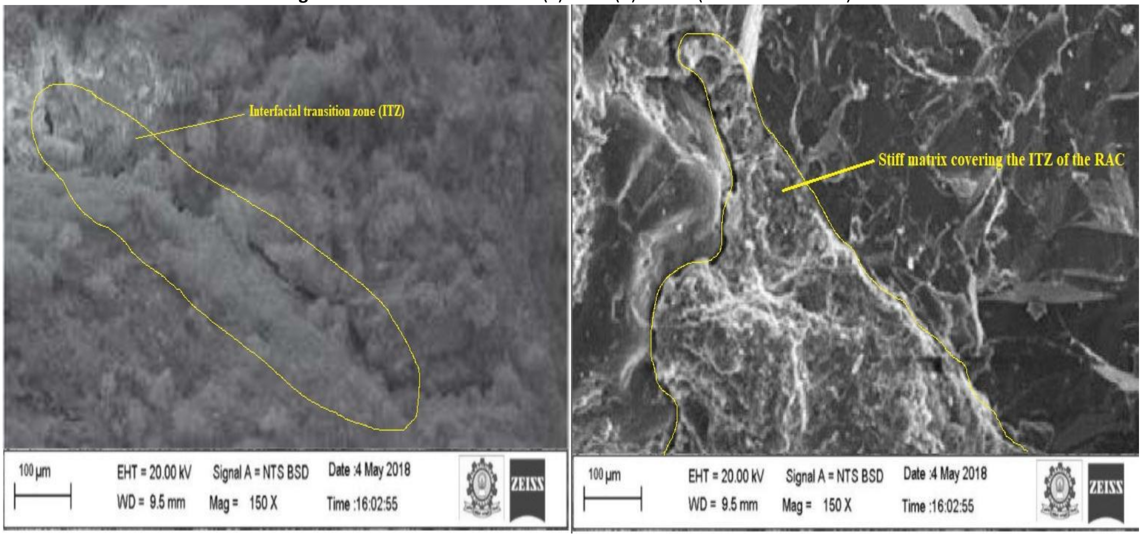
In RAC, ITZ plays a vital role in deciding the strength of concrete which occupies nearly 40% of the volume of matrix and also the weakest zone in RAC (Abdulla 2014). In NAC, though the ITZ becomes the weakest zone, in case of RAC the ITZ was still weak due to the porous nature of adhered mortar on the surface of RCA (Mindess et al. 2003, Mehta et al. 1990, Alexander 1996, Jia et al. 1986, Keru et al. 1988, Li et al. 2001, Popovics 1987, Xueqan et al. 1987). But the strength of RAC upon complete utilization is equivalent to NAC at 90 days which attribute to the effective hydration of cement particles that fills up the micro-cracks in ITZ accordingly improving the strength of RAC. Strength of RAC depends on the strength of ITZ, which eventually depends on the strength of w/c ratio. Maximum improvement in the strength of RAC was achieved at w/c ratio of 0.45 compared to w/c ratio of 0.5. This may be due to fact that the amount of free water required for cement hydration was absorbed by the adhered mortar causing decrease in the workability thereby reducing the strength beyond 50% of replacement (Ho et al. 2013). At w/c ratio of 0.45, new ITZ which governs the strength of RAC becomes stronger compared to old ITZ thereby increasing the strength of RAC (Ryu 2002, Otsuki et al. 2003). This was also evident through the experimental findings of (Neville 2003) wherein the strength of mortar as a deciding factor for concrete strength can be achieved through concrete prepared at lower w/c ratio.

Processing techniques to RCA tends to further improve the strength of ITZ in RAC and covers the adhered mortar surface of RCA rather than removal. In TSMA, water is added to the concrete mix under two stages, as upon the first stage of addition results in the development of a non-porous stiff matrix covering up the surface of RCA and the remaining water added during the second stage of mixing completes the process. Such mixing approach fills up the voids on the surface of RCA by stiffer matrix formed during the first stage of mixing preventing the absorption of excess water by RCA required for the hydration. In MMA, the first stage of mixing involves the addition of 75% of mixing water, cement and fine aggregate in the preparation of stiff matrix followed by the addition of RCA, wherein upon mixing for additional 90s, the formed stiff mortar coats the entire surface of RCA filling up the voids on the surface of RCA. This method in turn produces a superior and closely packed matrix compared to TSMA covering the entire surface of adhered mortar in RCA.

In SEMA, 75% of water is added to fine aggregate and cement particles before the addition of aggregates. Under such circumstances, the maximum water will be absorbed by the cement and sand particles in the production of a non-porous stiff matrix and thus leaving lesser water to be absorbed by the RCA. The sand-rich mortar produced during the first stage of mixing will coat the permeable surface of RCA thereby improving its quality. Also, water required by RCA during casting got reduced as adhered mortar on the surface of RCA was sealed by sand-rich mortar with lesser permeability. In DMA, initially aggregates and 50% of water was mixed, as a result of which water demand of RCA was satisfied during initial stage of mixing itself. In addition, a layer of low w/c ratio slurry sticks to the surface of RCA that impregnates through the micro-cracks of ITZ. Consequently, the micro-structure of ITZ in RAC was strengthened filling up the micro-cracks in the adhered mortar. Also, Followed by it the fine aggregate and the remaining water were added to the concrete mix resulting in an impermeable coat over the surface of RCA.

Figure 7 shows the micro-structure of the RAC prepared by NMA and MMA. It could be observed that the ITZ in RAC was weak with micro-cracks due to the presence of adhered mortar on the surface of RCA. However, the stiff matrix developed as a result of MMA wraps the cracks in the ITZ of the RAC.

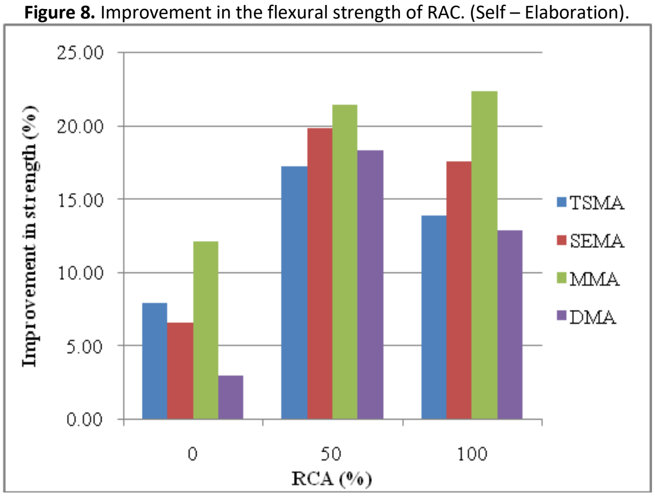
Figure 7. Microstructure of RAC (a) NMA (b) MMA. (Self – Elaboration).



Flexural strength

Improvement in the flexural strength of RAC prepared by various mixing approaches at 90 days is presented in Figure 8. It could also be observed that flexural strength also shows a rising trend with increase in the replacement of RCA till 50% at w/c ratio of 0.45. The maximum improvement in the flexural strength of 22.83% was observed with MMA at 90 days. Under the influence of mixing approach, the flexural strength tends to improve further even at 100% utilization of RCA. This attribute is due to the fact that ITZ between RCA and cement matrix was strengthened and tends to withstand more loading under the action of bending.

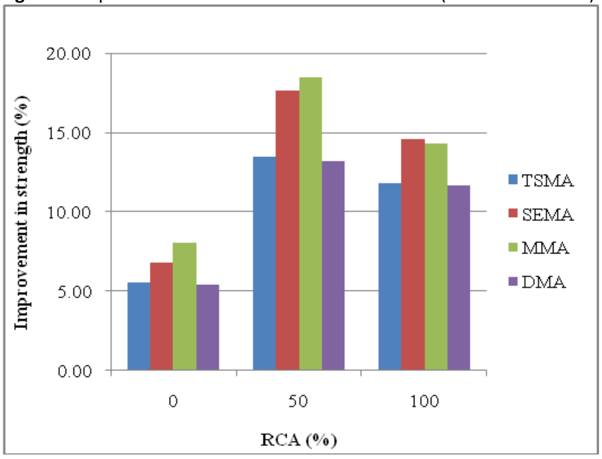
Figure 8. Improvement in the flexural strength of RAC. (Self – Elaboration).



Elastic modulus

Improvement in the elastic modulus of RAC prepared by various mixing approaches at 90 days is presented in Figure 9. The elastic modulus of RAC was lower than that of NAC due to decrease in the density of RCA (Table 1). Through NMA, the elastic modulus of RAC was lesser compared to NAC at 0.45w/c beyond 50% replacement. This is due to the lesser stiffness and density of RCA as a result of adhered mortar on its surface. In addition, elastic modulus of aggregates is higher compared to cement paste; reduced level of replacement will tend to increase the volumes of aggregates in concrete. Upon increase in the replacement of RCA, the porous nature of such increased RCA in concrete tends to reduce its elastic modulus; as a result of which elastic modulus of NCA and hardened cement paste will be more compared to the elastic modulus of RCA and hardened cement paste. Under the influence of mixing approaches, elastic modulus of RAC increases around 20% at 28 days and 16% compared to NAC at 90 days. This is because the stiff matrix prepared through mixing approaches tends to fill the micro-cracks of RCA covering the entire adhered mortar surface of RCA. Consequently, the stiffness of matrix increases eventually increasing the elastic modulus of RAC. Furthermore, addition of water at different stages during mixing reduces the excessive water absorption of RCA that is required for hydration of cement particles.

Figure 9. Improvement in the elastic modulus of RAC. (Self – Elaboration).



Failure pattern

The failure pattern of NAC and RAC is shown in the Figure 10. The zone of cracking for NAC and RAC was quite similar. During initial loading, no cracks were visible on the surface of the specimen. Upon increased loading, thin micro-cracks starts at the center of the specimens and propagates diagonally till the end in the shape of 'X'. In addition, spalling of concrete on the edges could be observed both in NAC and RAC when it reaches the peak load. After loading, visual observations indicate cracks were mainly observed in the ITZ of RAC. Also, the width of cracks upon loading of the specimen was more in RAC compared to NAC. Similarly in case of prism, no cracks were visible during initial loading. When the loading exceeds, cracks propagate vertically through the specimen and the specimen fails completely making a sound with some discontinuous cracks on the surface of the specimen. Upon visual observations, the cracks were observed through the ITZ. For RAC specimens prepared by TSMA, MMA, SEMA and DMA, the rate of resistance increases due to the improved quality of ITZ compared to RAC specimens prepared by NMA.

Figure 10. Failure pattern of NAC and RAC. (Self – Elaboration).

Conclusions

From the experimental investigations on the mechanical properties of RAC prepared with different mixing approaches, the following conclusion can be drawn:

- Compared to NCA, RCA possess higher porosity, weaker ITZ compared to NCA. This is due to the presence of adhered mortar with micro-cracks on the surface of RCA.
- The workability of RAC was less compared to NAC even after SSD due to the presence of adhered mortar on its surface. Processing techniques like TSMA, SEMA, MMA and DMA increases the workability properties of RAC through the formation of non-porous mortar film over the surface of RCA thereby reducing its water absorption.
- At early ages, there exists limitation on utilization of RCA in concrete preferably depending on its source. Conversely, RAC with complete utilization of RCA achieves target strength of required grade of concrete on extended curing for 90 days.
- Reduction in the w/c ratio of concrete mixes produces a stronger new ITZ compared to old ITZ that improves the strength of RAC.

- The compressive strength and flexural of RAC prepared by different mixing approaches are more compared to NAC. This is due to the complete coating of surface of RCA by stiff non-porous matrix.
- The elastic modulus of RAC was lesser compared to NAC due to lesser density and stiffness as a result of adhered mortar on the surface. Upon processing through various mixing approaches, the interface between the aggregate and matrix gets stiffened, enhancing the elastic modulus of RAC.
- The compression and flexural failure of NAC and RAC were quite similar, but the width of cracks on ITZ of RAC on uptake of load is higher compared to NAC. Upon processing, the width of the cracks gets reduced due to strengthening of ITZ thereby resulting in higher strength compared to RAC prepared by NMA.
- Among all mixing approaches, SEMA and MMA at 0.45w/c exhibits better results on complete utilization of RCA as a result of a stiff non-porous matrix produced during the mixing that completely coats the surface of RCA.
- Concerning all such aspects, processing techniques like SEMA and MMA would yield better results on complete utilization of RCA in concrete overcoming the difficulty on scarcity in construction materials thereby promoting the sustainability in construction.

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