Performance of Construction and Demolition Waste as Recycled Aggregates in Concrete – A Review

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Abstract

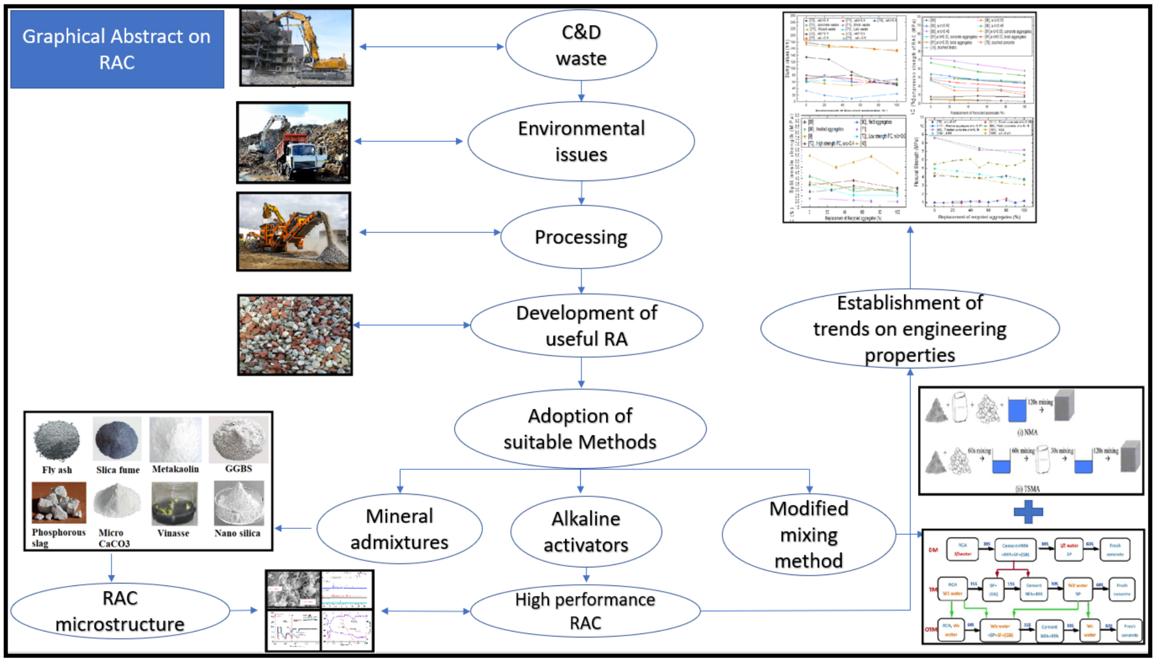
This article presents a structured and comprehensive review of the existing literature on physical, chemical, microstructure, and durability properties of recycled aggregate concrete (RAC). The engineering properties of concrete made from such recycled aggregates are critically analyzed by focusing mainly on the fresh and hardened states along with several characterization techniques such as SEM, EDX, XRD, FTIR and TG-DTA. Also, creep and shrinkage, the microstructure and durability of recycled aggregate concrete (RAC) were studied and evaluated critically. In addition, improvement techniques in its microstructure are also explored with efficient mixing approaches for the development of geopolymer recycled aggregate concrete. Furthermore, techniques to enhance the mechanical characteristics and long-term performance of recycled aggregate are distilled and divided into three categories: (1) lowering the porosity of recycled aggregate, (2) lowering the layer of old mortar on the surface of recycled aggregate, and (3) enhancing the property without changing the recycled aggregate. It is evident from the thorough examination that recycled aggregates can be used in concrete up to a certain amount. For the creation of sustainable and high-performance concrete, it is also necessary to incorporate mineral admixtures of micron, sub-micron, and nano size to address the drawbacks of recycled aggregates.

Keywords: Construction, demolition, recycled materials, concrete structures, microstructure, durability, sustainability.

Highlights

1. Detailed discussion is made by addition of mineral admixture, modified mixing approach and alkali activators for the improvement of RAC.
2. Detailed microstructure studies on RAC is studied and represented through several characterization techniques such as SEM, EDX, XRD, FTIR and TG-DTA.
3. Identification and establishment of different trends based on engineering properties and long-term performance of RAC.
4. Latest developments on RAC is included alongside the impact of carbon di-oxide curing, sea sand and sea water developed RAC and fiber reinforcement techniques etc.

GRAPHICAL ABSTRACT



LIST OF ABBREVIATIONS

RAC-Recycled Aggregate concrete

RA- Recycled Aggregate

FRA- Fine recycled aggregate

RCA- Recycled concrete aggregate

RBA- Recycled brick aggregate

NSC- Normal strength concrete

HSC- High strength concrete

GGBS- Ground granulated blast furnace slag

C&D – Construction and demolition

MSW- Municipal solid waste

RFA- Recycled fine aggregate

NMA- Normal mixing approach

TSMA- Two stage mixing approach

GRAC- Geopolymer Recycled Aggregate concrete

OPC-RAC – Ordinary Portland cement recycled aggregate concrete

C-S-H – Calcium silicate hydrate

NCA- Natural coarse aggregate

NAC- Natural aggregate concrete

FA- Fly Ash

SF- Silica fume

MK- Metakaolin

PHS- Phosphorous slag

PC- Parent concrete

MSA- Mean size of aggregate

ITZ- Interfacial transition zone

LIST OF CAPTIONS

1. Introduction

The debris developed during the reformation, constructional activities and the demolition practices of various structural elements and pavements gives rise to the construction and demolition (C&D) wastes (Wu et al., 2014). The demolition waste is made up of building materials like wall coverings, paint, paper, aggregate, wood, concrete, fasteners, and adhesives, whereas construction waste is a heterogeneous building material that comes from the construction activities with potential sources at design, procurement, handling, operation, and residual sources (Devi et al., 2020). The parts of C&D remnants are often divided into two groups: major and minor. The latter incorporates tiles, paints, glass, electrical fixtures, and panels, while the former is made of plastic, stone, steel, bricks, and wood (Jain, 2021). As per study conducted by technology information, forecasting and assessment council (TIFAC), the contractors play a major role for the C&D waste management. Both major and minor categories of materials that are salvaged during demolition are sold on the market at a reduced price compared to the cost of new materials, and those that cannot be reused are disposed of in landfills. While some municipal corporations strive to minimise C&D debris to extend the useful life of dump sites, while others admit it in their landfills (TIFAC 2000).

Three billion tonnes of waste are produced annually by the quick construction and demolition operations around the world, and this amount is only increasing (Akhtar & Sarmah, 2018). The majority of C&D waste is non-hazardous and inert, but it may also contain materials that are harmful to the environment, such as asbestos, organic pollutants, and heavy metals, particularly zinc (Duan & Li, 2016). Heavy metal leaching makes C&D waste more likely to pollute land and water (Zheng et al., 2017). Another difficulty with C&D waste is that it creates disposal issues, leading to the conversion of productive lands into dump sites, which in turn raises the cost of dumping at landfills (Bravo et al., 2015; Devi et al., 2020; Ma et al., 2020). In addition to these issues, C&D waste disposal causes landslides (Zheng et al., 2017; Trivedi et al., 2020). The need to recycle C&D waste on a wide scale is essential due to environmental concerns (Bui et al., 2017). It is stated that recycling C&D waste helps reduce the need for new resources, preserve land for future urbanization, protect the environment and ecology, reduce the costs associated with transportation and energy production, and prevent waste from ending up in landfills (Yuan & Shen, 2011).

The ecological footprint left by the building industry can be reduced by using C&D debris in place of natural aggregates (Silva et al., 2015). According to a study (Bui et al., 2017), this substitution can help save up to 60% of natural aggregates. Additionally, recycled aggregates (RA) minimise carbon dioxide emissions by 28% when compared to natural aggregates (Tam et al., 2018). Reusing C&D waste can assist the construction sector meet its rising need for aggregate due to a lack of natural resources (Kong et al., 2010). The C&D waste produced around the world is depicted in Figure 1 below (Aleksanin, 2019; Bester et al., 2000; Elchalakani & Elgaali, 2012; Environment and Climate Change Canada, 2000; Environmental Protection Agency., 2020; Huang et al., 2018; Jain et al., 2020; Kartam et al., 2004; Kim, 2021; López de Munain et al., 2021; Mah et al., 2016; Menegaki & Damigos, 2018; Nunes & Mahler, 2020; Ulubeyli et al., 2017; Villoria Sáez & Osmani, 2019; Zhao et al., 2021). It can be observed that China and India generate most of the C&D waste worldwide followed by the USA. On the contrary, most of the European nations are generating least number of C&D wastes except France, and Germany and the UK with African countries generating a moderate number of C&D debris (Trivedi et al., 2023).

According to the Central Pollution Control Board (CPCB), India produces an estimated 23.75 MT of C&D debris annually and that number is anticipated to double (CPCB, 2017). The Building Materials and Technology Promotion Council (BMTPC) has acknowledged that a shortage of traditional construction resources exists in India because the necessity for building materials for the years 2021–22 is expected to be close to 380 MT for cement and roughly 400 MT for aggregates. (BMTPC, 2018).

Due to the considerable volume of C&D waste generated worldwide, managing the waste has become a serious issue (Yuan & Shen, 2011). Every continent has its own methods for managing C&D residues; as an example, in Europe, there are strategies in place for managing site waste, items that can be recycled, and debris generated during building deconstruction is sorted and processed. When it comes to recycling C&D waste, mobile crushers and plasma membrane systems are potential equipment in some southern Asian regions (Hoang et al., 2020), while landfills and recycling are the current C&D waste supervision practises in Vietnam (Lockrey et al., 2016). Quality assurance schemes are currently in use (Gálvez-Martos et al., 2018); the circular economy technique, incentives, and market are present in the USA (Aslam et al. The 3R (reduce, reuse/recycle, and discard) strategy is used in Canada to handle C&D waste. (Yeheyis et al., 2013), the

Australian government is also promoting C&D debris management with emphasis on the 3R principle and circular economy (Zhao et al., 2021). Following the processing of the C&D waste, recycled aggregates are obtained. This could be abandoned asphalt pavement, tiles, brick masonry, or rejected concrete. Such type of concrete is known as recycled aggregate concrete (Trivedi et al., 2023; Verian et al., 2018). According to Safiuddin et al. (2013), the use of recycled aggregates from multiple sources helps preserve naturally occurring resources, a healthy ecology by lowering carbon dioxide emissions, and the issue of waste disposal all at once. In addition, this may lower down the soil and water table pollution that is prevalent due to huge pile ups of C&D debris.

This review is prepared using a thorough analysis of the literature that focuses on the microstructure of RAC, its characteristics, and its application potential. In addition, several research articles based on the newest advancements in RAC technology and the use of recycled aggregates as structural reinforcement in concrete have been gathered. The compilation effort assisted in determining the general cap for the incorporation of such recycled aggregates from the C&D sector in concrete for satisfying the regulations for sustainable design while maintaining the practicality of concrete, so encouraging the conservation of natural resources.

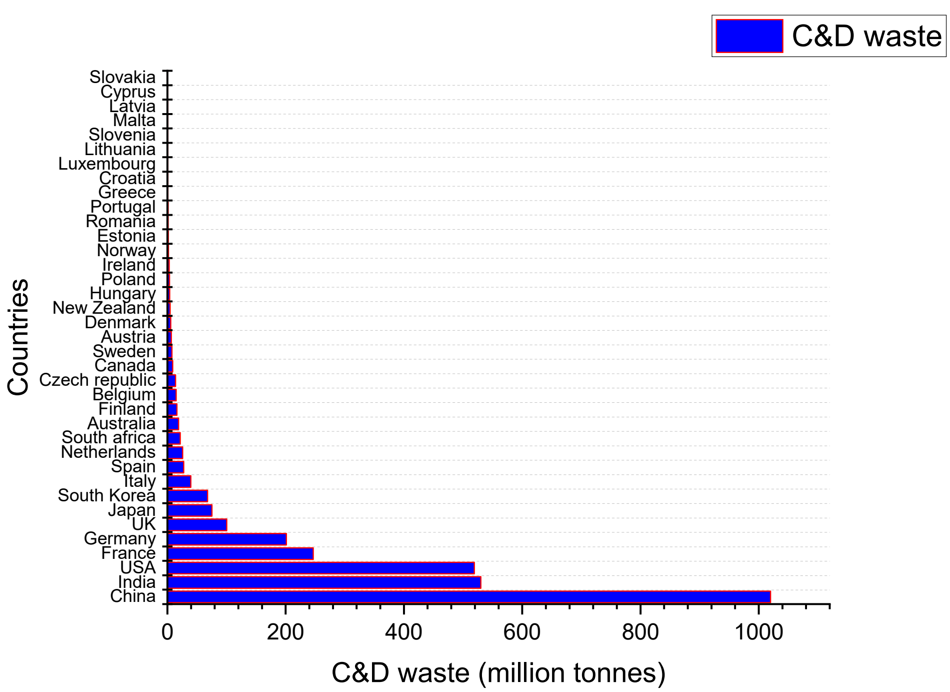


Figure 1 C&D waste statistics (Aleksanin, 2019; Bester et al., 2000; Elchalakani & Elgaali, 2012; Environment and Climate Change Canada, 2000; Environmental Protection Agency., 2020; Huang et al., 2018; Jain et al., 2020; Kartam et al., 2004; Kim, 2021; López de Munain et al., 2021; Mah et al., 2016; Menegaki & Damigos, 2018; Nunes & Mahler, 2020; Ulubeyli et al., 2017; Villoria Sáez & Osmani, 2019; Zhao et al., 2021)

2. Research implication and novelty

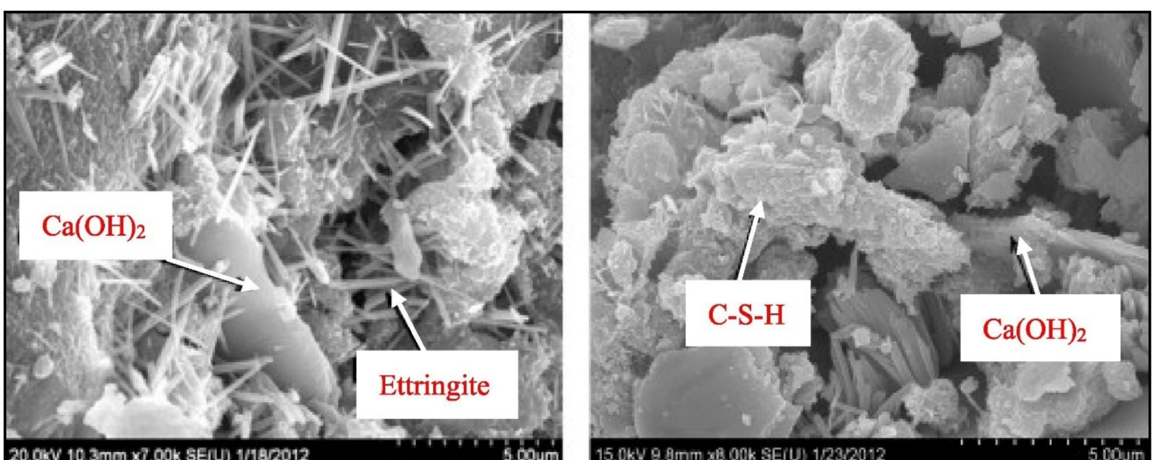
This state-of-the-art review gives information to the aggregate manufacturers, concrete producers, contractors, practitioners, and researchers about the effective management of C&D waste for their sustainable incorporation in concrete applications through adoption of latest developments such as modified mix design, carbon curing and various fiber reinforcement techniques. For a comprehensive understanding on RA and RAC, a detailed review is done combining all the vital researches from 2000-2024, alongside latest trends have been established based on addition of fillers, mineral admixture etc. Furthermore, the microstructural characterisation techniques have been thoroughly covered based on the adoption of novel technologies such as of biomineralization, nano SCMs, pressurised carbonation, vinasse and graphene oxide induced RAC mixes. Additionally, this work demonstrates that challenges in determining and characterising an appropriate type and amount of binder fractions and suitable mixing techniques that can potentially be engulfed in the sustainable production of RAC. Furthermore, this investigation validates the effectiveness of incorporating diverse size additives that are blended appropriately to eliminate the permeable pores, that in turn significantly improves the quality of RA, making it suitable to adopt in concrete applications.

3. Microstructure of recycled aggregate concrete (RAC)

3.1 Surface Morphology

The microstructure of RAC encompasses of two interfacial transition zone, older and newer ITZ (Kong et al., 2010; Li et al., 2012; Tam et al., 2005; Wang et al., 2020) .The density of ITZ in RAC is inferior as compared to NAC (Rao et al., 2019). The thickness of ITZ can range from 5 μm to over 80 μm depending on the moisture content of the RA (Adessina et al., 2019; Evangelista & Guedes, 2019; Xiao et al., 2013). A study observed that a lower water content RA results in an effective ITZ (Evangelista & Guedes, 2019). Figure 2 illustrates the SEM image of a typical RAC specimen (Wang et al., 2020) . It can be observed that the ITZ system of RAC comprise of $Ca(OH)_2$, other hydration products (namely C-S-H gel and ettringite), porosity and unhydrated cement particles. From Figure 3 it can be observed that compared to control concrete, RAC has more interfaces (Rao et al., 2019) . The interface between the original aggregate and the adhered mortar is referred to as the "old ITZ," while the interface between the attached mortar and the "new mortar matrix" is referred to as the "new ITZ."

The ITZ of RA has multiple pores, as observed in Figure 4 (Tam et al., 2009) . This aggregate is prone to significant water absorption because the pores are mostly distributed and formed in the layers of cement pastes close to the aggregate surface. From Figure 5 it can be observed that two stage mixing approach (TSMA) fills up the gaps and fissures of the old paste matrix adhering to the RA, coated it with cement paste, creating a stronger new ITZ (Li et al., 2012) . Figure 6 (a-d) illustrates a few bubbles of trapped air alongside a dense cement matrix in the area. The interfacial transition zone (ITZ) is where the cracks are inclined to develop that is leading to the failure of cement paste-aggregate bonding whereas Figure 7 (a-d) shows the propagation of primary as well as secondary fissures, with majority of cracks formation at the ITZ between cement matrix and aggregates (Thomas et al., 2020). Figure 8 (a-d) shows a similar density of cementitious matrix as observed in previous two cases with the only difference in the fissure size whereas figure 9 (a-d) illustrates the occurrence of primary fissure at ITZ and secondary fissure through cement paste (Thomas et al., 2020) .



(a) Old ITZ (b) New ITZ

Figure 2(a-b). SEM images of ITZs in RAC (Wang et al., 2020) (a) Old ITZ (b) New ITZ

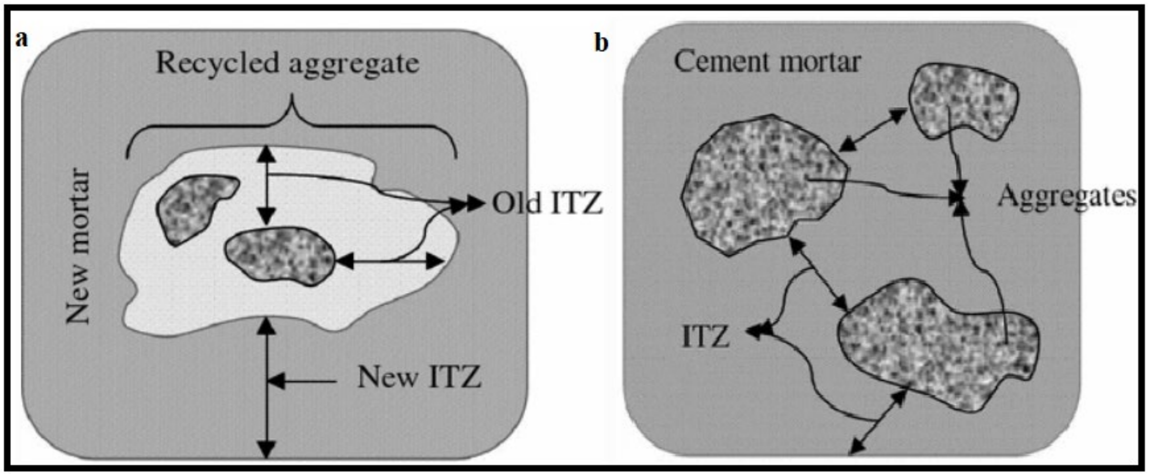


Figure 3(a-b). Images of ITZs (Rao et al., 2019) (a) In RAC (b) In Normal aggregate concrete

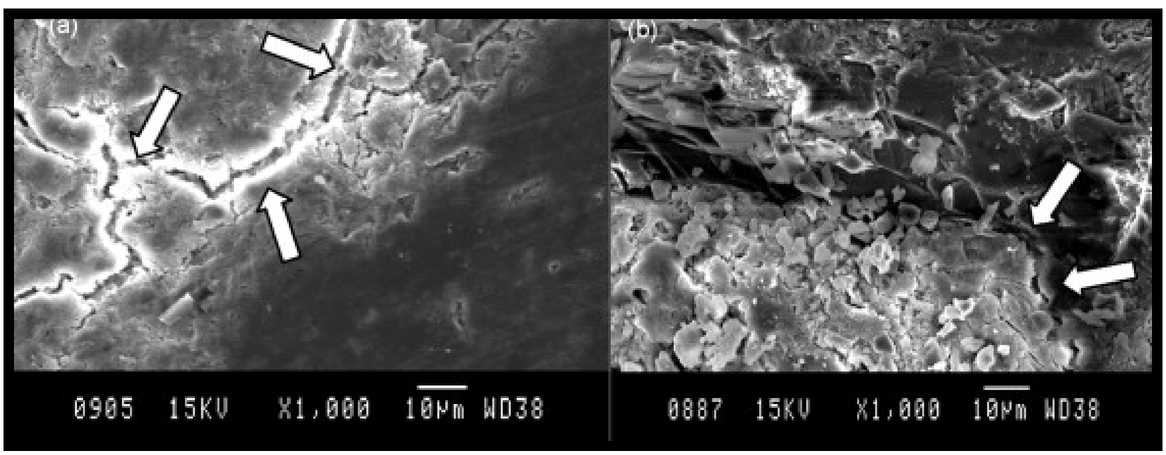


Figure 4(a-b). Cracks in the mortar remains on surface of RA (a) Old ITZ (b) New ITZ (Tam et al., 2009)

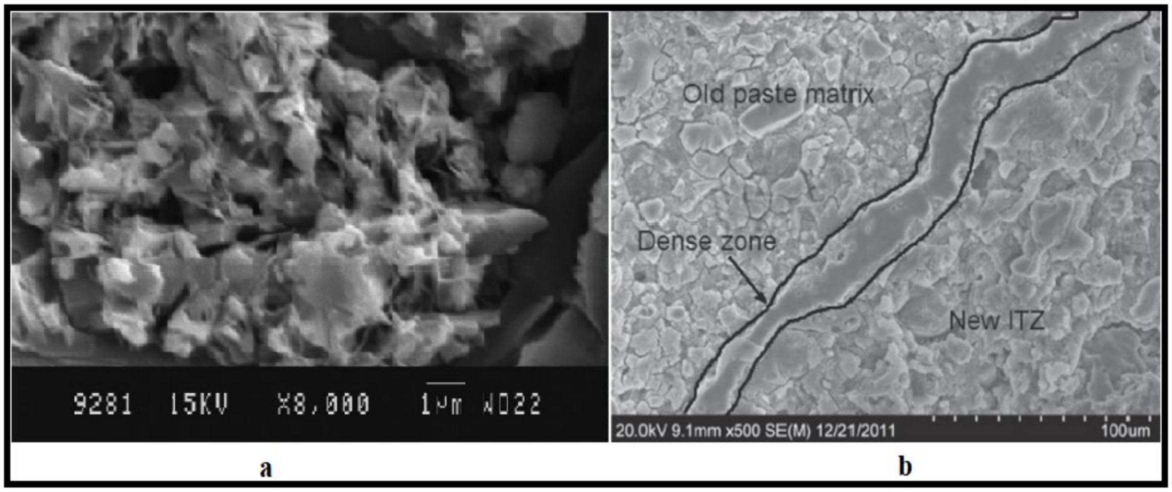


Figure 5 (a-b). SEM images of ITZs in RAC (a) C-S-H post TSMA (Tam et al., 2009); (b) High density (Li et al., 2012)

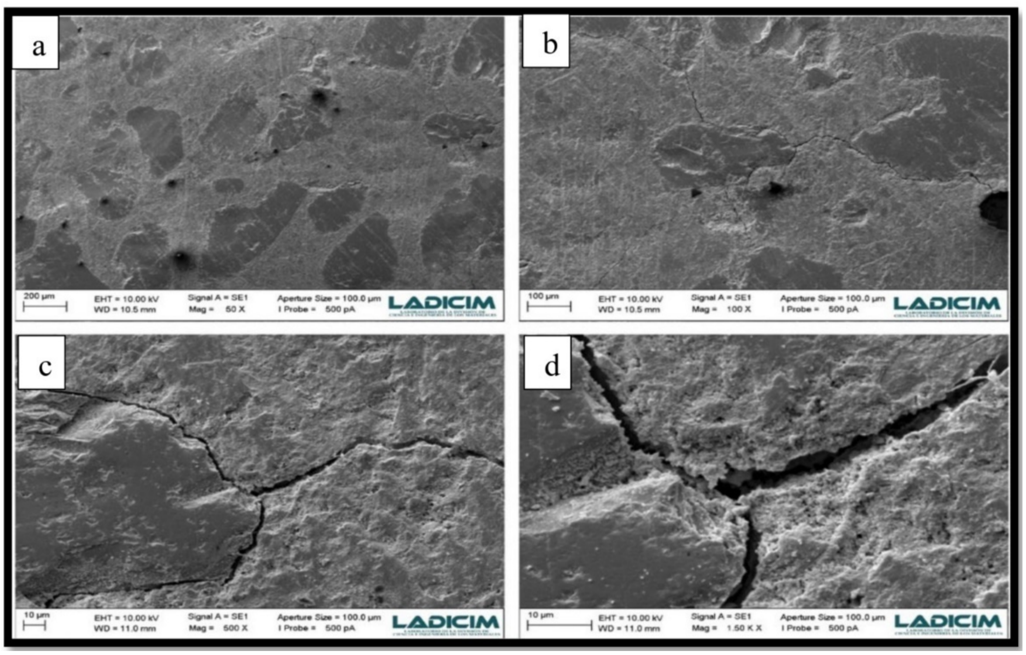


Figure 6 (a-d). SEM images at aggregate-cement interface with no recycling (a) 50x, (b)100x, (c)500x, (d)1500x (Thomas et al., 2020)

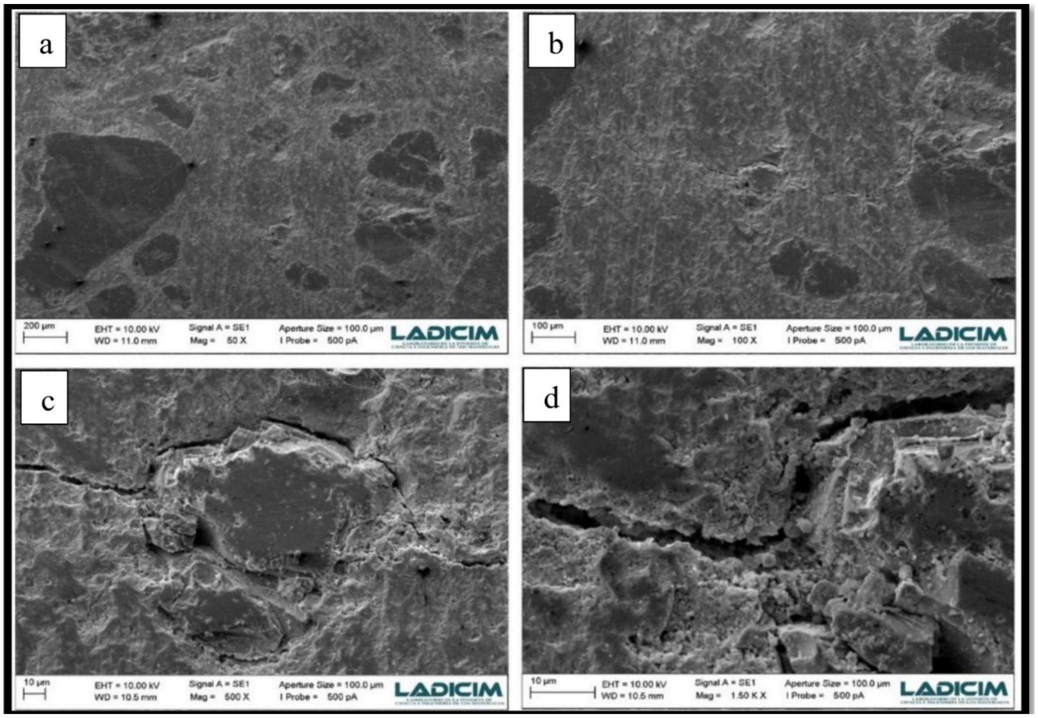


Figure 7 (a-d). Aggregate-cement interface post recycling (a) 50x, (b)100x, (c)500x, (d)1500x (Thomas et al., 2020)

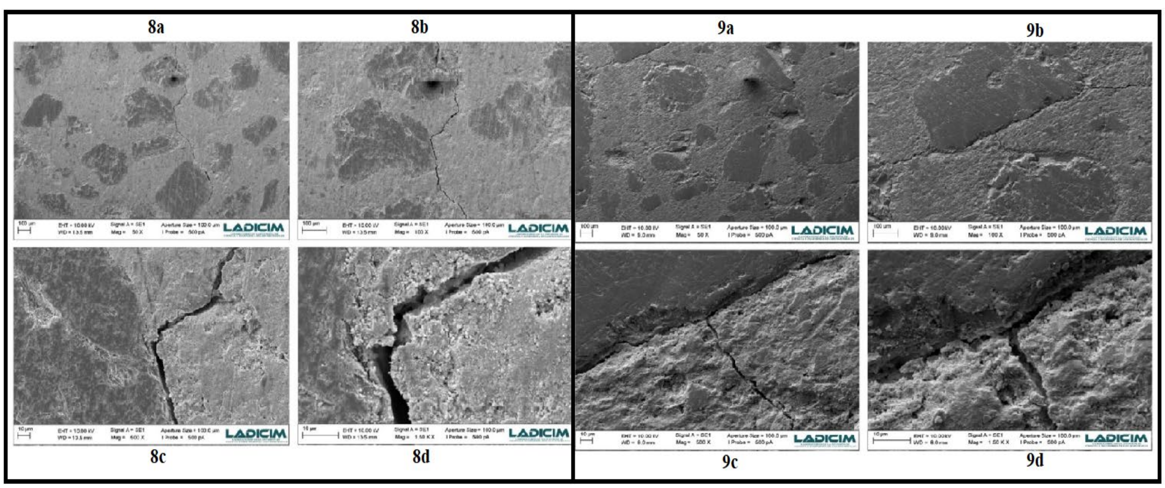


Figure 8 (a-d). SEM at aggregate-cement interface post second recycling, **9 (a-d).** Aggregate-cement interface post third recycling (a) 50x, (b)100x, (c)500x, (d)1500x (Thomas et al., 2020)

3.2 Surface elemental composition

This section represents a diverse elemental composition present in different RA or RAC samples analysed through EDX patterns. According to reports, the Ca/Si ratio for dense concrete often is lower than 2 (Goudar et al., 2019; Snehal et al., 2020). Figure 10 shows that the atomic percentage of Ca/Si for various investigations as compared to the control or untreated aggregate/concrete mix varies significantly. Among these studies, (Bian et al., 2022; Kazemian et al., 2019; Ozbakkaloglu et al., 2018) achieved Ca/Si ratio below 2. Such studies are representing the formation of favourable hydration products that further densified the microstructure.

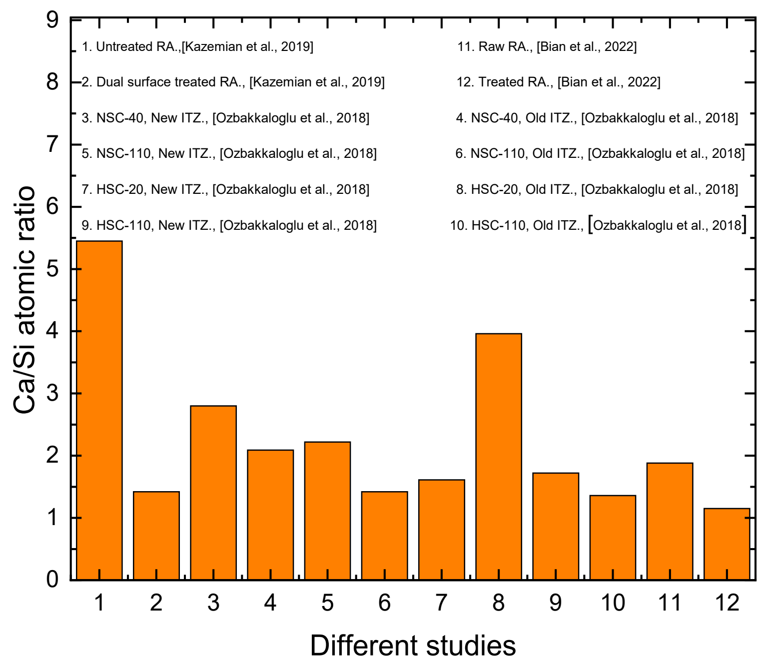
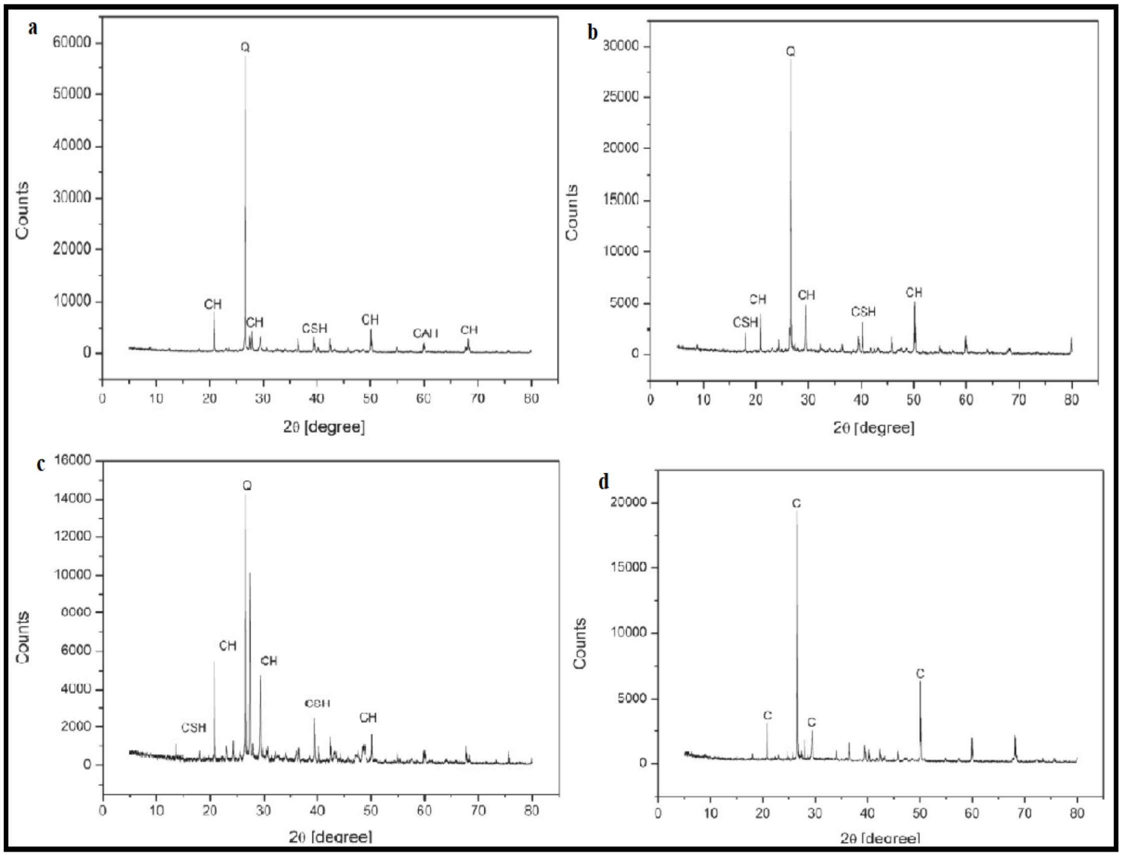


Figure 10. Ca/Si atomic ratio for RAC samples (Bian et al., 2022; Kazemian et al., 2019; Ozbakkaloglu et al., 2018)

3.2 Surface mineralogical composition

For brevity, X-ray diffraction (XRD) pattern of biomineralized RAC mix by (Rais & Khan, 2021) is presented in Figure 11.

Figure 11 shows the XRD analysis of bacteria incorporated RAC mix that further demonstrates the peaks of the calcite crystals. In the XRD patterns of the RAC and control concrete, the peaks of CSH and CH crystals are evident. (Rais & Khan, 2021).


a
b
c
d
Counts
2θ [degree]
Q
CH
CSH
CAH
C

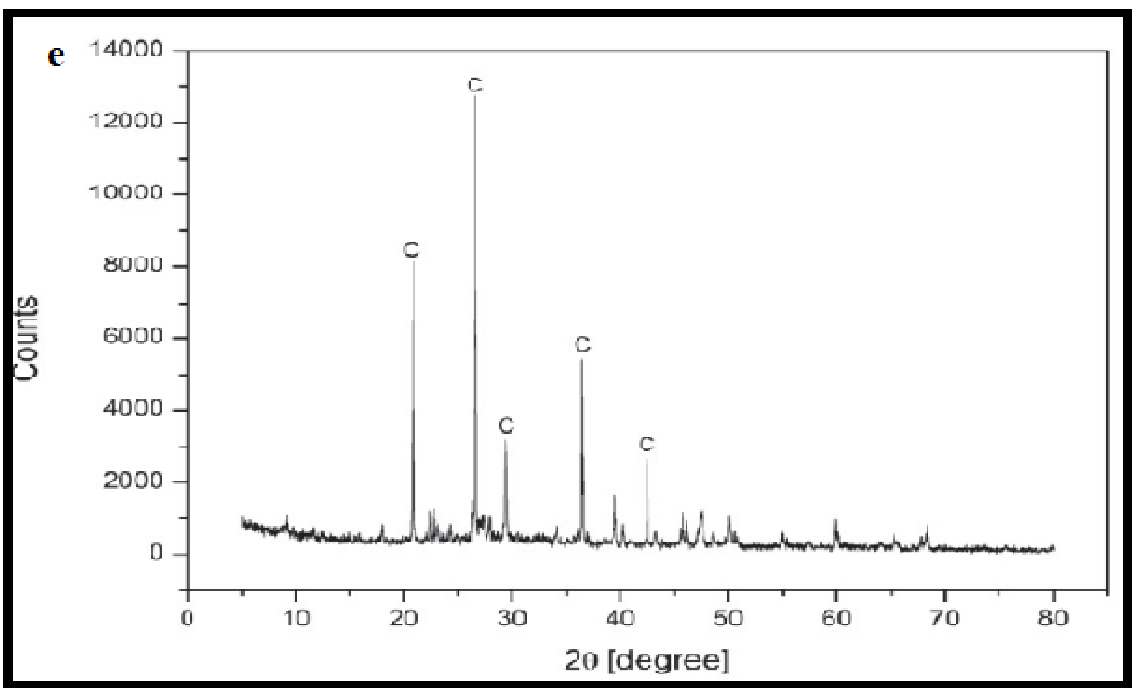
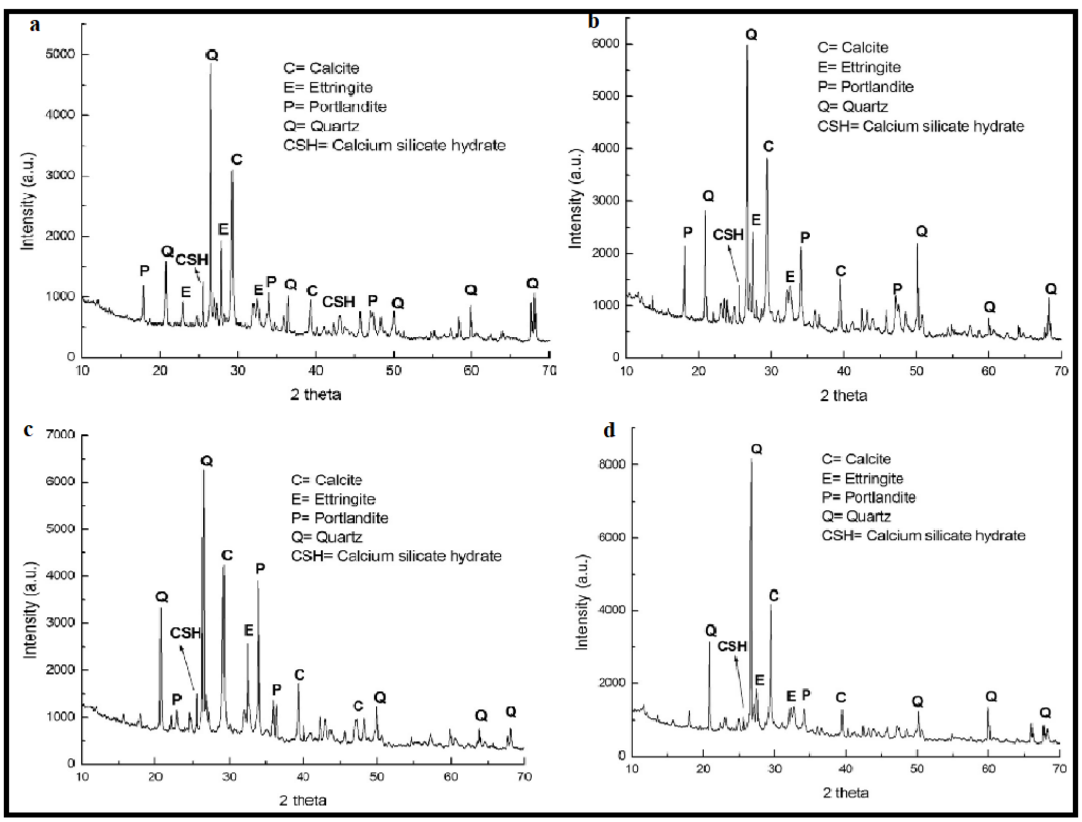

e
Counts
2θ [degree]
C

Figure 11. XRD pattern of (a) control RAC (b) RAC50 (c) RAC100 (d) Bacterial RAC50 (e) Bacterial RAC100 (Rais & Khan, 2021)

CH-calcium hydroxide; CAH-calcium aluminate hydrate; C-calcite; CSH-calcium silicate hydrate

From the XRD peaks shown in Figure 12 (a-g), it can be detected that the durability of these mixes enhanced by the inclusion of GGBS by the rise occurring with the peaks of quartz and calcite (Majhi & Nayak, 2019) . The XRD peaks for the bacterial RAC and raw RA is presented in Figure13. From Figure 13 (a-b), it is evident that the additional calcite is getting formed owing to the bacterial activity in the bacteria incorporated RAC mix (Sahoo et al., 2016) . From Figure 14., it can be detected that the addition of nano silica results in the formation of C-S-H which further makes the microstructure dense and compact by getting into the pores of mortar fraction (Wang et al., 2019).



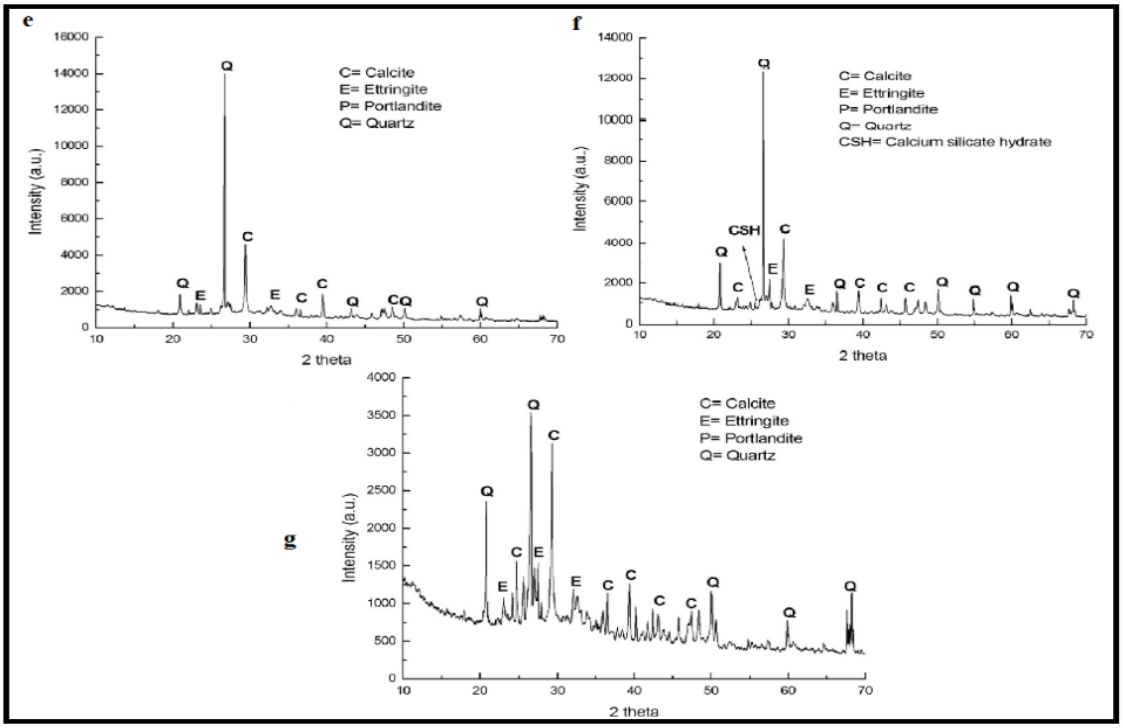


Figure 12. XRD peaks of (a) RG0C0 (b) RG0C50 (c) RG0C100 (d) RG40C50 (e) RG60C50 (f) RG40C100 (g) RG60C100 (Majhi & Nayak, 2019).

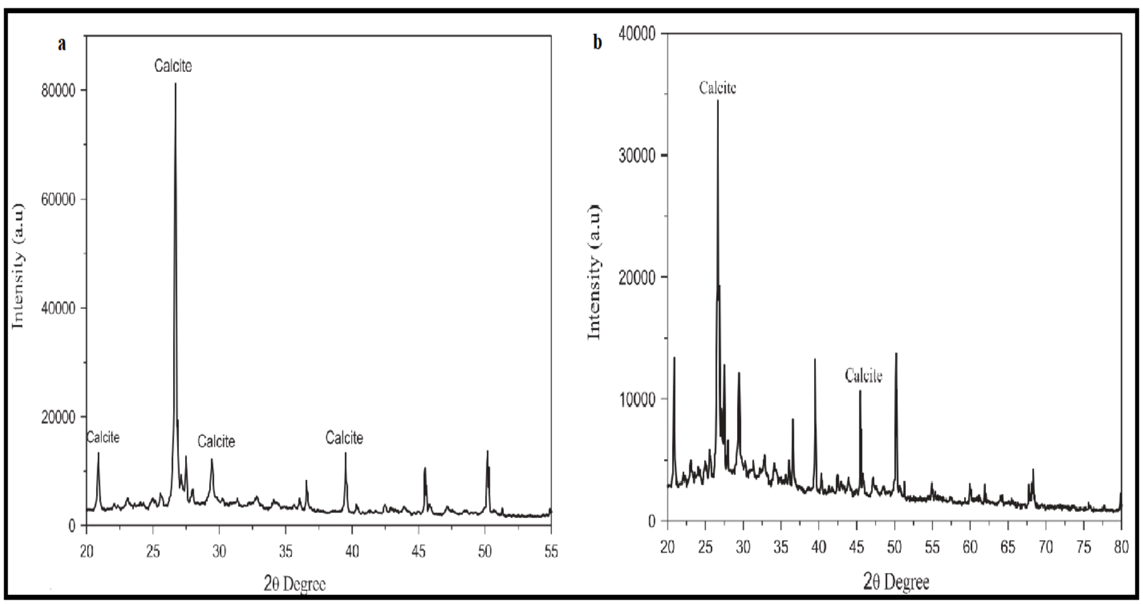


Figure 13. XRD peaks of (a) bacterial RAC and (b) raw RCA (Sahoo et al., 2016)

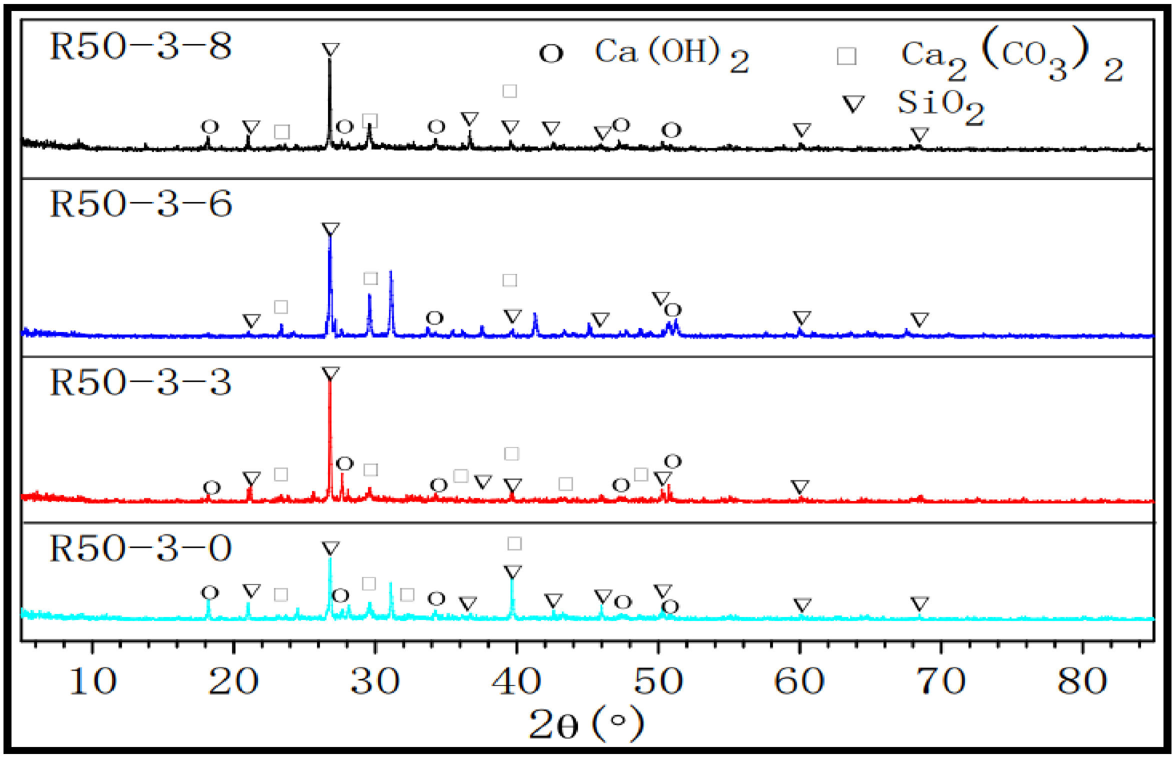


Figure 14. XRD pattern of RAC mixes blended with nano silica and basalt fibre (Wang et al., 2019)

Figure 15 shows that increasing percentage of MK, the peak intensity of portlandite ($Ca(OH)_2$) decreases owing to the reaction between active SiO_2 inside MK and $Ca(OH)_2$ with pozzolana to form C-S-H (Liu et al., 2021).

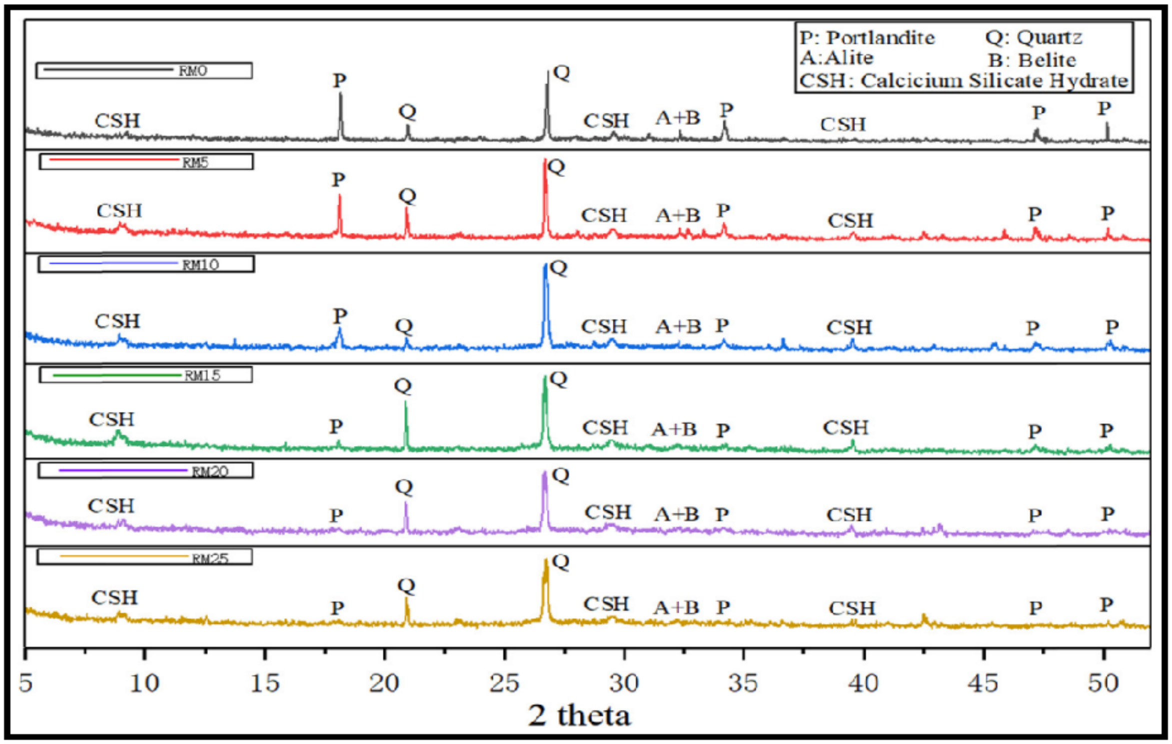


Figure 15. XRD pattern of RAC mixes blended with metakaolin (Liu et al., 2021)

Among these studies shown in Figures 11-15, the bacterial treatment to RA yields highest amount of C-S-H fractions. However, the GGBS incorporated RAC mixes reported an increase in the ettringite fractions in contrast to bacteria induced RAC mix.

3.3 FTIR characterization

When analysing cementitious materials like clinker or hydrated phases in the bulk or surfaces of concrete, Fourier-Transform Infrared (FTIR) spectroscopy shown a number of advantages (Horgnies et al., 2013; Patil et al., 2020; Sharath et al., 2023; Prasanna et al., 2023). Puertas et al. (2012) found the significant band of the distinctive C-S-H peaks shifts between 1100 and 900 cm^{-1} as shown in Table 1.

Figure 16 presents a secondary C-S-H, as shown by alterations in the Si-O-Si transmittance band at 750–800 cm^{-1}. The Si-O-Si transmittance bands were increased when recycled coarse aggregate with used Nano-silica (RCA-UNS) replaced 30% of the natural coarse aggregates (Shahbazpanahi et al., 2021). Figure 17 shows the formation of highly polymerized silica gel after both pressurised carbonation and liquid-solid carbonation (Liu et al., 2021) . In Figure 18, the characteristic peaks are indicating that the calcite and CH were consumed by the reaction between the fine RCA and TA (Wang et al., 2020) . The

FTIR studies revealed that the structure of the vinasse-infused concrete (Figure 19) had not undergone any chemical alterations (Tamashiro et al., 2022).

Table 1 Wavenumbers corresponding to various phases of concrete (FTIR) (Puertas et al., 2012)

Sl.no.	Clinker/hydrated phases	Al-O	O-H	O-H Capillary water	Si-O Asymmetric stretching	Si-O symmetric	Si-O (in plane)	Si-O (out of plane)	S-O $[SO_4]^{2-}$	C-O $[CO_3]^{2-}$	Ref
1	C_3S	-		-	938_s, 883_s, 812_l	-	430_s	522_s	-	-	(Puertas et al., 2012)
2	C_2S	-		-	995_S,900_s,844_S, 810_l, 518_s	-	-	-	-	-	(Puertas et al., 2012)
3	C_3A	898_s, 786_l, 739_s, 704_s, 588_l, 521_s		-	456_s	-	-	-	-	-	(Puertas et al., 2012)
4	C_4AF	Unwell determined bonds									
5	Afwillite	-		3352_l,1660_l	985_m, 963_s, 911_S	860_m, 781_m	450_s	617_l, 520_s 490_s	-	-	(Puertas et al., 2012)
6	C-S-H	-		3356_l,1640_l	1000_s, 950_S	814_m	456_s	667_l, 496_s	-	-	(Puertas et al., 2012)
7	Portlandite (CH)	-	3642_s	-	-	-	-	-	-	-	(Puertas et al., 2012)
8	Ettringite (AFt)	857_l, 537_m	3637_s	3431_m,1680-1640_l	-	-	-	-	1115_s, 617_m	-	(Puertas et al., 2012)
9	Monocarbo aluminate	954_l, 669_l, 535_s	3676_m, 3624_m, 3543_m	3363_m, 3005_m, 1650_l	-	-	-	-	-	1363_s, 873_m	(Puertas et al., 2012)

10	Hemicarbo aluminate	954_{l}, 671_{l}, 537_{s}	3676_{m} 3642_{m}, 3624_{m}, 3544_{m}	3367_{m} 3007_{m} 1645_{l}	-	-	-	-	-	1364_{s}	(Puertas et al., 2012)
11	Monosulfat e (AFm)	579_{m}, 525_{s}	3672_{m}, 3549_{m}	3423s, 1650_{m}	-	-	-	-	1150_{m}	1380_{l}	(Puertas et al., 2012)
12	Hydrogarne t	810_{m}, 537_{s}	3660_{s}	-	-	-	-	-	-	-	(Puertas et al., 2012)
13	Stratlingite	951_{s}, 524_{s}	3669_{l}	3442_{m}, 1652_{l}	1050_{s}, 452_{s}	-	-	-	-	-	(Puertas et al., 2012)
14	Vaterite									713_{l}, 875_{l}, 1423_{s}, 1479l,	(Puertas et al., 2012)

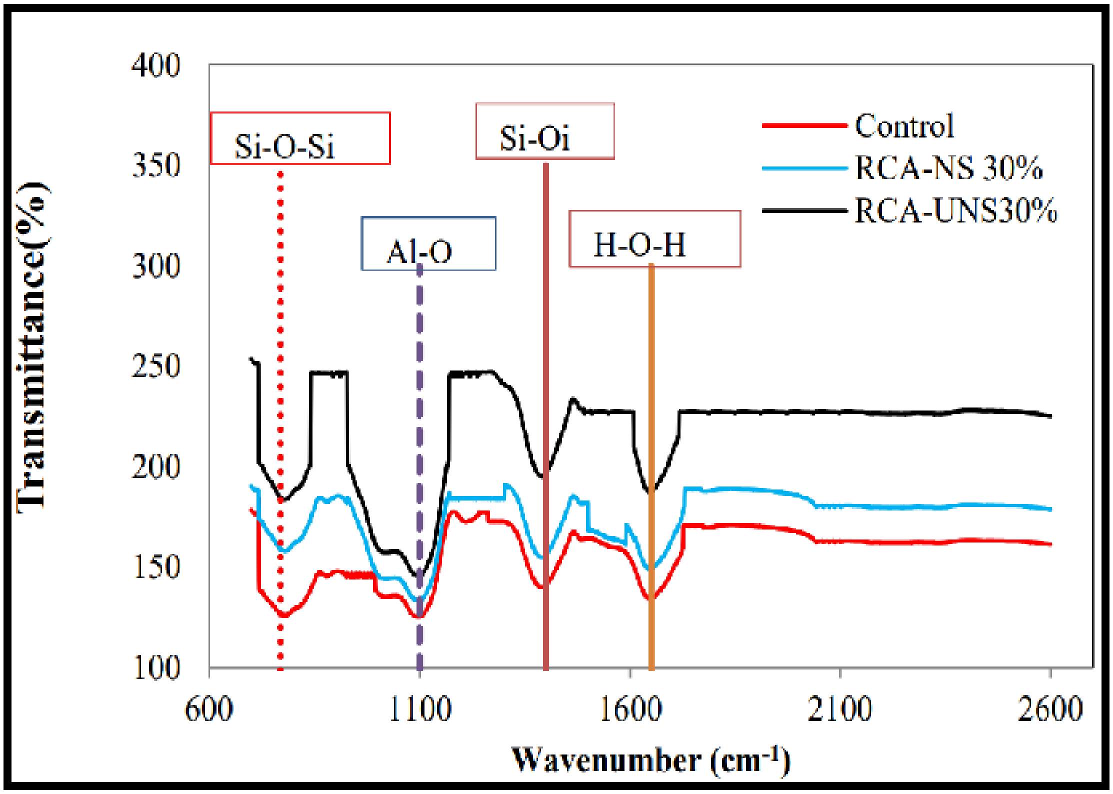


Figure 16. FTIR spectrum representing control, RAC-NS30% and RAC-UNS30% samples at 28 days (Shahbazpanahi et al., 2021)

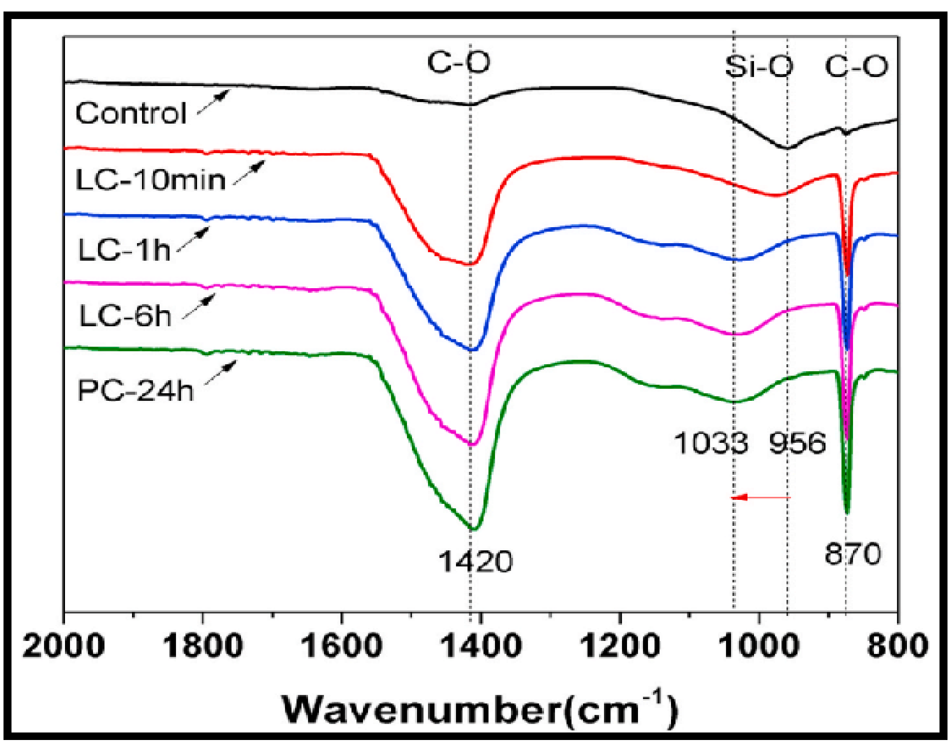


Figure 17. FTIR spectrum of RA post pressurised carbonation (Liu et al., 2021)

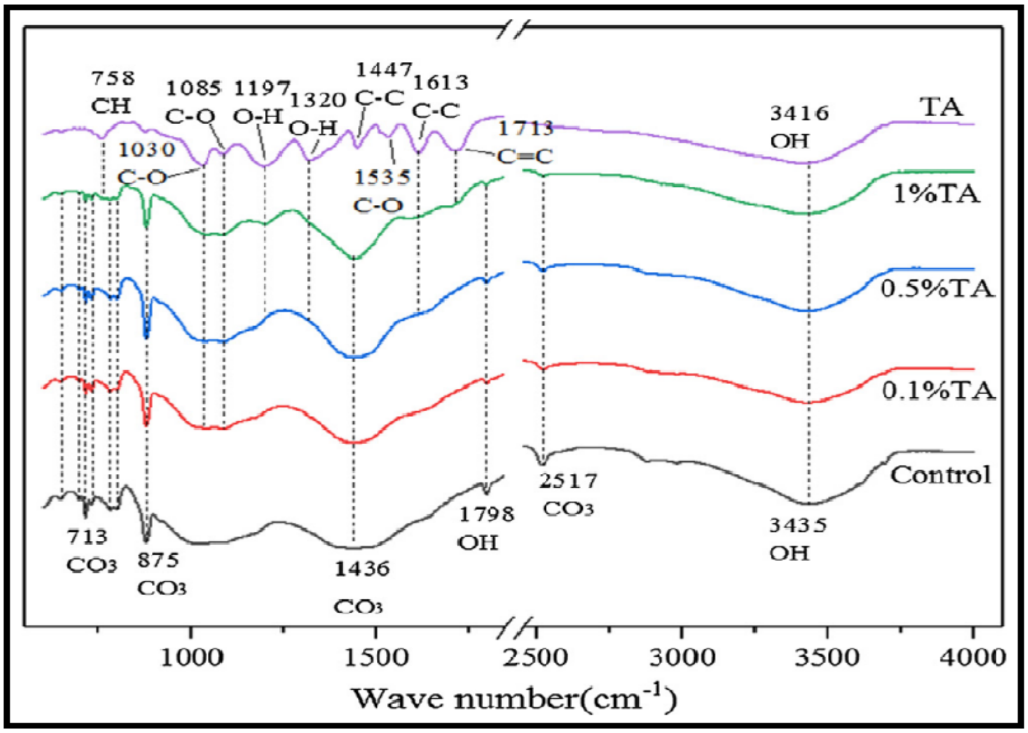


Figure 18. FTIR spectrum of fine RA treated with tannic acid (Wang et al., 2020)

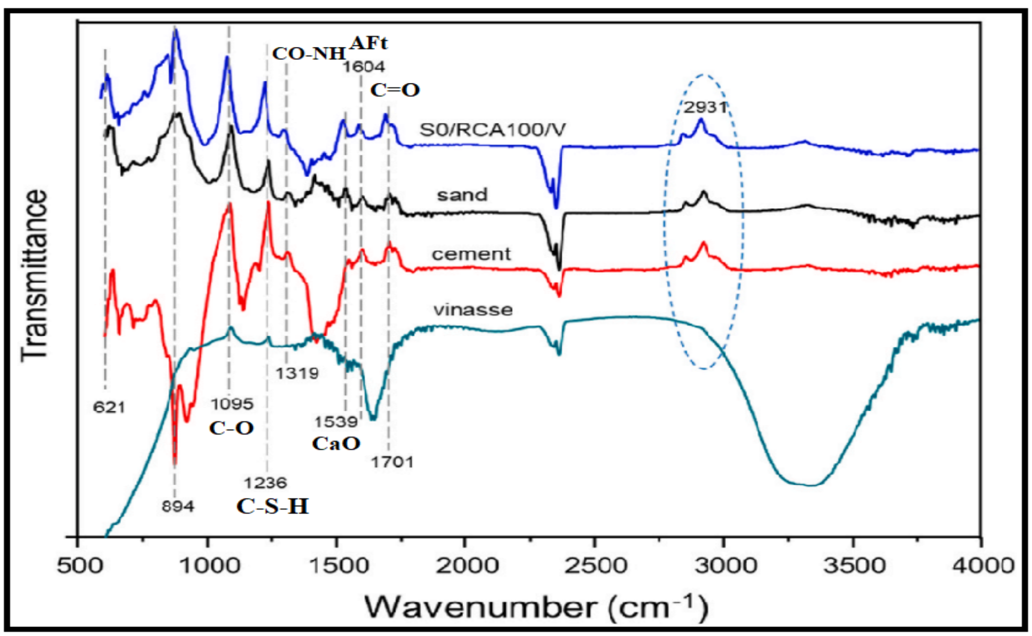


Figure 19. FTIR spectrum of modified concrete, sand, cement and vinasse (Tamashiro et al., 2022)

3.4 TGA characterization

The symbols in the equation below stand for the proportion of decomposed calcium hydroxide (CH%), whereas Wn% and CC%, respectively, reflect the percentages of bound water and calcium carbonate that have produced (Trivedi et al., 2023; Trivedi et al., 2024).

$$CH\% = (\%W_{CH}) \times (\frac{M_{CH}}{M_{H_2O}}) = (\%W_{CH} \times \frac{74}{18}) \quad (3)$$

$$W_n\% = W_T - W_{CH} \quad (4)$$

$$CC\% = (\%W_{CC}) \times (\frac{M_{CC}}{M_{CO2}}) = (\%W_{CC} \times \frac{100}{44}) \quad (5)$$

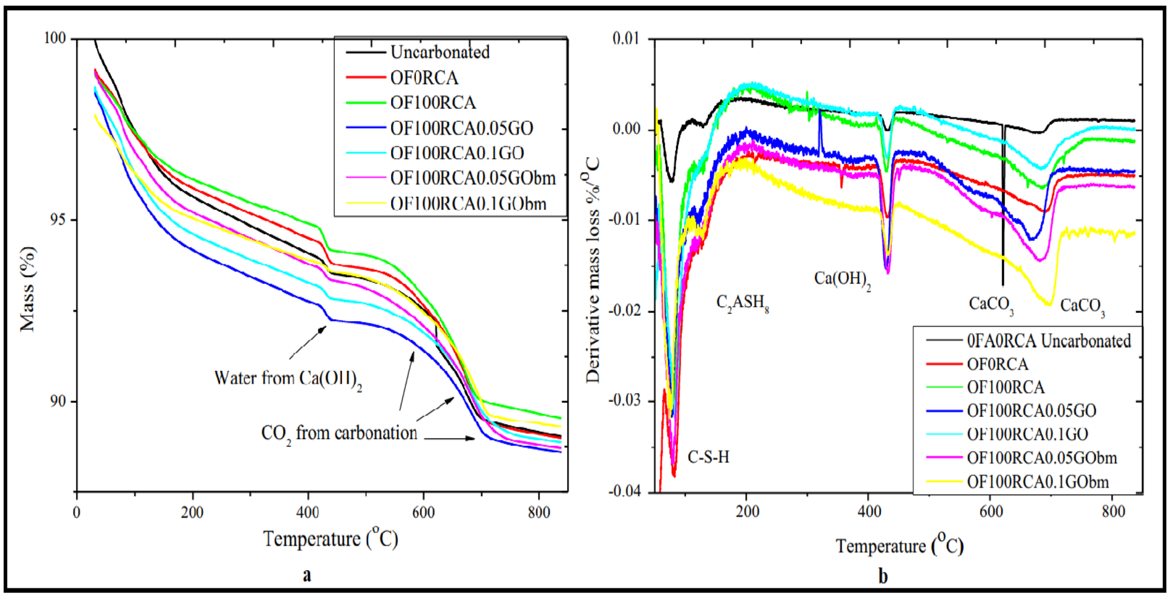


Figure 20(a-b). (a) TG curves and (b) DTG curves of RAC samples (Devi & Khan, 2020)

From the above Fig. 20 (a-b) it is understood that in case of accelerated carbonation, a declination is observed in the penetration of carbon di-oxide, owing to the assimilation of graphene oxide which provides a better pore to pore connectivity at the microstructure state (Devi & Khan, 2020).

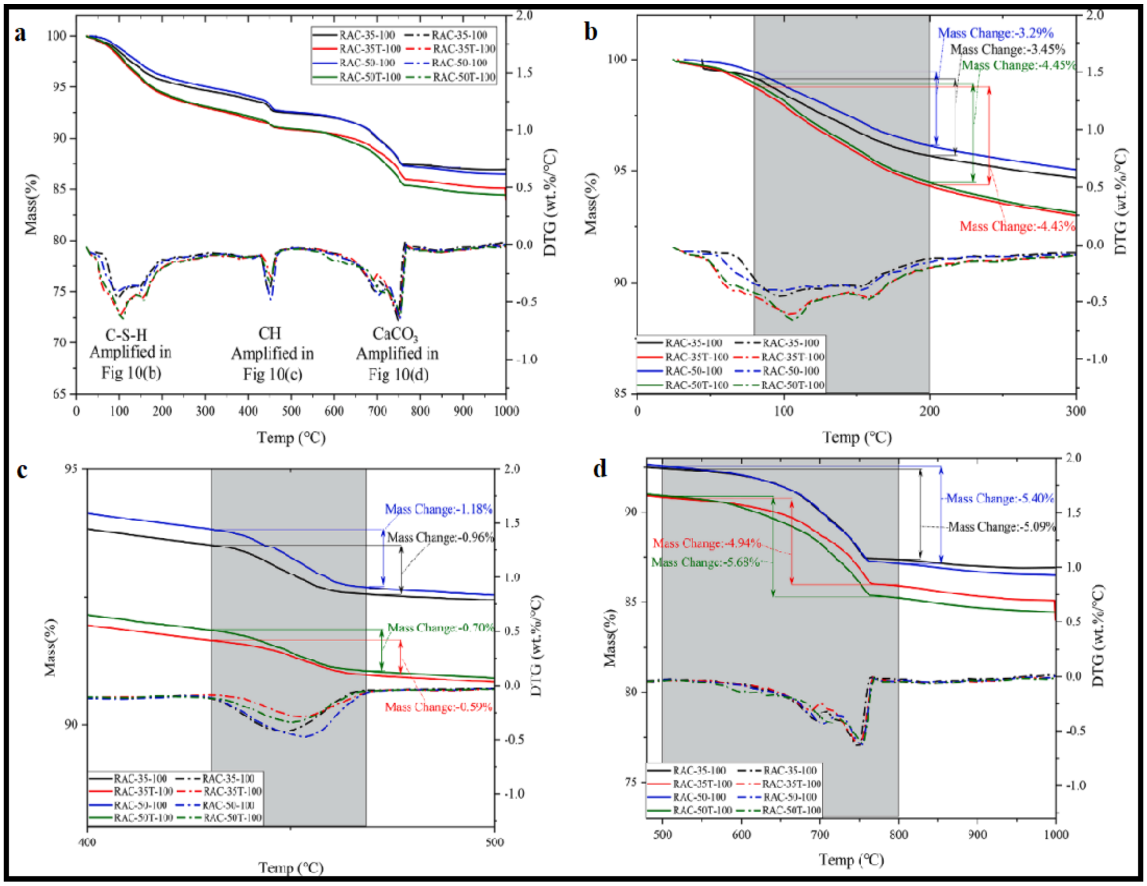


Figure 21(a-d). (a) TG-DTG plots of different RAC sample (b) C-S-H (80-200ºC); (c) CH (430-460 ºC); (d) $CaCO_3$ dehydration (500-800 ºC) (Wang et al., 2022)

From TG curves presented in Figure 21, it can be observed that the formation of an adhesive mortar is taking place that on further reaction with the crystallizer producing an improved microstructural site. Also, with increase in the water cement ratio, an additional amount of reactants are generating more C-S-H after reacting with the crystallizer (Wang et al., 2022).

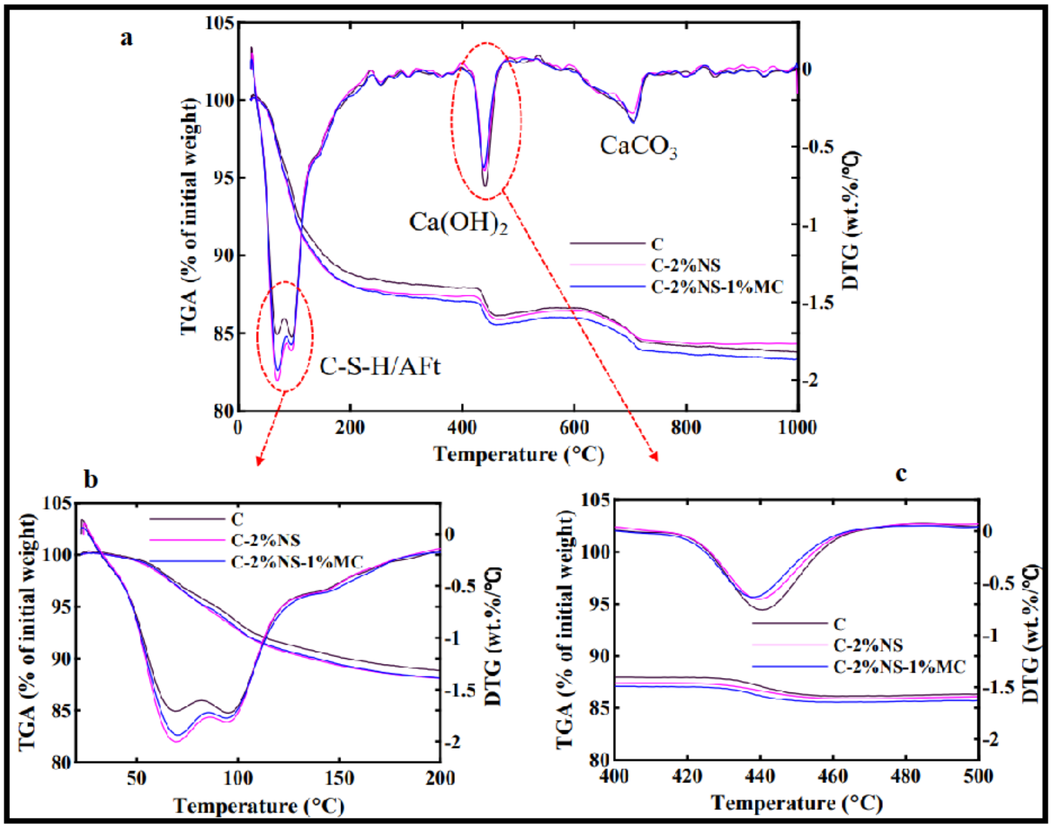


Figure 22(a-c). TG-DTG plots of (a)Nano silica (NS) and micro $CaCO_3$ (MC) admixed mortar samples; (b)C-S-H and (c) CH hydration (Yue et al., 2020)

From the TG-DTG curves presented in Figure 22, it is evident that the incorporation of NS and MC resulted in more consumption of CH crystals as compared to control sample. This rise in bound water is owing to the contribution form C-S-H, CH and ettringite phases post addition of NS and MC which further improves the rate of hydration in cement matrix and microstructure of modified composite (Yue et al., 2020)

4. Engineering Properties of Recycled aggregate concrete (RAC)

4.1. Fresh properties

Among the fresh state concrete properties, workability is the most important as it is related to the ease with which one can work with concrete or in terms of definition, workability is the amount of work done to achieve full compaction in concrete (Neville & Brooks, 1987). With respect to the NAC, RAC shows inferior workability (Gao et al., 2020; Hani et al., 2007; Nazarimofrad et al., 2017; Surya et al., 2013; Yang et al., 2011; Younis & Pilakoutas, 2013). This is basically accredited to the deprived shape properties of crushed RA when associated to natural aggregates and high absorption demand of RA (Lavado et al., 2020;

Matias et al., 2013). For achieving the comparable workability values, it must be ensured that the aggregates should be somewhat lower than the SSD condition. In direction to limit the water requirement in recycled aggregate, the incorporation of water reducing admixtures can be done (Verian et al., 2018). A study claimed that there is a methodical growth in the RAC slump occurred as the percentage of crushed concrete in the mix increases, whereas a diminution is detected with the accumulation of crushed brick content for fine substitution of aggregate in concrete (Khatib, 2005). However, it is found that with help of mineral or chemical admixtures, the loss of slump can be compensated (Faysal et al., 2020; Ju et al., 2020; Radonjanin et al., 2013; Somna et al., 2012)

4.2. Properties of hardened RAC

4.2.1. Compressive strength

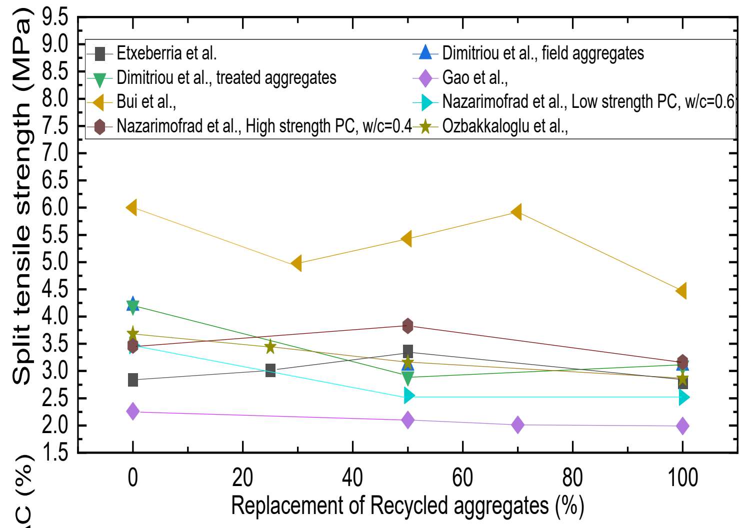
The strength in compression of RAC is a function of mean size of aggregate (MSA) (Shahidan et al., 2017). Other factors which affect the compressive strength is the source through which the recycled aggregates have been derived (Bravo et al., 2015). Based on extensive literature survey, it is found that with growing percentage of RA in concrete, the strength in compression goes on decreasing (Bai et al., 2020; Bui et al., 2017; Dimitriou et al., 2018) (Abed & Nemes, 2019; Etxeberria et al., 2007; Khatib, 2005; Kou et al., 2008; Zheng et al., 2018) However, research from Lotfi et al., (2015) proved that the loss in strength in compression by the accumulation of RA in concrete is less for mixes with higher targeted compressive strength as linked with the mixes with inferior targeted compressive strength (Kou & Poon, 2015). Another study claimed that the assimilation of FA and SF as a substitution of fine aggregate alongside adding a superplasticizer having an acrylic base could improve the strength in compression of RAC (Corinaldesi & Moriconi, 2009). In addition, it is also found that the assimilation of GGBS, MK, SF, phosphorus slag and FA as cement replacing materials significantly improved the strength in compression of RAC mixes (Bui et al., 2018; Dimitriou et al., 2018; Faysal et al., 2020; Ju et al., 2020; Kou et al., 2008; Lu et al., 2020; Muduli & Mukharjee, 2020; Nandanam et al., 2021; Radonjanin et al., 2013; Wang et al., 2013; Wang et al., 2020; Yaba et al., 2021). For achieving a comparable strength, it is investigated that aggregates subjected to sulphuric acid or scrubbing/heating treatment results in similar compressive strength as linked with the control concrete (Purushothaman et al., 2015). Also, the modification in the mixing approach (NMA to TSMA) could well lead to superior compressive strength in RAC

(Ozbakkaloglu et al., 2018). In a study it is also revealed that an alteration in the recycled fine aggregate could yield a similar compressive strength in RAC with respect to NAC even at 100% substitution rate (Kim et al., 2019).

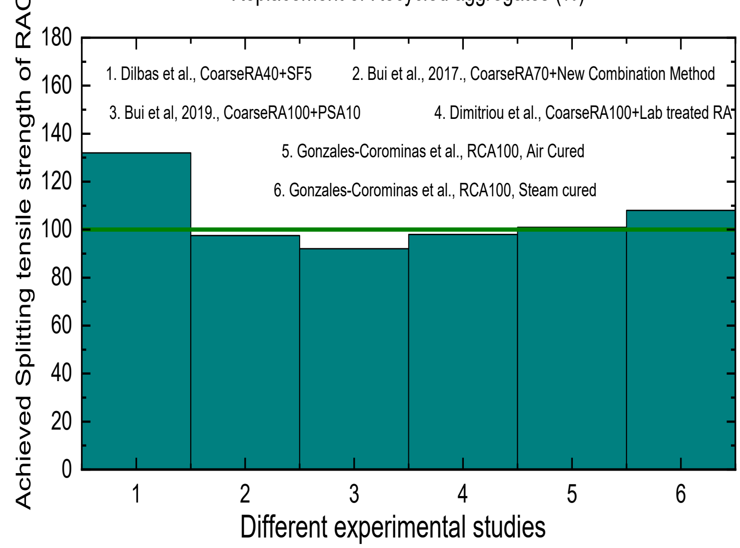
4.2.2. Split tensile strength and flexural strength

Shahidan et al., (2017) and Purushothaman et al., (2015) detected that the tensile strength of RAC is reliant on the size of RA. In another research it is found that the split tensile strength of RAC with respect to NAC is 10% minor, however there is no negative impact of RCA is detected as far as flexural strength is concerned even at full substitution of NCA by RCA (Safiuddin et al., 2013). The decrement in the split tensile strength and flexural strength with growing substitution percentage of RCA in NSC or HSC is confirmed by another research (Purushothaman et al., 2015). But research based on the consequence of carbon dioxide curing on RAC found a noteworthy surge in the strength in tension than that in the strength in compression (Chen et al., 2010). Also, it is reported by a number of studies that with a rise in the replacement ratio, a minor decline in the relative strength in tension of concrete took place (Bai et al., 2020; Bui et al., 2017; Dimitriou et al., 2018; Gao et al., 2020; Nazarimofrad et al., 2017; Ozbakkaloglu et al., 2018). Also, based on several experimental investigations, the similar observations were made for flexural strength of RAC (Barhmaiah et al., 2020; Chen et al., 2010; Dimitriou et al., 2018; Yang et al., 2011) and both these investigations can be observed from Figure 23(a) and 24 respectively. The state of recycled aggregate also has an impression on flexural strength of RAC (Verian et al., 2018). From the other research, the impact of full substitution of RA resulted in a 20% mean loss in flexural strength of RAC (Dimitriou et al., 2018). Also, a study observed concrete made with full substitution of aggregate resulted in 10% inferior tensile strength with respect to reference concrete and the usage of SF further progressed the RAC properties (Mukharjee & Barai, 2014). Another experimental investigation found that the nature of coarse aggregates, its crushing strength and surface characteristics are having the stimulus on the split tensile strength of RAC (Matias et al., 2013). It is to be noted that a dissimilar trend is noticed by the studies conducted by Chen et al., (2010) and Dimitriou et al., (2018) where the strength in flexure of RAC mixes improves after 50% replacement levels. This is owing to the adoption of RA from higher grade parent concrete and appropriate pre- treatment of RA specimens (Chen et al., 2010; Dimitriou et al., 2018).

Also, through literature the consequence of nano silica induction in concrete is investigated and it is found that the same material become vital in filling the concrete voids and produced a robust and dense ITZ as equated to control concrete, thus improved the concrete strength in tension (Mukharjee & Barai, 2014). The consequence of silica fume on splitting tensile strength of RAC is investigated and its incorporation up to 5% significantly upgraded the splitting tensile strength of RAC mix (Dilbas & Çakır, 2020) a similar kind of improvement is seen when steam curing is adopted which caused 8% escalation in the splitting tensile strength of RAC as compared with the control concrete (Gonzalez-Corominas et al., 2016). Based on the RA's amount, range, category and quality, there is an advanced or minor relative tensile strength damage amongst the NAC and RAC (Silva et al., 2015). Figure 23 (b) presents the percentage achieved splitting tensile strength of various RAC mixes as related to the control concrete which involves the assimilation of different mineral admixtures as well as diverse curing conditions and it can be detected that the accumulation of 5% SF and introduction of steam curing results in superior splitting tensile strength of RAC with respect to the control mix even with complete substitution of RA.



23(a)



23(b)

Figure 23. Split tensile strength of (a) RAC (Dimitriou et al., 2018; Bui et al., 2017; Ozbakkaloglu et al., 2018; Etxeberria et al., 2007; Nazarimofrad et al., 2017; Gao et al., 2020); Figure 23(b) Mineral admixture admixed RAC mixes (Bui et al., 2017, 2019; Dilbas et al., 2014; Dimitriou et al., 2018; Gonzalez-Corominas et al., 2016)

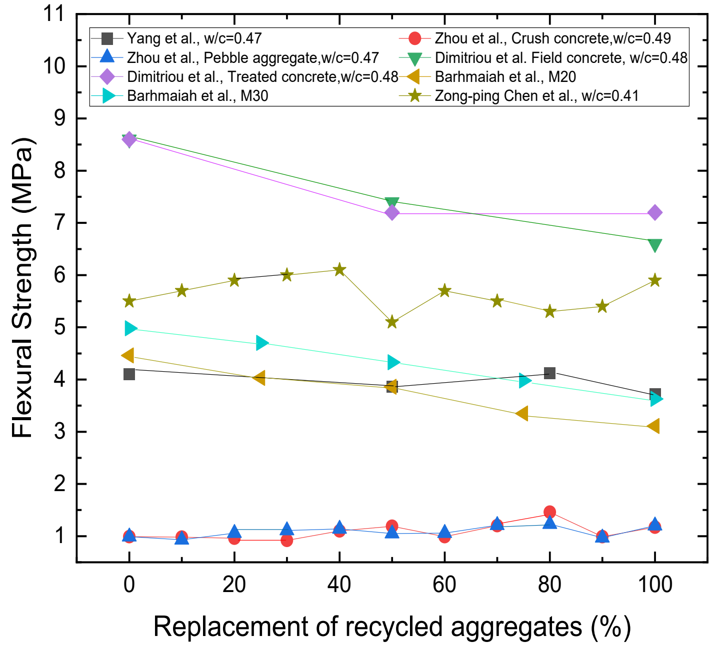


Figure 24. Flexural strength in RAC (Yang et al., 2011; Zhou & Chen, 2017*; Barhmaiah et al., 2020; Chen et al., 2010)

***Relative flexural strength**

4.2.3. Bond Strength

In an experimental investigation, a 10% fall in the bond strength of the RAC at 100% substitution by RA is studied (Rao et al., 2007). Research carried out by (Malešev et al., 2010) highlighted that the bond between RAC and reinforcement is not mainly prejudiced by RAC instead influenced significantly by the cement paste. It is also found that the bond strength can be enhanced by adding SF or FA in the RAC mixes (Ramasamy et al., 2021). Another experimental study claimed that the concrete mixes with high volume waste materials, i.e., 50% Coarse RA and 40% GGBFS, 50% Coarse RA and 60% GGBFS, 100% Coarse RA and 40% GGBFS and 100% Coarse RA and 60% GGBFS satisfied the bond strengths of the concrete mixes of M25, M20, M15 grades as specified by IS 456 (2000) (Majhi & Nayak, 2019). The dependency of bond stress on quality of parent concrete is also studied in which it is found that there is a significant drop in bond strength when RA is obtained from inferior-strength and lightweight PC, indicating the straight stimulus of parent concrete (PC) quality on the transmission of stresses and bond to the entrenched steel bars (Behera et al., 2014). Figure 25 presents the variation of bond strength in concrete mixes incorporating deformed bar and plane bar and it can be observed that in case of deformed bar, the bond is due to mechanical anchorage and friction where as in case of plane bar, the bonding is influenced by the concrete and rebar.

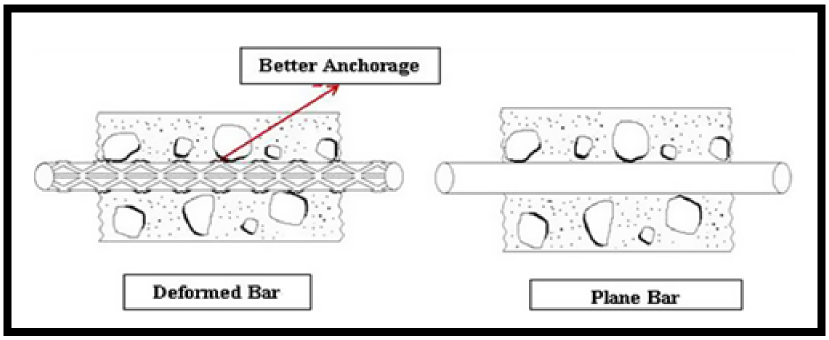
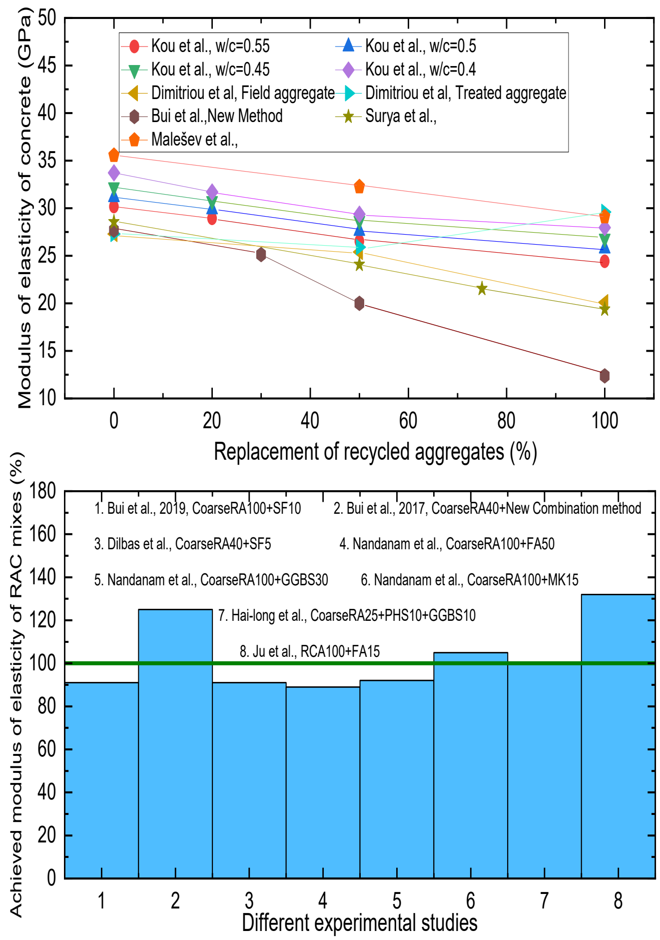


Figure 25. Bond strength in RAC (Behera et al., 2014)

4.2.4 Young's modulus

In various experimental investigations, the consequence of RA on the elastic modulus of RAC is examined and based on the experimental outcomes, with rising content of RA, the elastic modulus decreases (Bui et al., 2017; Dimitriou et al., 2018; Etxeberria et al., 2007; Kou et al., 2008; Malešev et al., 2010). This can be understood by the fact that RA are more vulnerable to deformation than raw aggregates and the modulus of concrete rely significantly on the aggregate moduli (Etxeberria et al., 2007). Another study reported that the low stiffness and bulk density of RA are responsible for the downfall of elastic modulus of RAC mixes (Zhou & Chen, 2017). A similar reduction is also reported alongside the effect of curing age and w/c ratio on the elastic modulus, as it is found that the same parameter shown an increment with reduction in the water cement ratio or surge in curing age (Kou et al., 2008). In attempt to explore the improving methods for elastic modulus in RAC, the accumulation of high range water reducing admixture proved that the same property can be enhanced even with 50% replacement of concrete induced RCA in the mix (Abed & Nemes, 2019). Similar trends were observed in another study where the laboratory treated recycled aggregates improved the elastic modulus of RAC mixes as compared that of raw RAC aggregates (Dimitriou et al., 2018). Figure 26(a) presents the variation of elastic modulus of RAC mixes on different percentages of RA and it is clear that with rising percentage of RA in concrete, the elastic modulus is decreasing.

However, the shortcomings of RA on elastic modulus can be rectified by using phosphorus slag, fly ash, GGBS, silica fume etc (Bui et al., 2017, 2019; Dilbas et al., 2014; Ju et al., 2020; Nandanam et al., 2021; Wang et al., 2013). The detailed representation of elastic modulus on the incorporation of various mineral admixtures is presented in Figure 26(b) below and it can be observed that with the assimilation of fly ash or metakaolin, the modulus of elasticity of RAC can be made comparable or superior than control mix even at complete substitution of RA.



26(a)

26(b)

Figure 26. 28 days Elastic modulus in (a)RAC (Malešev et al., 2010; Dimitriou et al., 2018; Bui et al., 2017; Surya et al., 2013; Kou et al., 2008) ; Figure 26(b). RAC with mineral admixtures (Bui et al., 2017, 2019; Dilbas et al., 2014; Ju et al., 2020; Nandanam et al., 2021; Wang et al., 2013)

4.3. Durability Properties

4.3.1. Carbonization

From the literatures, it is evident that the carbonation depth enhances with the increasing content of recycled aggregates, assuming all the supplementary aspects are equivalent (Kou & Poon, 2013; Levy & Helene, 2004; Silva et al., 2015) as can be observed from Figure 27. The investigation of complete substitution of RCA in concrete may reason up to twice the carbonation depth with respect to control concrete (Silva et al., 2015). Other parameters like water to binder ratio, amount of mineral pozzolana influences the carbonation depth of RAC. For example, the carbonation depth grows proportionally with the accumulation of pozzolanic materials, this may be attributed to the drop of the alkali percentage and the C-S-H formation (Sim & Park, 2011). Other literature investigated the effects of the quality of RA, its substitution percentage, binder percentage, the type of mineral admixture, and it is experimentally revealed that the higher strength parent concrete found to safeguard against carbonation in RAC specimens, with the substitution of coarse RA up to 70% and accumulation of mineral admixtures as fractional exchange of cement specifically 10% by mass (Xiao et al., 2012). A similar observation of increase in carbonation depth with respect to water binder ratio is concluded in an experimental investigation (Otsuki et al., 2003). In case of recycled fine aggregate concrete (RFAC), the carbonation depth surged with reduction in minimum particle size of recycled fine aggregate. If water binder ratio is remained to be fixed, the confrontation to carbonation drops with the amplification of RFA amount (Geng & Sun, 2013). The carbonation depth of RAC with respect to substitution of recycled aggregates is shown as below.

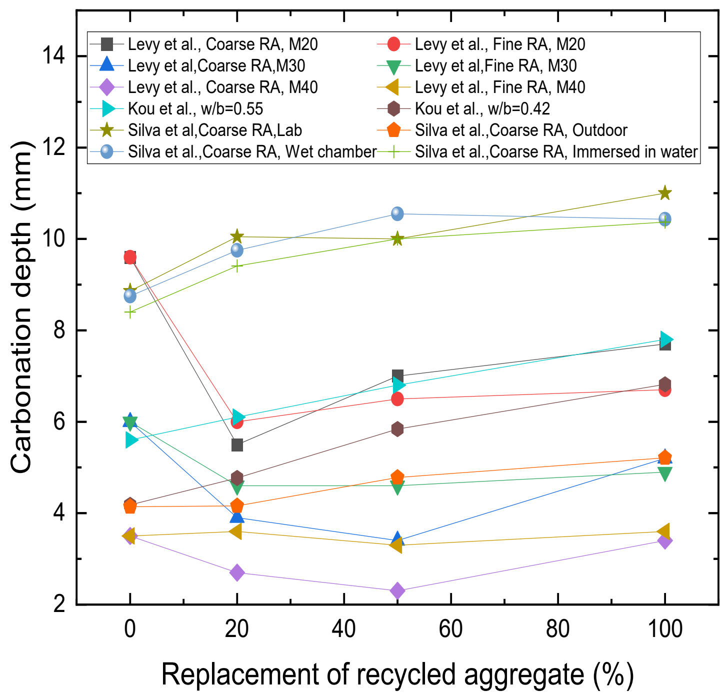


Figure 27. Carbonation depth RAC at 28 days in different conditions (Kou & Poon, 2013; Levy & Helene, 2004; Silva et al., 2015)

4.3.2 Chloride penetration

Chloride ion penetration is the measurement of the depth up to which the chloride ions present in the environs pierce into the concrete (Das et al., 2012). Through several literatures it is confirmed that the recycled aggregates incorporation in substitution of natural aggregates in concrete mixes promotes the chloride ion penetration (Andreu & Miren, 2014; Kenai, 2018; Kou et al., 2008; Özalp et al., 2016; Shaikh & Nguyen, 2013). In other experimental analysis, the effect of curing time on chloride penetration is analysed and it is found that with age, the penetration becomes weak as the microstructure of concrete becomes denser with curing time (Sim & Park, 2011). When other parameters like water binder ratio (w/b) are investigated, it is claimed that a higher w/b can control the chloride ion penetration in the concrete owing to the enhancement in the ITZ (Otsuki et al., 2003). In order to explore the controlling measures for chloride penetration in RAC, a number of experimental investigations are reported and it is confirmed that the incorporation of mineral admixture and modifying mixing approach can progress the chloride resistance in RAC (Otsuki et al., 2003; Sim & Park, 2011). Figure 30(a) presents the variation of chloride ion penetration against the substitution percentage of natural aggregates by RA. It can be detected from the Figure that with growing substitution percentage of RA, the penetration goes on increasing.

Also, through several literatures it is proved that application of mineral admixtures as supplementary cementitious materials resulted in controlling the chloride ion penetration in RAC mixes (Dimitriou et al., 2018; Faysal et al., 2020; Kou et al., 2011; Nandanam et al., 2021). Figure 30(b) presents the percentage achieved chloride ion penetration of the various RAC specimens with respect to the control mix and by the integration of various mineral admixtures as SCMs, the chloride ion penetration can be controlled.

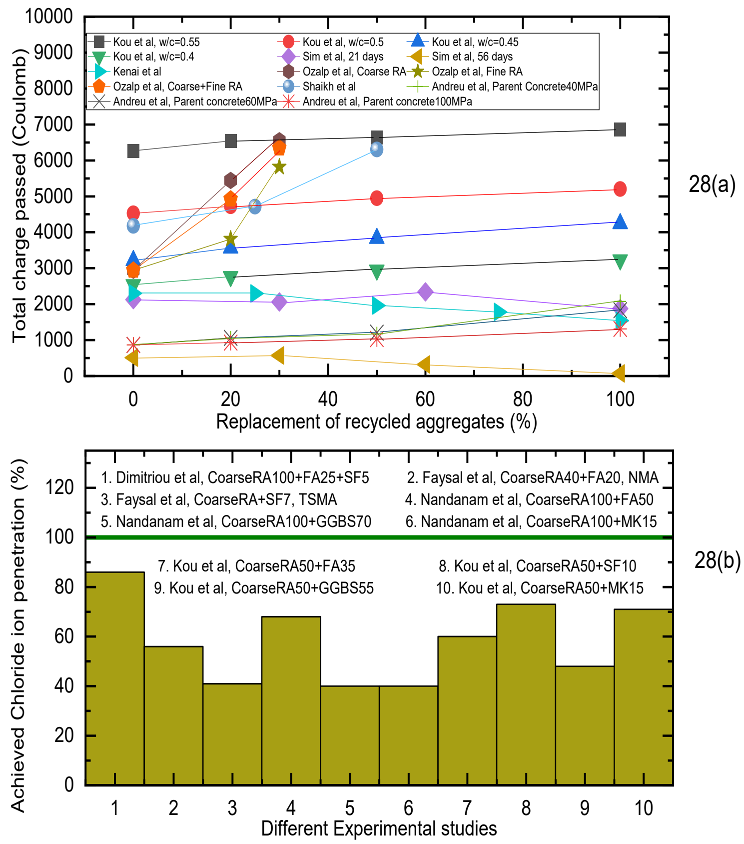


Figure 28. Chloride penetration in (a) RAC (Andreu & Miren, 2014; Kenai, 2018; Kou et al., 2008; Özalp et al., 2016; Shaikh & Nguyen, 2013) ; Figure 28 (b) RAC with mineral admixture (Dimitriou et al., 2018; Faysal et al., 2020; Kou et al., 2011; Nandanam et al., 2021)

4.4 Shrinkage and Creep

4.4.1 Drying shrinkage

The values of drying shrinkage were found proportional to the percentage of RA in the concrete, indicating that the above property is more evident in RAC with respect to NAC (Liang et al., 2020). In a study, it is found that drying shrinkage is mainly dependent on paste percentage, water to cement ratio and controlled by aggregate particles (Safiuddin et al., 2013). Another study claimed that a large shrinkage strain is witnessed as the proportion of RA surges in the mix (Ozbakkaloglu et al., 2018). In a study it is found that the drying shrinkage declines with the incorporation of waste powder from C&D debris (Ma et al., 2020). Also, the methods like carbonation treatment diminishes the drying shrinkage of RAC (Liang et al., 2020). A study claimed that the drying shrinkage can be controlled by incorporating RA from better concrete grade of higher strength (Kou & Poon, 2015). Research reported by Duan & Poon, (2014) states that concrete made with the superior quality of RA, minor shrinkage values were reported. It is also reported by the authors that drying shrinkage of concrete improved with the curing days. The representation of drying shrinkage with respect to age of RAC mixes is shown in Figure 29 and it can be detected that at various substitution percentages of fine and coarse RA, the drying shrinkage is increasing with respect to age of the mix.

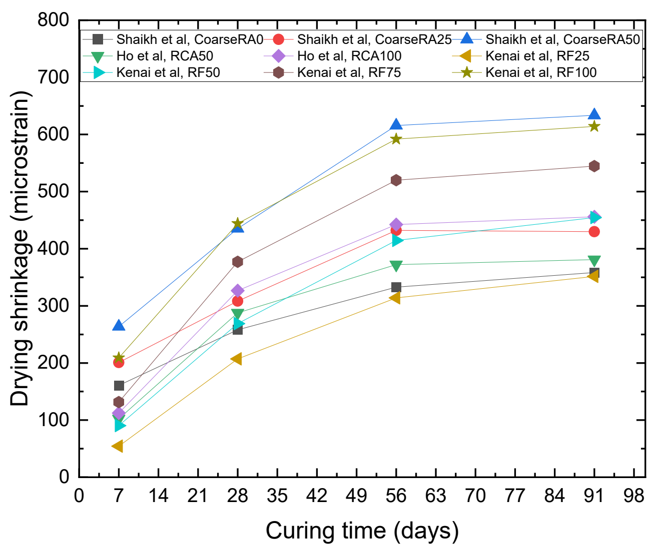


Figure 29. Drying shrinkage in RAC (Yong Ho et al., 2013; Kenai, 2018; Shaikh & Nguyen, 2013)

4.4.2 Creep

An experimental investigation concluded that on full substitution of natural aggregates by the RA, the creep deformation got increased by 50% at 180 days of time period (Domingo et al., 2010). Most of the studies have reported that creep deformation surges with the integration of RA in replacement of natural aggregates in concrete mixes (Chinzorigt et al., 2020; Fathifazl et al., 2011; Geng et al., 2016; Kou & Poon, 2012; Seara-Paz et al., 2016; Tam et al., 2015). Apart from replacement percentage of RA, creep of RAC is primarily prejudiced by the existence of old residual mortar and new mortar (Kou & Poon, 2012). The same observation is endorsed in a study in which the effect of water cement ratio (w/c) of source concrete and RA mix concrete is explored and it is found that the creep deformation is more affected by the higher w/c of the parent concrete and lower w/c of the RA concrete (Geng et al., 2016). The moisture state of RCA also has an impression on the creep of RAC mix as an experimental study concluded that pre-soaked RCA at below saturated surface dry (SSD) condition resulted in a balanced creep at early age (Henschen et al., 2012). Another investigation on long term creep includes recycled brick aggregates (RBA) as both coarse and fine aggregate substitution in concrete and through results, it is reported that the creep is acceptable up to 20% substitution for structural applications (Gayarre et al., 2019). Through a study, the addition of FA as a partial substitution or accumulation of cement is found to be helpful in controlling the creep deformation in RAC mixes, owing to the pozzolanic reaction that happened due to accumulation of fly ash (Kou & Poon, 2012). Figure 30 presents the graphical variation of creep strain up on incorporation of different recycled aggregates in concrete mixes and it can be detected that with assimilation of recycled coarse and brick aggregates, creep strain goes on swelling with age.

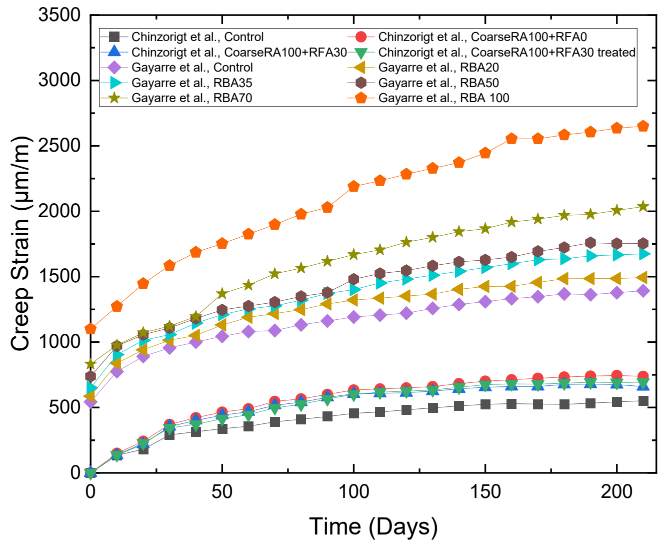


Figure 30. Creep strain in RAC (Chinzorigt et al., 2020; Gayarre et al., 2019)

5. Techniques for improving properties of Recycled aggregate concrete (RAC)

With respect to the benefits and shortcomings of the application of RA in the concrete, various techniques are investigated based on the extensive literature survey, which are further classified into following categories.

5.1. Modifying mixing process

Numerous studies supported the use of the two-stage mixing technique (TSMA) in place of the standard or normal mixing strategy (NMA) for RAC. The created TSMA can increase the RAC's strength (Tam et al., 2006). Another study developed a modified TSMA approach, which involved adding cement to the first step of the mix and silica fume to the premix ($TSMA_{sc}$). This approach was found to increase the RAC's strength in compression, tension, flexure, and young's modulus.

A study carried out by Shaikh et al., (2018) proved that the presoaking of recycled coarse aggregates 2% nano-silica solution followed by presoaking of resulted in an enhancement in the engineering properties of RAC. Similarly, research from (Dimitriou et al., 2018) used the modified recycled treated aggregates in concrete i.e., laboratory, treated and field aggregates and due to treatment, the recycled aggregate achieved better than the control concrete. Figure 31 presents the different mixing approaches of some of these techniques and as a result the densification of ITZ is taking place.

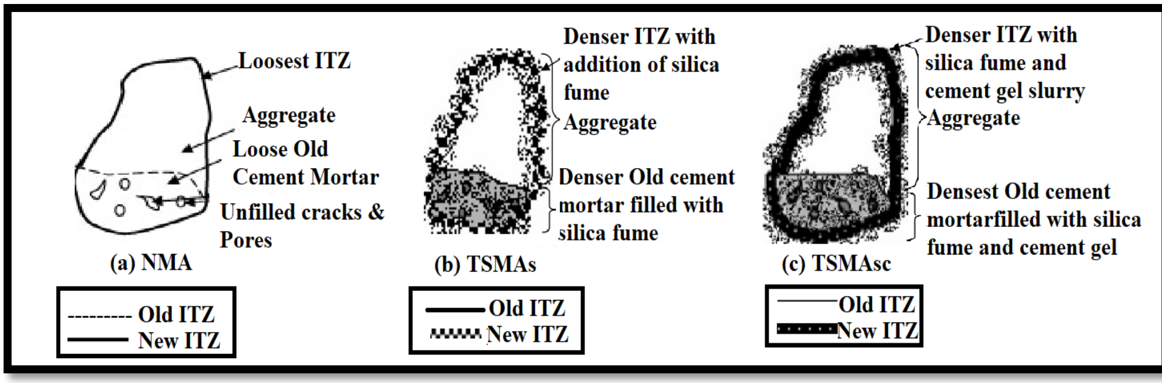


Figure 31. Mixing approaches (a) NMA (b) TSMA$_s$ and (c) TSAM$_{sc}$ (Tam & Tam, 2008)

5.2 Incorporation of filler materials (micron, submicron to nano size) in RAC

According to Awoyera & Okoro, (2019), silica fume and GGBS were added as micro fillers to RAC, and the findings showed that both materials' compression strength increased by 6% and 17%, respectively. Research by Babalola et al., (2020) similarly supported the combination of FA and SF as filler materials in RAC, and the results demonstrated an increase in the strength in compression and durability properties of the improved RAC mix. A rise in the mechanical characteristics of RAC was achieved by assimilation of perlite powder with an optimal percentage of 15% in addition to the aforementioned ingredients (Abed & Nemes, 2019). According to another study, adding marble as a filler material increased the strength of RAC in comparison to natural aggregate concrete at an ideal percentage of 5% (Belagraa et al., 2017). Younis & Mustafa (2018) looked into substituting silica nanoparticles for cement in RAC, and it was shown that doing so produced RAC with a similar split tensile strength to the control mix while also reducing its water absorption. Research from (Zhang et al., 2016) investigated the use of nano slurries for the surface treatment of RA in concrete in order to advance the ITZ of RAC, which subsequently produced an improvement in the microstructure of RAC. A decrease in the water absorption of RAC mix was seen in an experimental investigation by Singh et al. (2018) that investigated the impact of presoaking RA in nanosilica and ureolytic/non uneolytic bacterial environments. Additionally, there has been a rise in RAC density as well as an improvement in RAC mix durability. The combined use of nano silica and basalt fibre in RAC was researched by Zheng et al. in 2021. It was also noted that the same materials produced a densified RAC as a result of the mix's decreased porosity.

Yue et al. (2020) conducted a similar study in which the effect of nano silica (NS) and micro calcium (MC) carbonate as fillers in RAC was examined. Based on the findings, an improvement in the microstructure and mechanical properties is reported. Another experimental analysis looked at using nanoscale silica and nanoscale titanium dioxide together as filler material, and it found that the pore structure of RAC had improved. Further information indicates that the same fillers increased the mix's resistance to chloride ion diffusion thereby indicating the influence of nano silica and on durability aspects of RAC.

6 Utilization of Recycled aggregates for development of geopolymer concrete and as fine aggregates in concrete

6.1 Development of Geopolymer Recycled aggregate concrete (GRAC)

Various researches unanimously endorsed the use of geopolymer in RAC, like coarse RA and the fine RA helped to develop a novel green concrete geopolymer having fly ash as base. Literature observations proved that the increment in the w/c is accountable for the downfall of the engineering properties in geopolymer recycled aggregate concrete (GRAC) (Liu et al., 2016). Another study claims that in the prepared RAC, the inclusion of GGBFS and FA-based geopolymer results in an excellent sulphate resistance property and simultaneously improved the compactness of RAC (Xie et al., 2019). Similarly, a study explored the amalgamation of the recycled concrete aggregates as a substitution of coarse aggregate in geopolymer concrete with a base of high calcium fly ash and the results indicated a 93% strength recovery in compression with respect to the crushed limestone based geopolymer concrete (Nuaklong et al., 2016). A study determined 12-24 hours as an optimum curing time for attaining the required characteristics in a fly ash-GGBS based GRAC (Wang et al., 2020). In attempt to advance the microstructure of RA based geopolymer concrete, inclusion of various fillers and mineral admixtures is added i.e., rice husk ash and nano silica based geopolymer concrete shows comparable strength than geopolymer based NAC at an age of 28 days (Nuaklong et al., 2020). Other materials such as metakaolin is used as a fractional substitution for high calcium fly ash (HCF) in geopolymer binder, proved to provide significant enhancement in the mechanical and abrasion properties of concrete (Nuaklong et al., 2018). Figure 32 (a-b) presents the scanning electron micrograph images of GRAC and OPC-RAC matrix at similar water cement ratio and a proper bonding can be detected in the former case between the old cement paste and the synthesized geopolymer paste thereby the porous nature of the microstructure is eliminated which is existing in the ITZ of OPC-RAC matrix.

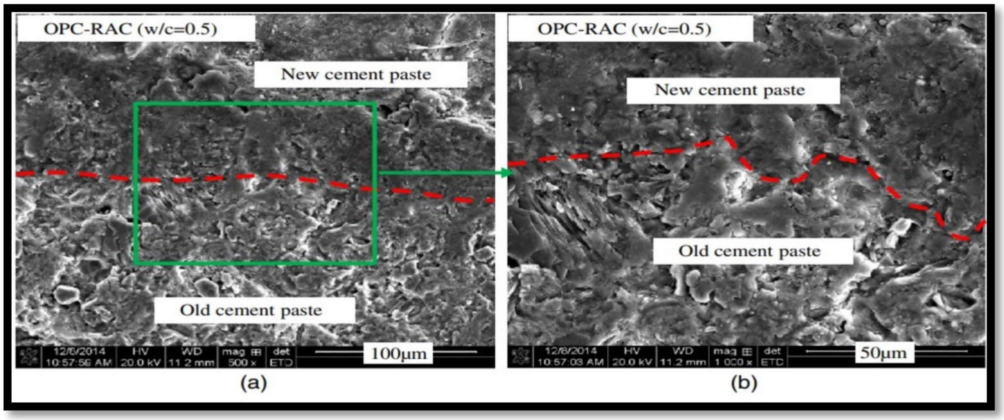


Figure 32. SEM images of (a)GRAC (b) OPC-RAC (Liu et al., 2016)

6.2 Recycled aggregates as a replacement of fine aggregates in concrete

A study incorporated fine RA as a fractional and full substitution of natural sand in concrete and a increase is observed in the water absorption and slump value of the resulting concrete alongside decrement in the compressive strength and modulus of elasticity as compared to the control mix (Chan & Sun, 2006). Research from Kou & Poon, (2009) inspected the assimilation of fine recycled aggregate (FRA) in concrete as 25-100% substitution of natural fine aggregates and based on the experimental investigation, it is observed that at fixed w/c ratio the strength in compression declined whereas a surge in the drying shrinkage is detected at the same time. However same study conveyed that the incorporation of FRA improved the resistance against chloride ion penetration at a fixed slump value. Another research utilizes crushed bricks and crushed concrete as a substitution of fine aggregates in concrete and based on the outcomes, it is reported that the accumulation of the former caused a strength declination up to 30%. However, the later resulted in a comparable strength value with respect to the control mix (Khatib, 2005). A study from Anastasiou et al., 2014 reported that the joint utilization of steel slag and mixed C&D waste as a substitution of fine aggregates in concrete resulted in 30 MPa strength alongside satisfactory durability criterion for low grade concrete applications. The accumulation of crushed concrete waste as an interchange of fine aggregates in concrete is endorsed by Fan et al., 2016 and Señas et al., 2016. The former study documented that the crushing process, replacement ratio of aggregate significantly affects the mechanical and durability properties of the subsequent concrete. Even the complete substitution of fine RA in lieu of natural aggregates is supported in an experimental investigation for a reasonable strength property of the resulting concrete (Hassan et al., 2021). An experimental analysis from Evangelista & de Brito, 2007 proved that the substitution of FRA up to 30% of natural aggregate or sand does not disturb the mechanical properties RAC in substantial terms. Figure 33 illustrates the achieved strength in compression of various RAC mixes with FRA as a substitution to natural fine aggregates in concrete and it can be observed that with an optimum percentage of 25-30%, the substitution of fine RA can be done to achieve comparable strength.

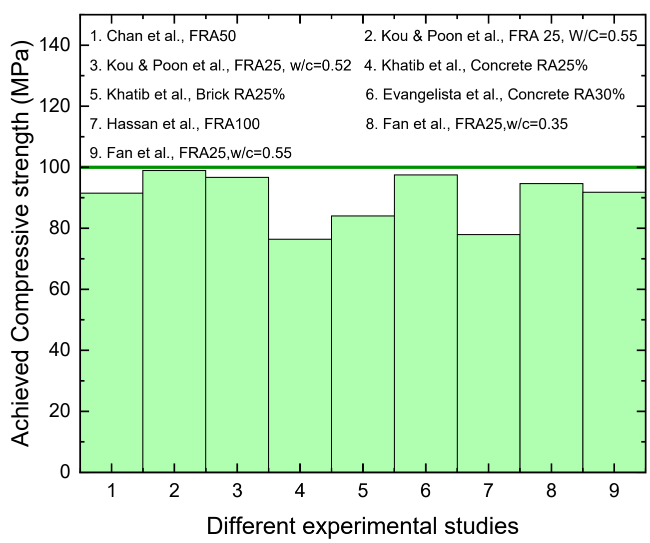


Figure 33. Percentage achieved compressive strength of RAC (Chan & Sun, 2006; Evangelista & de Brito, 2007; Fan et al., 2016; Hassan et al., 2021; Khatib, 2005; Kou & Poon, 2009)

7. Latest technologies on Recycled aggregate concrete

7.1 Carbon dioxide curing of RAC

CO_2 can be utilized for improving RA and RAC. The two currently utilized methodologies are carbon conditioning and carbon-curing in which the former method is of greater practicality. The main advantage of carbon curing is it can provide quicker early-age strength for concrete and carbonation of RA can be accomplished former to concrete mixing (Tam et al., 2020). A detailed investigation of carbon conditioning in recycled aggregate (RA) is carried out with varying RA replacement percentages of 0%, 30% and 100% and it is observed that the porosity and water absorbance of RA is decreased. Also, with the improved quality of RA, CO_2 emissions from the aggregate helped to fill the openings in the concrete composition, creating a better-quality bond matrix from the formation of calcite. Other properties such as workability, compressive, flexural, split tensile strength and elastic modulus observed an improvement post carbon conditioning (Liang et al., 2020; Tam et al., 2016; Zhan et al., 2014). Liang et al., 2020 further observed that carbonation efficiency of RA with small particle size is greater than aggregate with large particle size. Zhan et al., 2013 investigated that carbon dioxide curing helps in attaining higher compressive strength and low drying shrinkage in RAC mixes.

7.2 Fiber reinforced Recycled aggregate concrete (FRAC)

Fiber reinforcing is an influential practice that avoids and decelerates the micro-cracks inside the concrete matrix and accordingly outcomes in an upgraded strength, ductility, crack pattern, fracture energy properties in the frailer recycled aggregates (Ahmed & Lim, 2021; Chan et al., 2019). Based on the literatures, various types of fibers for example glass fiber, polypropylene fiber, steel fiber and basalt fiber can be incorporated in the RAC and based on respective investigations, it is found that steel fiber caused the strength enhancement of RAC, polypropylene fiber resulted in reduction of shrinkage cracks in cementitious composites whereas basalt fiber proved to improve the tensile strength and glass fiber provided the thermal stability in recycled aggregate concrete (Ahmed & Lim, 2021). The accumulation of polypropylene fibers in RAC is also endorsed in other studies on the substance of rise in the flexural and split tensile strength at an optimum fiber content of 0.5% (Das et al., 2018). In other researches it is also evident that higher fiber content tends to increase the Youngs modulus and residual flexural strength in fiber reinforced RAC (Chan et al., 2019). In a study, the consequence of crumb rubber with steel fibered recycled aggregate concrete (RSRAC) is investigated and it is found that this combination enhances the compressive ductility and toughness of RSRAC at 2% optimum rubber content (Xie et al., 2015). Also, the durability properties such as sulphate attack resistance of RAC with NaOH treated crumb rubber was investigated and it proved to be useful in terms of enhancing the sulphate attack resistance of RAC at optimum dosage of 20% NaOH treated crumb rubber with size range of 0.16-0.30 mm (Li et al., 2021).

7.3 Incorporation of sea water and sea sand in Recycled aggregate concrete

The joint utilization of seawater and coarse RA promotes the development for a sustainable concrete, however the potential risk associated with sea water application in concrete is the corrosion of steel reinforcement due to abundance of chlorides present in seawater. Recent studies on the application of seawater in RAC demonstrated a downfall in the workability, mechanical properties and durability characteristics (Younis et al., 2020). Also, the sea water effect in the RAC produces quick initial setting effect alongside employing blast furnace slag cement with sea water in RAC can cause the minimum plastic shrinkage but on the same time increases the drying shrinkage (Etxeberria et al., 2016). The association of sea water sea sand in RAC is studied and it is found that this addition upgraded the mechanical performance of RAC, but worsens the early-age cracking behavior in the mix (Xiao et al., 2019). Another investigation concluded the feasibility of using sea water sea sand based recycled aggregate concrete (SSRAC) columns as SSRAC columns outperformed the RAC columns in terms of strength and deformability with a peak load capacity exceeding 17% higher than the latter (Zhang et al., 2019). Also, it is studied that with respect to normal aggregate concrete, sea water sea sand mixed concrete developed an early strength, whereas the long-term strength is found to be comparable. It is further explored that the durability issues of sea water sea sand concrete could be wiped out through a blend of mineral admixtures for the concrete with the reinforcement of fiber reinforced polymer (FRP) (Xiao et al., 2017). Other studies incorporated sea sand and RAC in glass fiber reinforced polymer tube (GFRP) resulted in some important findings such as sea sand and coarse RA diminished the strength and deformation of specimens and sea sand was found to delay the transverse deformation while the coarse RA improved the same (Huang et al., 2021).

8. Concluding Remarks

This review article comes up with a detailed investigation about microstructure and engineering properties of recycled aggregate concrete and its application in the structural elements. In order to make the recycled aggregate concrete comparable with control concrete, various improvement techniques and several latest trends are explored.

By adopting suitable process techniques recycled aggregates can be generated from the construction and demolition waste that can be utilized in the production of high performance concrete. The inclusion of recycled aggregates in cement and concrete industry is a unanimous solution towards safeguard of natural resources (amid crunch situation between its demand and availability) and protection of the environment and ecology by cutting down the carbon dioxide emissions. Even though there found to be some short-comings in the attainment of engineering properties of concrete with the addition of RA as partial or full replacement with that of natural aggregates, it is observed that the properties of RAC can be modified with the addition of various mineral and chemical admixtures such as GGBS, MK, FA, SF, phosphorous slag and several fillers like nano silica, vinasse or others agro-industrial by-products. In particular, addition of 30-50% FA or 5-10% SF by weight is observed to result suitable workability in RAC mixes and higher strength in compression and tension whereas incorporating up to 15% MK and 75% GGBS by weight illustrates higher compressive strength and resistance to chloride ion penetration in RAC mixes. The advantages of mineral additions comprise microstructure densification and improved binding capacity in the RAC system however, the early strength is found to be slightly lower in such mixes than that of the control mix. Henceforth, an optimum percentage of mineral additions and suitable mix design is necessary to achieve desired performance in RAC mixes. Further, if a mixture designer adopts different approaches of mix design alongside the inclusion of fillers (micron, submicron to nano size), performance of RAC can be enhanced significantly. Comprising a complex and vulnerable microstructure, observations from SEM studies revealed that the inclusion of treated RA with pozzolanic slurry solution is helpful in enhancing the hydration at microstructural scale. Further, the adoption of dual and triple stage mixing can significantly reduce the porosity of the RAC mixes and contributes to a dense and compact microstructural matrix. Apart from the modification at the mix design approaches, treatment of RA with recycled fine powder followed by carbonation curing, dual surface treatment, incorporation of high strength RA, nano silica and bacterial RAC can further lead to an improvement in the compressive strength properties. Several other techniques such as biomineralization, nano silica addition, slag and basalt fibre-based RAC, phase changed carbonized RA, tannic acid coated RA, milled graphene oxide and sodium silicate modified RAC are helpful in strengthening the microstructure of RAC as observed by XRD, FTIR and TG-DTA analysis. Developments on the geopolymer RAC is also documented in this article alongside the latest developments on RAC such as carbon dioxide curing, inclusion of sea water and sea sand based RAC mix and fiber reinforced RAC. The feasibility of sea sand merged RAC is supported with the joint inclusion of suitable fiber reinforcement and mineral admixtures in order to match the durability standards of the control mix.

Future Scope

1. Performance of RAC under different curing conditions is not well known. Thereby, more experimental research is required under this area.
2. Geopolymer RAC needs an extensive investigation particularly for long term mechanical and durability performances.
3. A holistic approach is necessary to be adopted towards the optimum mix design for RAC mixes.
4. Limited research manuscripts are available on high and ultra-high performance RAC. This area needs further research.

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