Research Article

Performance Enhancement of Recycled Aggregate Concrete – An Experimental Study

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Abstract
Extensive studies have been performed on the mechanical and durability properties of the concrete prepared with recycled coarse aggregates (RCA), however, only the modest consideration has been given to the studies on the behavior of RAC prepared by different mixing approach techniques. This study presented the mechanical properties of the recycled aggregate concrete (RAC) with different percentages of RCA prepared by normal mixing approach (NMA), two-stage mixing approach (TSMA) and sand enveloped mixing approach (SEMA) techniques. The manufactured concrete mixtures were tested for compression, tension, flexure and elastic modulus at 7, 28 and 90 days. The results indicated that the mechanical properties of the RAC (with 100% of RCA) prepared through TSMA and SEMA were improved by 9.36 and 12.14% at 28 days. Prolonged, prolonged curing to TSMA and SEMA mixtures improved the mechanical properties of the RAC that was nearly equal to normal aggregate concrete (NAC) prepared by NMA.

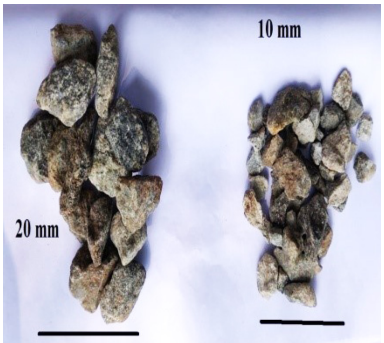
Keywords: Recycled aggregates, Normal mixing approach, Two-stage mixing approach, Sand enveloped mixing approach, Mechanical properties

1 Introduction

The increase in the demand for concrete is growing rapidly with an increase in industrialization and urbanization over decades. Nearly 70–80% of the volume of the concrete comprises of both fine and coarse aggregates. With the recent estimate, the global aggregate demand was increased to 3.8 tonnes per capita (WBCSD). Such an increased need for aggregates in concrete production depletes the natural resources and imparts huge energy consumption on the production and transportation of raw materials. Meanwhile, 1/10th of every production of concrete ends up as wastes [1]. The USDOT estimates that nearly 123 million tons of construction and demolition (C&D) wastes are being produced through demolition of concrete structures every year. Similarly, the produced C&D wastes around the world estimates to be 20–30% of total solid waste. Such C&D wastes were dumped in the landfill due to the ineffectiveness in the safe disposal. During the past few decades, many researchers utilized RCA as a suitable alternative to natural coarse aggregate (NCA) for the manufacture of sustainable concrete. However, the poor quality of recycled coarse aggregate (RCA) due to the adherence of mortar on its surface has limited its structural applications.

Puthussery *et al.* used a 50-year-old demolished building as RCA and found that the RCA absorbed 6 times more water content compared to NCA [2]. It is also reported that replacement of RCA beyond 25% reduced the strength of the RAC due to the increased pore volume of RCA. Koper *et al.* collected RCA from the concrete mixtures prepared with 0.35 to 0.6 w/c ratios and observed that the properties of the RAC with RCA from the parent concrete with lower w/c ratio mix was improved [3]. Similar studies by Lavado *et al.* indicate that the RCA from parent concrete with lower w/c ratio (0.35) and prolonged concrete mixing improved the bulk density and the strength of the recycled aggregate concrete (RAC) [4]. Abdel-Hay *et al.* cured the concrete mixtures with 0, 25, 50, and 100% of RCA under normal curing, open-air and painted curing and observed that the strength and permeability were less under paint cured specimens and more underwater cured specimens [5]. The report indicated that paint curing sealed the surface of the specimens and that reduces the permeability of RAC and increased the strength of the RAC. Bui *et al.* developed a new method to pack the NCA and RCA in such a way that the entire particle sizes of NCA were packed with the relevant particle sizes of RCA [6]. The results indicate an improvement in the replacement of RCA from 30% (conventional method) to 50% (new method) with 22.7% improvement in the strength of the RAC. A similar study Mwasha *et al.* on effective particle packing and pre-soaking of RCA developed a RAC with the highest compressive strength of 83 MPa [7]. Results indicate a decrease in the slump of pre-saturated RCA when compared to unsaturated RCA and also the strength difference of 17% at 28 days. Pacheco *et al.* used 25, 50, and 100% of RCA with fly ash, CEM II, C280, and OPC to manufacture NSC and HSC mixtures and found that the strength was reduced by 10% for all mixtures excepting fly ash and HSC [8]. This is due to the increase in the porosity of RAC mixtures whereas for fly ash and HSC mixtures, the micro-structure of the RAC was densified with fly ash with an effective w/c ratio. Mohammed Ali *et al.* investigated the influence of well and potable water on the properties of RAC with 0, 25, 50, and 100% of RCA and observed a 30% decrease in the slump and 8.5% decrease in the strength of RAC for well water [9]. Vieira *et al.* collected a 48 h. old RCA from a RMC plant in Brazil and observed that the RCA was feasible for structural applications with characteristic strength less than 30 MPa [10]. Sony *et al.* prepared NSC and HSC mixtures with 0, 20, 40, 60, 80 and 100% of RCA and observed a reduction in the strength of 9.8, 13.5, 11 and 9.2% for NSC mixtures and 11, 11.3, 10.3 and 10.8% for HSC mixtures [11]. Such decrease was due to the higher porosity of the concrete mixtures resulting from the adherence of mortar on RCA. All these studies report on the decrease in the strength of RAC with increase in the replacement of RCA due to the presence of micro-cracks on the surface of RCA. Several studies on treatment to RCA [1], [10]–[16] with silica fume, slurries, acids, microbes, admixtures etc. was developed to improve the quality of RCA. However these studies focus either on removal of adhered mortar or coating the adhered mortar with additional treatment techniques or materials which will not be viable under practical circumstances on large scale.

Tam *et al.* proposed a two-stage mixing approach (TSMA) to coat the porous surface of RCA with impermeable mortar and found that the strength of the RAC was enhanced by 14% with 30 to 40% of RCA [17], [18]. Further Tam *et al.* diversified the TSMA with silica fume and silica fume + cement [19]. It is reported that strength improvement of 16.28% with the former and 11.92% with the latter was observed at 28 days. The use of silica fume and cement fills up the micro-cracks on the RCA and densifies the interfacial transition zone (ITZ) of RAC and thus enhancing the strength of the RAC. Liang *et al.* used 100% RCA and compared the effectiveness of TSMA, mortar mixing approach (MMA), and sand enveloped mixing approach (SEMA) for low strength and high strength concrete mixtures and observed that SEMA (0.45 w/c ratio) and MMA (0.49 w/c ratio) mixtures show better properties compared to normal mixing approach (NMA) mixtures [20]. Andal *et al.* prepared RAC with 30 to 100% of the preserved quality of RCA by TSMA and observed that preserved quality of RCA mixtures show better mechanical properties compared to ordinary RCA mixtures at the same grades [21]. Ozbakkaloglu *et al.* used 25, 50, and 100% of 7 mm and 12 mm size RCA to manufacture the RAC mixtures by TSMA [22]. It is observed that the workability, hardened density of TSMA mixtures was better compared to NMA mixtures due to the reduction in the porosity of RAC. Faysal *et al.* investigated the influence of mineral admixtures on the properties of RAC with TSMA technique and observed that mixtures prepared with admixtures by TSMA show a decrease in the workability and enhancement in the strength of RAC due to the improvement in the quality of ITZ



(a) NCA

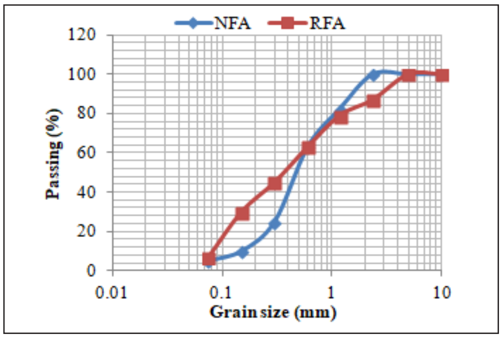
(b) RCA

Figure 1: Visual appearance of aggregates.

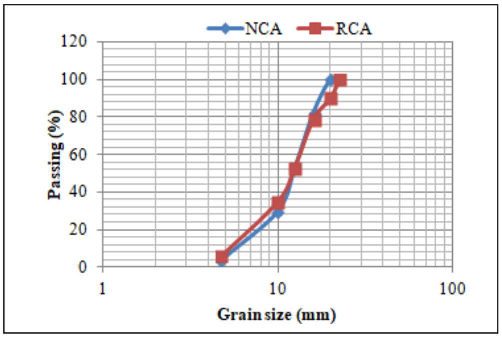
[23]. The above review on the literatures indicated the lack of studies on the effect of advanced mixing techniques such as TSMA, MMA, SEMA etc. on the properties of RAC under prolonged curing. So, this study investigates the mechanical properties of RAC with different percentages of RCA at 7, 28 and 90 days.

2 Experimental Program

2.1 *Materials*



(a) Fine aggregate



(b) Coarse aggregate

Figure 2: Particle size distribution curves.

Type I ordinary portland cement (OPC) based on ASTM C150 standarded [24] was used for preparing the concrete mixtures. NCA was collected from the local suppliers at Madurai, India and the RCA was collected from an old demolished building at the institution. The river sand collected from the local suppliers was sieved to 1.18 ~ 2.36 mm and used as natural fine aggregate (NFA) in the concrete. The impurities from the collected RCA were initially removed and the crushed with jaw crusher and sieved to 10 ~ 20 mm. Similarly, the NCA collected from the local suppliers were sieved to 10 ~ 20 mm to achieve better particle packing. Figure 1 shows the collected NFA, NCA and RCA used in the study. The gradation curves of coarse aggregate and fine aggregate obtained through sieve analysis are shown in the Figure 2. The NCA was replaced with 0, 10, 30, 50, 70, 90 and 100% of RCA by its weight. Initially NFA, NCA and RCA were washed and pre-saturated for 24 h and oven-dried for 5 h to maintain the surface saturated dry density (SSD). This reduces the additional absorption of the water by aggregates during concrete mixing and thus improving the fresh properties of the concrete [1], [7], [25].

Table 1 shows the physical properties of aggregates used in the study. It is observed that the RCA showed higher water absorption and lower density compared to NCA. This is due to the higher porosity of RCA resulting from the presence of adhered mortar [26], [27].

Table 1: Physical property of aggregates

Aggregate	Particle Size (mm)	Specific Gravity	Absorption (%)	Density (kg/m^3)
NFA	2.36	2.74	0.94	1528
NCA	20 mm	2.71	0.87	1976
RCA	20 mm	2.52	6.13	1431

2.2 *Concrete mixtures and testing*

Various advanced methods such as TSMA, SEMA, MMA, double mixing method, and triple method have been proposed to improve the properties of RAC [17], [20], [28]. In this present study, TSMA and SEMA were used along with NMA for the manufacture of concrete mixtures. Table 2 shows the mix proportions of different concrete mixtures. A total of 21 batches were prepared out of which 7 batches of each were prepared using NMA, TSMA, and SEMA approaches. The concrete mixtures were prepared to achieve a characteristic strength of M30 grade concrete at 28 days. Three different batches with NCA prepared using NMA, TSMA and SEMA were used as reference concrete. In NMA, the pre-saturated NFA, NCA, RCA, and cement were blended in the mixer for 3 min followed by the addition of water gradually and mixed for 5 min further. In TSMA, the pre-saturated NFA, NCA and RCA were blended for 60 s and 50% of water was added and mixed for another 60 s. Followed by, binder and the remaining water was added and mixed for 60 s. The water was added to the concrete mixtures under two stages and hence the name “TSMA”. In SEMA, the NFA was mixed with 75% of water for 30 s and followed by; the binder was added and mixed for further 45 s. To the mixture, the NCA, RCA and the remaning water was added and mixed for 90 s. Since the NFA binder was prepared to coat the surface of RCA, it is termed as “SEMA”. The concrete mixtures prepared by NMA, TSMA and SEMA were poured in the moulds, compacted effectively and the top surface of the moulds were levelled. It is then allowed to dry for 24 h and cured under controlled conditions for the respective ages (7, 28 and 90 days) and tested for its mechanical properties. The workability was evaluated through a standard slump cone of 10 cm top dia, 20 cm bottom dia, and 30 cm height. The compressive strength was evaluated with 150 mm cube specimens and the split tensile strength and elastic modulus were determined on cylindrical specimens with 150 mm × 300 mm. The flexural strength was determined on prisms of 500 mm × 100 mm × 100 mm. For normal aggregate concrete (NAC) and RAC, the workability was evaluated as per ASTM C143 [29]. The density of the hardened concrete at 28 days was determined as per ASTM C642 [30]. The compressive strength and flexural strength were determined as per ASTM C39 [31] and the split tensile strength was determined as per ASTM C496 [32]. The parameters for evaluation include replacement ratio and mixing approaches. For each test, average of three samples was tested to evaluate its properties. The XRD scanning in the range of 20° to 80° was used for the analysis of RCA. The samples of the tested specimen were collected suitably, grounded to fine powder and mounted on an aerosol suspension chamber to evaluate the various chemical constituents of RCA. The microstructure of RCA was analyzed by scanning electron microscopy (SEM). The images were obtained using Carl Zeiss EVO 18 apparatus. The samples of the tested specimen were collected suitably, air-dried under laboratory conditions and coated with thin-film for effective backscattering of images.

Table 2: Concrete mix proportions

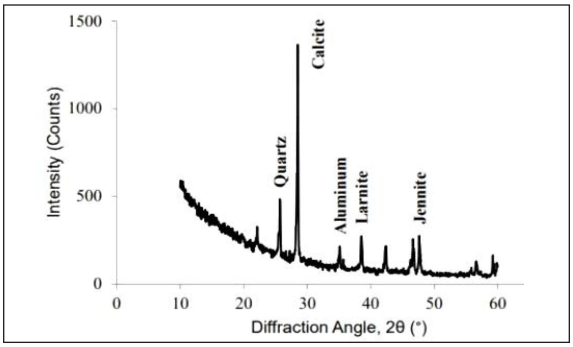
Mix ID	R – 0	R – 50	R – 100
RCA (%)	0	50	100
Cement (kg/m^3)	410	410	410
NFA (kg/m^3)	789	789	789
NCA (kg/m^3)	1034	517	0
RCA (kg/m^3)	0	517	1034
Water (kg/m^3)	186	186	186
w/c ratio	0.45	0.45	0.45
Mixing	1,2,3	1,2,3	1,2,3

1 – NMA; 2 – TSMA; 3 – SEMA

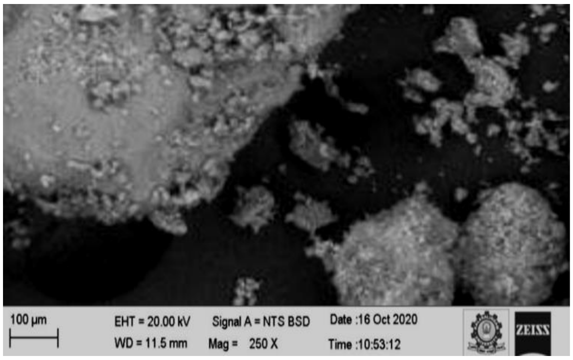
3 Results

3.1 *Material properties*

From the Table 1, it is found that only water absorption of the RCA was not within the BIS limits and it is better compared to NCA. This is due to the lower quality of the RCA used in the study. In comparison with NCA, a 7% decrease in the specific gravity and 85.8% increase in the water absorption of RCA were observed. This is due to the micro-cracks developed on



(a) XRD



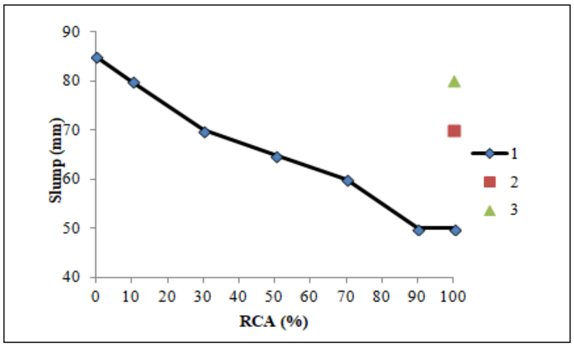
(b) SEM

Figure 3: XRD and SEM images of RCA.

the adhered surface of RCA [15], [33]. Figure 3 shows the XRD patterns and SEM images of the RCA used in the study. From the XRD patterns, it is observed that, the highest peak was found to be calcite and quartz. The Bragg's angle of quartz and calcite was 26.4° and 29.1°. The peak of quartz indicated the crystalline nature to be favourable in the formation of C-S-H and C-A-S-H gel. The highest peak of calcite was due to the adherence of cement particles on the surface of RCA. From the SEM images, adhered mortar on the RCA was visible through the loose irregular cementitious particles. The loose irregular particles smeared on the surface prossessed micro-cracks that increased the porosity of the RCA.

3.2 *Workability*

Figure 4 shows the workability of the concrete mixtures prepared by NMA, TSMA, and SEMA. From the results, it is observed that the workability of the RAC decreased with an increase in the percentage of RCA [22], [25]. This was due to the increased porosity of the RCA that absorbed more water during concrete mixing. Also, the RCA possessed adhered mortar on its surface that caused high internal friction inside the concrete and thus reduced the workability of the concrete. However, the workability of the concrete increased with an increase in the RCA for TSMA and SEMA approaches. In TSMA and SEMA, the matrix filled the micro-cracks and pores on the RCA surface and thus leaving the mixing water for proper hydration [18], [22].



1 – NMA; 2 – TSMA; 3 – SEMA

Figure 4: Workability of concrete mixtures.

3.3 *Mechanical properties*

3.3.1 Compressive strength

The compressive strength of the hardened concrete prepared by NMA, TSMA, and SEMA at 7, 28, and 90 days is shown in the Figure 5. Each result in the graph represents the average value obtained from testing three cube samples of 150 mm. The compressive strength of NAC was achieved with the characteristic target strength (39.22 MPa) at 28 days. However, for all mixtures, it is observed that as the RCA increases, the compressive strength of the RAC increases to 50% replacement levels and beyond which it decreased. For instance, by NMA, the strength of the R–50 was increased by 6.08% whereas the strength of R–100 was decreased 9.86% at 28 days. Such a decrease in the strength of RAC was attributed to the adherence of mortar around the natural aggregate in the RCA [11], [21]. Upon curing for 90 days, the strength of the R–50 was increased by 10.81%, and the strength of the R–100 was decreased by 7.4%. The improvement in the strength was mainly due to the densification of

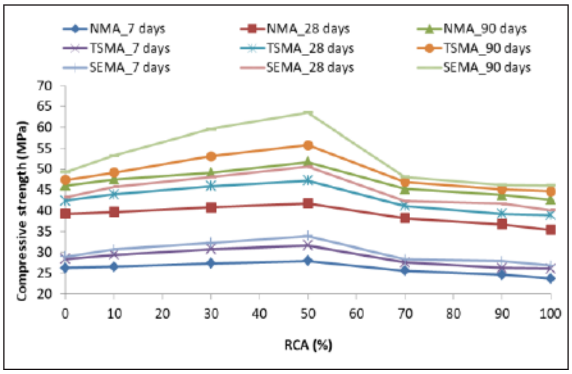


Figure 5: Compressive strength.

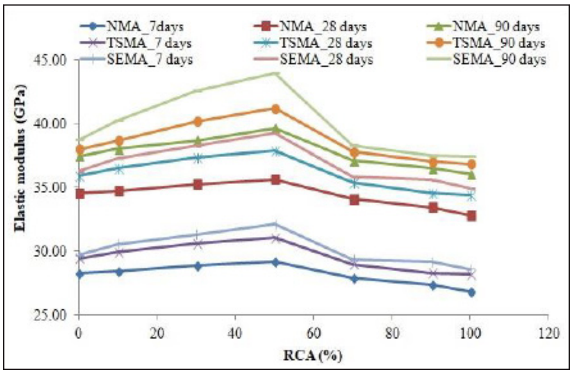


Figure 6: Elastic modulus observed in this work.

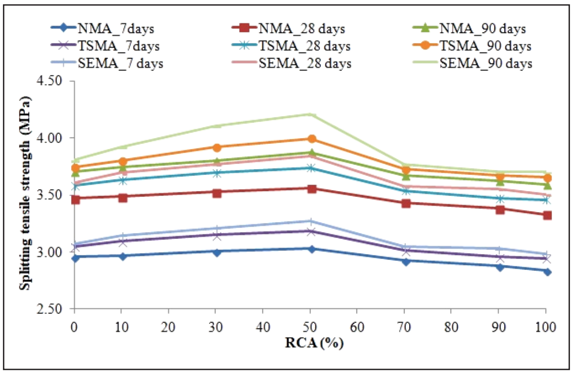
micro-structure of the RAC and thus improving the strength of the RAC. It can also be observed that the strength of the mixtures prepared by TSMA and SEMA was higher compared to NMA at all replacement levels and curing ages [17], [19], [20], [25], [34]. With TSMA, the strength of R–50 was increased by 10.26% at 28 days and 15% at 90 days in comparison with R–0 at 28 days, whereas the strength of R–100 was reduced by 8.21% and 5.88% at 90 days respectively. Similarly with SEMA, the strength of R–50 was increased by 14.57% at 28 days and 22.40% at 90 days in comparison with R–0 at 28 days, whereas the strength of R–100 was reduced by 7.19% and 6.64% at 90 days respectively. The surface modifications to the RCA through TSMA and SEMA develop non-porous stiff matrix that coats the surface of RCA and thus strengthens the ITZ of the RAC.

3.3.2 Elastic modulus

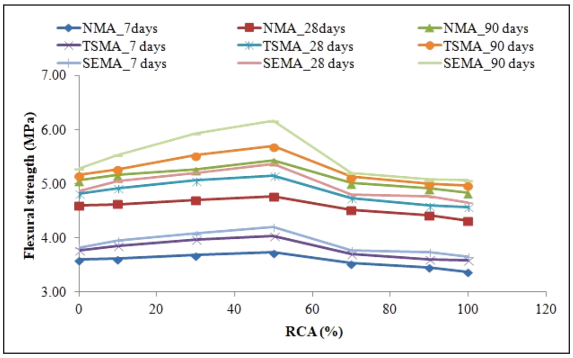
The elastic modulus of the hardened concrete prepared by NMA, TSMA, and SEMA at 7, 28, and 90 days was shown in the Figure 6. Similar to the results of compressive strength, with a lower percent of RCA, the elastic modulus of RAC was higher than with the higher percent of RCA [11], [22], [35]. With NMA, the elastic modulus of R–50 was increased by 3.08% at 28 days and 5.56% at 90 days, whereas the elastic modulus of R–100 was decreased by 5.06% at 28 days and 3.76% at 90 days. The elastic modulus of the RAC was highly dependent on the stiffness, density, and replacement of RCA [36], [37]. So, a decrease in the elastic modulus was observed with higher replacement, lower density, and inferior quality of RCA. The adhered mortar on the RCA reduces the stiffness (i.e., bonding between RCA and new mortar) of the concrete and thus reducing the elastic modulus of the RAC. With TSMA, the elastic modulus of R–50 was increased by 5.27% at 28 days and 7.81% at 90 days, whereas the elastic modulus of R–100 was decreased by 4.20% at 28 days and 2.97% at 90 days. Similarly with SEMA, the elastic modulus of R–50 was increased by 7.57% at 28 days and 11.90% at 90 days, whereas the elastic modulus of R–100 was decreased by 3.66% at 28 days and 2.47% at 90 days. It was observed that TSMA and SEMA approaches increase the elastic modulus of the RAC which is due to the improvement in the stiffness bonding of RCA with the new mortar [19], [20]. The impermeable mortar covering the RCA increased the stiffness of the RAC and thus increased the elastic modulus of the concrete.

3.3.3 Splitting tensile strength and flexural strength

The splitting tensile strength and flexural strength of the hardened concrete prepared by NMA, TSMA, and SEMA at 7, 28, and 90 days were shown in the Figure 7. From the results, it can be observed that both tensile strength and flexural strength of RAC decreases with an increase in the RCA. This may be attributed to the weakness of the ITZ due to the presence of adhered [38]. With TSMA and SEMA approaches, the split tensile strength and flexural strength were further increased compared to NMA at all curing ages. The TSMA and SEMA approach techniques wrapped the surface of RCA preventing the excess absorption of mixing water by the RCA and thus enhanced the strength of the concrete [22], [23].



(a) Splitting tensile strength



(b) Flexural strength

Figure 7: Splitting tensile strength and flexural strength.

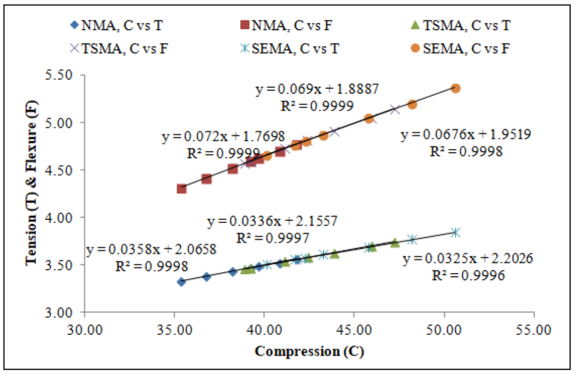


Figure 8: Relationship among mechanical properties.

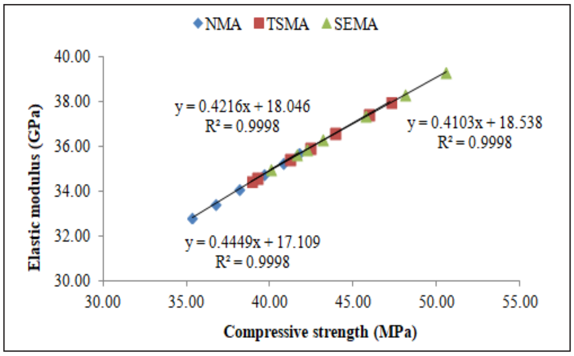


Figure 9: Relationship between compressive strength and elastic modulus.

4 Discussion

The investigation on the influence of NMA, TSMA, and SEMA approaches on the fresh and mechanical properties of RAC with different percentages of RCA was performed. All the physical properties of the collected RCA were poor compared to NCA with higher water absorption. Such an increase is due to the inferior quality of the collected RCA [39]. So, the RCA was pre-saturated before its use in the concrete to achieve SSD. The optimal level of replacement of RCA was obtained to be 50%, and beyond that affected affects the mechanical properties of the concrete. For NMA mixtures, an increase in RCA% decreased the fresh and mechanical properties of the RAC. This is due to the higher porosity resulting from the presence of adhered mortar surrounding the natural aggregates in RCA. Also, it was observed that increased decreased decreases the strength reduction of the RAC. From the results, it could be observed that the strength of R–100 was decreased by 9.86% at 28 days and only 7% at 90 days. This was due to the densification of the microstructure of the RAC, and as the curing period increased, the pore connectivity reduced. This promoted effective hydration and thus increased the mechanical properties of the RAC. Figure 8 shows the correlative analysis between the compressive strength, split tensile strength, and flexural strength of concrete mixtures prepared by NMA, TSMA and SEMA approaches at 28 days. In all cases, high regressive factor beyond 0.996 was achieved that indicates the highest level of correlation among the measured parameters. Also, it was observed that irrespective of replacement levels, the compressive strength of TSMA and SEMA increased in linear with NMA but the percentage of incremental strength varies.

Figure 9 shows the relationship between compressive strength and elastic modulus of RAC mixtures prepared by NMA, TSMA, and SEMA. It is observed that a high correlation of 0.999 was achieved in the case of all mixtures. The correlation study infered the strength of the concrete is directly dependent on the elastic modulus of the RAC. The elastic modulus of the RAC depended on the stiffness of the RCA with the matrix. Higher porosity due to the presence of adhered mortar reduces the stiffness of the RCA. So, the elastic modulus of RAC was reduced and thus reduced the compressive strength of the RAC.

As we know, ITZ determines the strength of the concrete, so increase in the replacement of RCA weakens the ITZ of the RAC [17]. NAC possesses only one ITZ between the NCA and the mortar whereas the RAC possesses two ITZ with one between NCA and old mortar and the second between RCA and new mortar [19]. The latter ITZ is the weakest link in RAC due to the higher porosity of RCA [23], [25]. So, the concrete mixtures were prepared with two mixing approaches, such as TSMA and SEMA to coat the surface of porous RCA with impermeable mortar and to strengthen the ITZ of the RAC. In TSMA, the water was poured in two stages with first developing a stiff matrix and that seals on the surface of RCA and the second completes the process of mixing with sufficient water for the process of hydration. In SEMA, nearly 75% of water was used during the first stage of the mix of cement and NFA, developing a stiff mortar that wraps the RCA added during the second stage of mixing. Also, only remaining 25% of water will be available to the RCA and thus leaving minimal water to be absorbed.

Concerning to structural applications, the poor quality of RCA reduced its structural application in the raw form. It is therefore used as filling materials, base course layer of roads, foundations etc. However, the RAC mixtures prepared with pre-saturated RCA through TSMA and SEMA tend to exhibit good strength that might enhance its structural applications in the construction of partition walls, beams, columns etc.

5 Conclusions

The mechanical properties of the RAC mixtures prepared by NMA, TSMA, and SEMA with different percentages of RCA have been presented. From the experimental results obtained, the following conclusions are described:

1. The water absorption of RCA was higher compared to NCA due to its higher porosity as a result of the adherence of mortar.
2. An increased in the replacement of RCA increased the slump of the concrete, however, the TSMA and SEMA mixtures showed lesser slump value even with 100% of RCA.
3. The optimal replacement of RCA in the concrete mixtures was obtained to be 50% with the strength of 41.76 MPa at 28 days and 51.67 MPa at 56 days. However, the 100% utilization of RCA decreased the strength of the concrete by 9.86% at 28 days.
4. The compressive strength of R–50 mixtures prepared by TSMA and SEMA was increased by 10.26% and 14.57% at 28 days and 15% and 22.4% at 56 days. The enhancement in the compressive strength of the RAC by TSMA and SEMA was attributed to the coating of RCA with impermeable mortar.
5. The split tensile strength of R–50 mixtures prepared by TSMA and SEMA was increased by 6.80% and 9.44% at 28 days and 10.06% and 15.12% at 56 days.
6. The elastic modulus of R–50 mixtures prepared by TSMA and SEMA was increased by 5.26% and 7.56% at 28 days and the elastic modulus of R – 100 mixtures prepared by TSMA and SEMA was decreased by 4.20% and 3.68% at 28 days.
7. A high level of correlation was achieved between various parameters such as compression, tension, flexure and elastic modulus of the concrete mixtures prepared by NMA, TSMA and SEMA approaches at 28 days.

The experimental findings suggested that the use of 50% of RCA is feasible to manufacture RAC with better properties compared to NAC. Also, the replacement of the conventional mixing approach (NMA) with advanced mixing approaches (TSMA) would yield better mechanical properties to the RAC. These findings indicated that RAC prepared by either TSMA or SEMA can be a suitable alternative to NAC in structural applications, and thus surmounting the effect of scarcity of aggregates in the construction.

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