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Sustainable treatment approach to dumped construction waste with acids and CO_2 for its effective re-utilization in concrete

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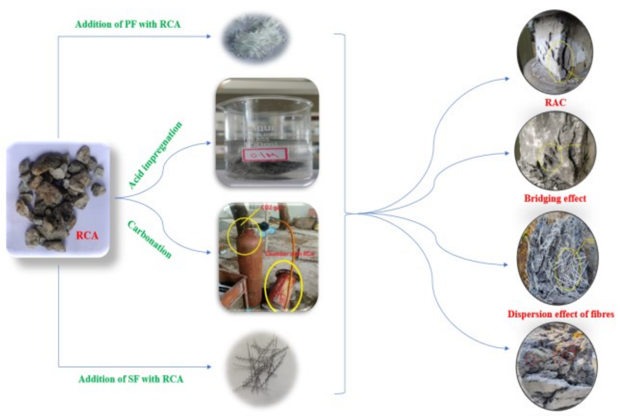
Graphical abstract



Abstract

Dumping of construction wastes has become one of the serious concerns in the construction industries subsequent to the scarcity of construction materials, specifically aggregates. Extensive research works have been performed to utilize the dumped waste as aggregates, yet its substandard properties affect the concrete. Furthermore, several treatments were proposed to improve the quality of aggregates such as microbial, slurry etc, but the brittleness of concrete remains unavoidable. This research discusses the effect of acid treatment and carbonation treatment on recycled concrete aggregates (RCA) and the impact of hybrid fibres on concrete properties. The steel fibres (SF) and polypropylene fibres (PF) were optimized to 1.5% and 1.0% with 100% treated RCA to assess the concrete's hardened properties and water absorption. The study reports that the carbonation treatment to RCA performs better compared to acid treatment and the mix with the use of hybrid fibres shows enhanced properties than single fibres. The strength of the mix with 100% carbonated RCA 1.5% SF and 1.0% PF was 57% higher than that of recycled aggregate concrete (RAC) and the water absorption of similar mix was found to be lower than other mixes. Microstructural investigations through SEM and XRD were also performed to support the research findings.

Keyword: Recycled concrete aggregates, acid treatment, carbonation treatment, steel fibres, polypropylene fibres, hybrid fibres

1. Introduction

The surplus use of natural resources by construction industries in past times had led to the depletion of it resulting in serious environmental issues. Meanwhile, the generation of solid wastes from demolition of structures results in dumping issues and thus affecting environmental integrity. The rapid generation of construction & demolition (C&D) wastes is a significance of urbanization that raises the necessity of modern structures and demolition of existing structures. Worldwide, 37% of C&D wastes are disposed in landfill, 33% were dumped, 19% were recycled and only 11% were treated (Global snapshot of waste management, 2018). In India, 150 MT of C&D wastes are generated and that accounts for nearly 40% of C&D wastes around the globe. Such serious concern about the depletion of natural resources causing scarcity of construction materials and dumping of C&D wastes needs to be addressed. Several research studies encompass on reusing the concrete segments of C&D wastes as RCA in the concrete (Sivamani *et al.* 2023, Sivamani *et al.* 2021, Sivamani *et al.* 2022, Sivamani *et al.* 2023a). These studies infer the destitute characteristics of RAC with RCA ensuing from the adherence of mortar on it surface. RCA was inferior compared to natural coarse aggregate (NCA) owing to its higher water absorption subsequent from the micro-voids on the smeared mortar attached to it.

Researchers around the globe have worked on the deficit on recycled aggregates with suitable treatment techniques with acids, microbes, slurry, carbon dioxide, polymers etc. (Karthikeyan *et al.* 2023) observed that bio-deposition of RCA with *Bacillus Subtilis* lowered the water absorption by 33% and enhanced the strength by 12.63%. (Sivamani *et al.* 2022a) recycled finer fractions of RCA and observed that TSMA enhanced the strength of RAC by 12% to 17%. The water absorption and porosity of RAC were also reduced by 7.5% and 15.4% respectively. (Saravanakumar *et al.* 2016) treated RCA with different acids such as HCl, H_2SO_4 and HNO_3 acids and observed that H_2SO_4 acid was more efficient in lowering the water absorption of RCA and improving strength of RAC by 20% compared to other acids. (Revathi *et al.* 2015) used HCl and H_2SO_4 acids to treat RCA and found that the water absorption of RCA with former treatment was lowered by 41.02% and the latter treatment was lowered by 48.07% and the strength of RAC former and latter treatment was enhanced by 9.45% and 10.88%. (Russo and Lollini 2022) carbonated RCA both naturally and through acceleration technique, and found a 3% decrease in water absorption with the natural method and a 20% drop with the accelerated one. The strength was enhanced by 17.52% with natural carbonated RCA and by 10.11% with accelerated carbonated RCA. (Luo *et al.* 2018) carbonized RCA at 0.1 MPa to 0.8 MPa for about 6h to 72h and observed that optimizing the CO_2 pressure to 0.4 MPa for 72h lowered the water absorption by 27% and enhanced the strength by 14.5%. (Lu *et al.* 2019) carbonated RCA and observed finer fractions perform better compared to coarser fractions with reduction in water absorption by 30% for finer fractions and 22% for coarser fractions. The strength of RAC with 50% of carbonated RCA was enhanced by 17% and drying shrinkage was reduced by 16.7%. It was observed that predominant treatments such as acid impregnation, carbonation, bio-deposition tend to enhance the characteristics of RCA through mortar removal or mortar coating adhered on its surface. (Arunkumar *et al.* 2023) observed that replacement of polypropylene aggregate exceeding 15% affects the concrete strength in conjunction with use of recycled water. (Mavroulidou *et al.* 2010) observed that use of recycled tyre as coarse aggregate produces strength equivalent to normal concrete and a 11%reduction upon its use as fine aggregate owing to the reduction in the relative density of tyre particles. (Naveen Arasu *et al.* 2023) observed 20 to 30% strength improvement in the concrete with 0.04% substitution of recycled-nano-material owing to its micro-filling ability.

Fewer other researches varied the perspective of enhancing the strength of RAC through supplementation of fibres rather than improving the quality of RCA. (Chen *et al.* 2021) used 1% of chopped basalt fibre and observed that strength was enhanced by 7.8%. It was also observed that optimizing the RCA to 20% and basalt fibre to 0.5% replicate strength equivalent to the control concrete. However, at constant 1% of basalt fibre, the strength of RAC lowers with rise in the RCA. (Anand *et al.* 2023) developed aerated concrete block (ACB) with recycled aggregates, wood fibres and binders and observed that GGBS incorporated mixtures show enhancement in concrete properties and better resistance to shrinkage and chemical attacks. (Moghadam *et al.* 2021) used recycled steel fibre (SF) with RCA from different grades of concrete and observed that use of 1% of recycled SF reduced the workability by 55% and addition of RCA reduced by the workability by 38%. Also, the strength of RAC was reduced up to 27% and with 1% of recycled SF the strength was enhanced by 11%. (Anand *et al.* 2023) investigated loading rates on strength and fracture behaviour of ACB with construction waste and observed that increasing the loading lowers the elastic modulus, however incorporation of chopped wood steel fibre enhances the elastic modulus of ACB. (Bayraktar *et al.* 2023) used SF of different aspect ratio and found that the workability of RAC reduces with rise in the SF and also increase in the aspect ratio lowers the workability of RAC. The strength of RAC with SF optimized to 2% enhances the strength by 5.8% but decreases beyond 2% replacement. (El Ouni *et al.* 2022) studied the behaviour of hybrid steel-polypropylene fibre reinforced RAC and observed that addition of 1% SF enhances the strength of RAC by 14% and hybridisation of 0.85% of SF and 0.15% of PP fibres enhanced the strength by 51%. (Anand *et al.* 2023) observed optimizing chopped SF in ACB with RCA, fly ash and gypsum show up to 20% enhancement in compressive strength and 18% enhancement in flexural strength. (Gao *et al.* 2020) used SF of different volumetric fractions and observed a reduction in the workability of RAC with increase in the SF. The strength of RAC with 1% of SF was enhanced by 3.81% compared to the same mix without SF. Also, optimizing SF to 1.5% improves the durability of RAC, beyond which it affects. The review of literatures signify that fibre addition tend to enhance the characteristics of RAC but the adherence characteristics of fibres especially the non-metallic fibres with recycled aggregates needs more investigation. The smearance of mortar on the RCA tend to reduce the bonding of fibres with it. Extensive research was conducted only to study the effect of fibres on the RAC with untreated RCA. This paper investigates the influence of SF (metallic) and polypropylene fibres (PF) (non-metallic) on the behaviour of acid treated and carbonation treated RAC mixes. In this study, the RCA was treated with HCl acid (ARCA) and CO_2 (CRCA) to enhance the quality of RCA and the RAC mixes were manufactured with treated RCA and SF, PF and hybrid fibres (SF+PF) to investigate the RAC properties.

2. Research methodology

2.1. Concrete materials

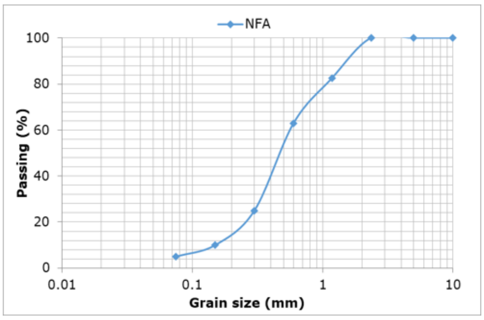
Type I ASTM cement was utilized and the properties of cement tested in accordance with ASTM C-150 (2018) is given in Table 1. The filler materials such as river sand relative to 1.18~2.36 mm was utilized as natural fine aggregate (NFA) and river gravel relative to 10 mm~20 mm was used as NCA. The concrete boulders obtained from a demolished building were fractioned to size equivalent to NCA and used as RCA in the concrete. The NCA was substituted with 100% of RCA by volumetric fraction method. The initial water absorption of RCA would be higher (Moghadam *et al.* 2021) and so to counteract, the RCA was pre-saturated for 24h and air-dried prior to its utilization in the concrete. The gradation curves of aggregates is shown in Figure 1. Potable water with its quality and properties as specified in IS 456 (2009) was used to manufacture concrete and curing of concrete. Two fibres namely steel fibre (SF) and polypropylene fibre (PF) were used in the study. The adherence of fibre with RCA was investigated with the used of both metallic (SF) and non-metallic (PF) fibres. The hooked end SF was chopped to a length of 60 mm and the PP fibre was chopped to a length of 12 mm and both the fibres are having 1 mm diameter and thus the aspect ratio of SF and PF was maintained at 60 mm and 12 mm. Table 2 depicts the properties of SF and PF utilized in the study. The visual of the concrete materials used in the study is depicted in the Figure 2. Figure 3 depicts the micro-structure of RCA, ARCA and CRCA. It could be observed that reduction in the mortar smeared on the RCA upon acid treatment in the RCA (Figure 3b) and $CaCO_3$ precipitate on surface of RCA upon carbonation treatment in the RCA (Figure 3c).

Table 1. Physical properties of cement

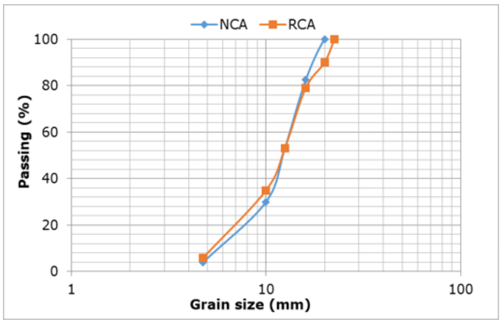
S. No	Test description	Test values
1	Early set time (mins)	32
2	Final set time (mins)	560
3	Surface area (m^2/kg)	267
4	Consistency (%)	26

Table 2. Properties of fibres

S. No	Properties	Steel fibre (SF)	Polypropylene fibre (PF)
1	Length (mm)	60	12
2	Diameter (mm)	1	1
3	Aspect ratio (l/d)	60	12
4	Tensile strength (MPa)	1900	450
5	Specific gravity (G)	7.4	0.85
6	Elastic Modulus (GPa)	190	3.5

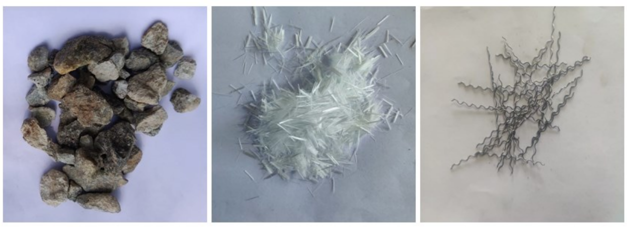


(a)



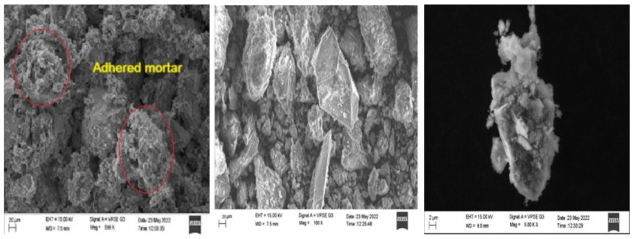
(b)

Figure 1. Gradation curves (a) NFA (b) NCA



(a) (b) (c)

Figure 2. Visual (a) RCA (b) PF (c) SF

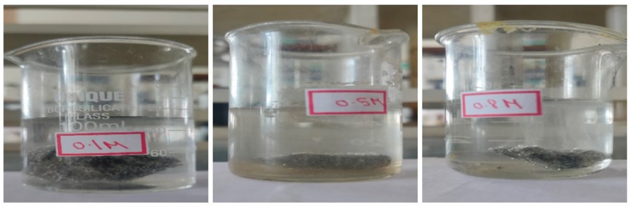


(a) (b) (c)

Figure 3. Microstructure images (a) RCA (b) ARCA (c) CRCA

2.2. Treatments

The RCA obtained from the concrete fractions of C&D possess smeared mortar on its surface. The adhered mortar hold micro-voids that rises the perviousness of RCA and weakens its interface with new mortar. So, the RCA was soaked in HCl acid and subjected to CO_2 pressure with the intend wherein the former tend to remove the smeared cement particles on RCA and the latter coat the micro-voids on the smeared mortar. Figure 4 shows the experimental set up (sample) for acid treatment. To optimize the molarity of acid impregnation, the RCA was soaked with 0.1 mol/L, 0.5 mol/L and 0.8 mol/L of HCl acid. The prepared RCA was initially weighed and immersed in different molarities of HCl acid for 24 hours. The set up was disturbed periodically to ensure the effectiveness of acid treatment to RCA. After 24 hours, the RCA was collected, cleaned for efflorescence with water, open-dried under laboratory conditions and weighed. The variations in the weights were computed and the molarity with highest decrease in the water absorption was optimized for further studies.



(a) (b) (c)

Figure 4. Acid treatment to RCA (sample) (a) 0.1 mol/L (b) 0.5 mol/L (c) 0.8 mol/L

Figure 5 shows the experimental set up of carbonation treatment. To optimize the pressure of CO_2, the RCA was treated with CO_2 at 0.1, 0.2 and 0.4 bar for 24 hours. The prepared RCA was initially weighed and placed in the carbonation chamber with 99.5% pure CO_2 at 25°C with 65% R.H. The RCA in the chamber was subjected to CO_2 pressure of 0.1, 0.2 and 0.4 bar for 24 hours. The CO_2 treated RCA was the cooled under room temperature and surfaces of RCA was cleaned and weighed. The variations in the weights were measured and the CO_2 pressure with highest decrease in the water absorption was optimized for further studies.

2.3. Concrete mixtures

The concrete mixtures are prepared with optimized percentages of fibres, untreated RCA, RCA treated with acids (RC_a) and RCA treated with CO_2 (RC_c) as per IS 10262

(2009). Table 3 shows the mixture details with the quantities of ingredients to manufacture concrete. Four batch groups of concrete namely control concrete (NAC), RAC with untreated RCA, RAC with treated RCA and RAC with fibres was used in this study. The concrete mixes are labelled as AxSFyPPz, wherein in ‘A’ indicates the percentage of RCA in which RCA can be either ‘R (untreated RCA)’ or ARCA (acid treated RCA)’ or CRCA (Carbonated RCA); ‘x’ indicates the percentage of either treated or untreated RCA; ‘y’ indicates the percentage of SF and ‘z’ indicates the percentage of PF. The control concrete was manufactured at 0.45 w/c ratio at attain a strength of M30 grade concrete. The NCA was replaced with 100% of RCA by volume and SF and PF dosed at 1.5% and 1% by volumetric fraction throughout the study.

In the manufacture of concrete mixtures, primarily the NFA and cement were blended for 120s and NCA was added and the blended for 60s. Followed by 70% of water was poured to the mix and the blending was continued for 120s and the rest 30% of water along with required volume of fibres were added and the blending was continued for 120s (Anand and Chakraborty, 2021). The most predominant problem arise during addition of fibre was that bundling of fibres and so the fibres were added gradually rather than one at a time and bundled fibres were manually separated during mixing. The mixing was further continued for 120s to ensure proper mixing of all concrete ingredients. The fresh concrete mixes were assessed for its workability and moulded into cubes (150 mm), cylinders (150 mm x 300 mm) cylinders and prisms (500 mm x 100 mm x 100 mm). The moulds were initially prepared before concrete manufacture to ensure the casting were completed within 5 minutes of manufacture. The samples were demoulded after hardening and cured under laboratory conditions to investigate its properties at the required curing ages.

Table 3. Concrete mix proportions

Mix No	Mix ID	(kg/m^3)						SF (%)	PF (%)
		Cement	NFA	NCA	RCA	ARCA	CRCA		
M1	R0SF0PF0	413	799	1029	0	0	0	0	0
M2	R100SF0PF0	413	799	0	935	0	0	0	0
M3	R0SF1.5PF0	413	799	1029	0	0	0	1.5	0
M4	R100SF1.5PF0	413	799	0	935	0	0	1.5	0
M5	R0SF0PF1.0	413	799	1029	0	0	0	0	1.0
M6	R100SF0PF1.0	413	799	0	935	0	0	0	1.0
M7	AR100SF0PF0	413	799	0	0	935	0	0	0
M8	CR100SF0PF0	413	799	0	0	0	935	0	0
M9	AR100SF1.5PF0	413	799	0	0	935	0	1.5	0
M10	CR100SF1.5PF0	413	799	0	0	0	935	1.5	0
M11	AR100SF0PF1.0	413	799	0	0	935	0	0	1.0
M12	CR100SF0PF1.0	413	799	0	0	0	935	0	1.0
M13	AR100SF1.5PF1.0	413	799	0	0	935	0	1.5	1.0
M14	CR100SFF1.5PF1.0	413	799	0	0	0	935	1.5	1.0

2.4. Concrete testing

The properties of the aggregates were tested as per ASTM C33. The workability of concrete mixtures were tested using slump cone test as per IS 1199 (2018). The fresh concrete mixes were moulded into 150 mm cubes to evaluate the compressive strength (CS) in accordance with ASTM C39. The tensile strength (TS) of concrete mixes were evaluated with cylinders in accordance with ASTM C496 and the elastic modulus (EM) of concrete mixes were evaluated with cylinders in accordance with ASTM C469. The water absorption (WA) of concrete mixes was tested in accordance with ASTM C642. All the tests were done under laboratory conditions in three trials to determine the average value.

3. Results and discussions

3.1. Optimization of treatments dosage

The optimization of treatments (both acids and CO_2) were ensured through water absorption of RCA as it is the predominant factor that affects its quality. Figure 6 shows the optimization of molarity of HCl acid to treat the RCA. The WA of RCA was 87.6% higher than NCA and that encompass on the acid treatment to RCA. The WA of ARCA (0.1M) was 5.5% and is 9.39% lesser than RCA. The WA of ARCA (0.5M) was 30.14% lesser than RCA, while the WA of ARCA (0.8M) was only 12.85% lesser than RCA. It could be observed that till 0.5M the reduction in the WA was increasing while at 0.8M the reduction in the WA of RCA tends to reduce and thus optimizing the concentration of HCl to treat RCA at 0.5M. The attribute to increase in the WA at higher molarity of HCl acid was that the erosion of RCA surface and thus its highly porous.

(a) (b)

Figure 5. Carbonation treatment to RCA (a) experimental set up (b) carbonation pressure fixing

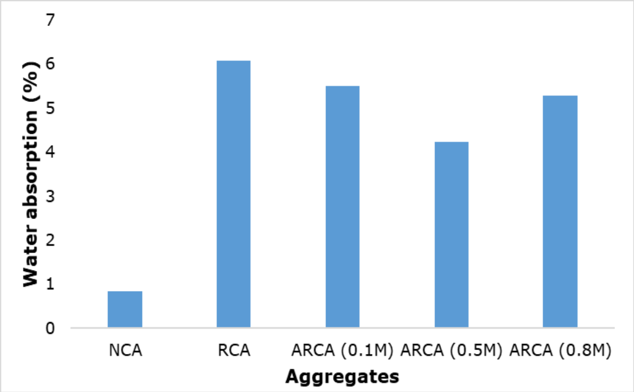


Figure 6. Optimization of molarity of HCl acid

Figure 7 shows the optimization of CO_2 pressure for carbonation treatment to RCA. The WA of CRCA (0.1bar) was 4.58% and is 24.54% lesser than RCA. The WA of CRCA (0.2bar) was 40.03% lesser than RCA, while the WA of CRCA (0.4bar) was only 12.02% lesser than RCA. It could be observed that till 0.2bar the reduction in the WA was increasing while at 0.4bar the reduction in the WA of RCA tends to reduce and thus optimizing the CO_2 pressure at 0.2 bar. Such attribute is that higher CO_2 pressure unstiffens the RCA and induces crack in it and thus higher porosity was observed. Based on the optimization of CRCA and ARCA, 17 mixes were optimized to evaluate the fresh and hardened properties as shown in the Table 3.

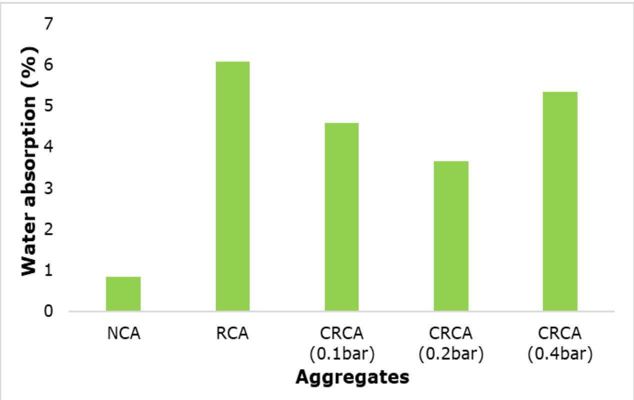
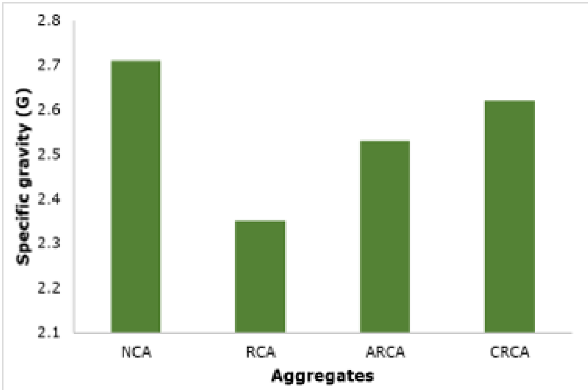


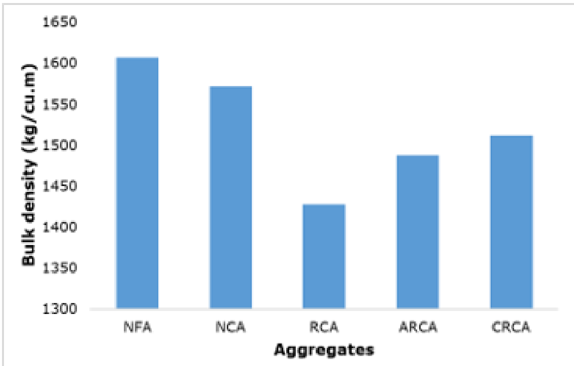
Figure 7.Optimization of CO_2 pressure

3.2. Material properties

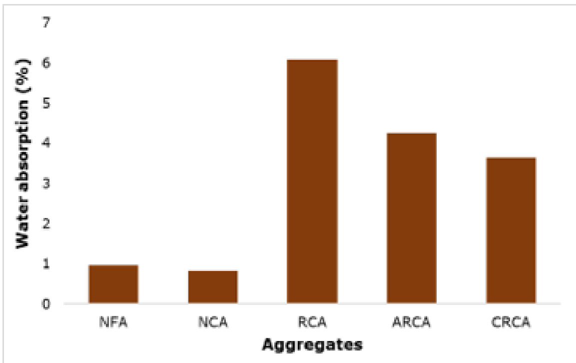
Figure 8 shows the properties of NCA, RCA, ARCA and CRCA. Figure 8(a) shows the specific gravity of aggregates, Figure 8(b) shows the bulk density of aggregates, Figure 8(c) shows the water absorption of aggregates and Figure 8(d) shows the abrasion value and impact value of aggregates. It is observed that treatments to RCA enhanced the quality of RCA. The most inferior characteristics of RCA was its increased porosity subsequent from the mortar smeared on its surface (Sivamani & Kamaleshwar 2022b, Sivamani *et al.* 2021a). The acid impregnation and carbonation to RCA reduced its WA and enhanced the quality of RCA. The specific gravity of RCA was 2.35, which was 13.28% lesser than NCA. The specific gravity of ARCA and CRCA was 2.53 and 2.62, which was 7.11% and 10.30% higher than RCA. Similarly, the bulk density of RCA was only 1572 kg/m^3 which was 9.16% lower than NCA. The bulk density of ARCA and CRCA was improved and observed to be 1487 kg/m^3 and 1512 kg/m^3. The WA of RCA was observed to be 6.07% which was 87.6% higher than NCA. The specific gravity of ARCA and CRCA was 30.14% and 40.03% lesser than RCA. Similar trends to improvement in abrasion value and impact value was observed with ARCA and CRCA compared to RCA. The acid treatment to RCA slackens the mortar smeared on the RCA and reduces its porosity and thus improvement in the quality were observed (Malathy *et al.* 2023, Ismail *et al.* 2014). The carbonation treatment to RCA involves the reaction between CO_2 and $Ca(OH)_2$ on the RCA to precipitate $CaCO_3$. The precipitated $CaCO_3$ lids the micro-voids on the smeared mortar on the RCA and improves its quality (Kaliyavardhan *et al.* 2017, Kim 2022). The former technique (acid) tends to remove the slack cement particles on the RCA whereas the latter technique (carbonation) seals the micro-voids on the smeared mortar surface of the RCA.



(a) Specific Gravity of aggregates



(b) Bulk density of aggregates



(c) Water absorption of aggregates

Figure 8.Physical properties of aggregates (a) Specific gravity (b) Bulk density (c) Water absorption (d) Abrasion and Impact value

3.3. Workability

Figure 9 shows the workability of the optimized concrete mixes. It was found that addition of RCA reduces the workability of the RAC. The workability of M2 was reduced by 42.22% than M1. The increase in porosity of RCA slurps up the water, decreasing the water requirement to manufacture stiff concrete mix and henceforth the workability of RAC reduces (Sivamani *et al.* 2021, Saravanakumar *et al.* 2016). However, the workability of M7 and M8 was enhanced by 17.46% and 22.38% compared to M2 and reduced by only 30% and 25.55% compared to M1. Both treatment techniques have reduced the WA of RCA (as could be evident in figure 7c) and thus improvement in the workability was observed in M7 and M8.

The addition of fibres tends to reduce the workability of the concrete. The workability of M3 and M5 was reduced by 18.89% and 21.11% compared to M1. However, the mix with both RCA and fibres tend to show further reduction in the workability. The workability of M4 and M6 was reduced by 48.19% and 52.23% compared to M1. Meanwhile the mix with treated RCA and fibres tend to show marginal enhancement in the workability of the RAC. The workability of M9, M10, M11 and M12 was reduced by only 33.31%, 26.59%, 35.16% and 38.91% compared to M1. The addition of hybrid fibres with RCA tend to further lessen the workability of RAC. The workability of M13 and M14 was reduced by 36.34% and 43.81% compared to M1.

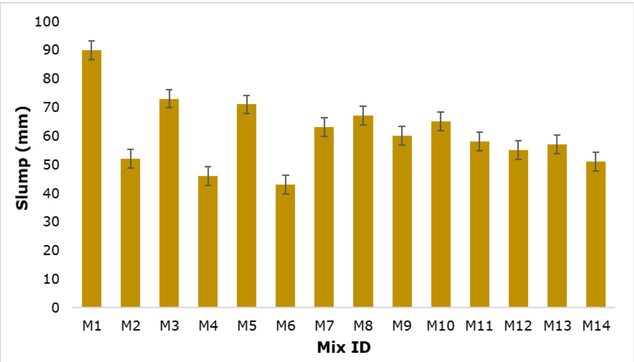


Figure 9. Workability of optimized mixes

3.4. Compressive strength

Figure 10 depicts the CS of the optimized mixes. The CS of the RAC was lowered by 18.93% at 7 days and 16.41% at 28 days compared to NAC. It is obvious that porous characteristics of RCA slurps up more water and thus the CS of RAC was reduced (Karthikeyan *et al.* 2023, Sivamani *et al.* 2021). The CS of M3 (NAC with 1.5% of SF) was enhanced by 9.30% and 15.39% and the CS of M5 (NAC with 1% of PF) was enhanced by 2.79% and 4.13% at 7 and 28 days. The higher tensile strength and elastic moduli of the SF and PF improves the strength of the NAC. However, the strength enhancement with PF was lesser compared to SF owed to its lower tensile strength and lower elastic moduli (as mentioned in Table 2). The CS of M4 (RAC with 1.5% of SF) was enhanced by 1.98% at 7 days and 3.04% at 28 days, while the CS of M6 (RAC with 1% of PF) was reduced by 27.30% at corresponding ages. It could be observed that the CS tend to reduce for the mix with the combination of RCA and PF. The attribute is that the slacked cement particles on RCA affects the bonding of fibres with the RCA and the matrix and thus the CS tend to reduce. In general, RAC has two interfacial transition zone (ITZ) with the prime between RCA and smeared mortar and tributary between old ITZ and new ITZ. The latter ITZ show inferior bonding due to the slacked cement particles on RCA and thus the CS tend to reduce.

The treatments to RCA tend to decrease the porosity of RCA and enhances the CS of RAC. The CS of M7 was 3.26% and 12.86% higher than M2 at 7 days and 28 days and reduced by only 18.41% and 4.10% at 7 days and 28 days than M1. The impregnation of RCA in HCl acid augments the latter ITZ in RAC by eradicating the smeared mortar on the RCA and thus enhancement in the CS was observed (Saravanakumar *et al.* 2016, Revathi *et al.* 2015). The CS of M8 was 7.07% and 16.30% higher than M2 at 7 days 28 days and reduced by only 12.82% at 7 days and equivalent to M1 at 28 days. The exposure of RCA to CO_2 interacts the $Ca(OH)_2$ on RCA with CO_2 to precipitate $CaCO_3$ and that seals the micro-voids on the RCA. This ensures strengthening of ITZ by proper adherence of CRCA with the cement matrix and thus enhancement in the CS was observed (Russo and Lollini 2022, Lu *et al.* 2019).

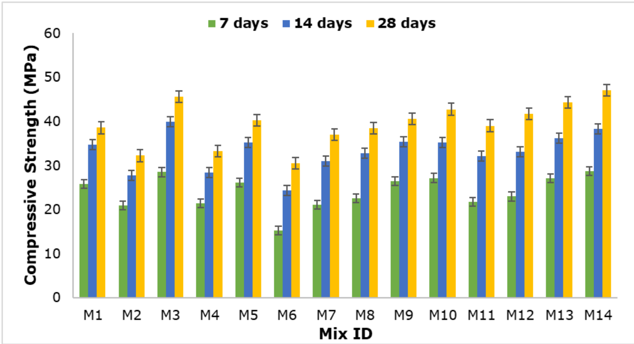


Figure 10. Compressive strength of optimized mixes

The RAC mix with treated RCA and fibres tends to show further enhancement in the CS. The CS of M9 was 10.33% and 20.68% higher than M2 at 7 and 28 days, and 2.15% and 5.07% higher than M1 at 7 and 28 days respectively. The CS of M10 was 21.45% and 24.65% higher than M2 at 7 and 28 days, and 4.86% and 9.83% higher than M1 at 7 and 28 days respectively. The addition of SF develops bridge against the crack propagation, increasing the stiffness and henceforth enhancement in the CS was observed (Ouni *et al.* 2022, Afroughsabet *et al.* 2017). However, the CS of M11 was 3.48% and 17.44% higher than M2 and the CS of M12 was 8.72% and 22.69% higher than M2 at 7 and 28 days respectively. It was observed that addition of PF tend to reduce the CS compared to SF. The PF are non-metallic agglomerate fibres that has deficit in effective dispersion and adherence with mortar surface and thus decrease in the CS was observed. The addition of hybrid fibres tend to further increase the CS of RAC. The CS of M13 was 22.56% and 27.32% higher than M2 at 7 days and 28 days and the CS of M14 was 27.01% and 31.50% higher than M2 at 7 days and 28 days. Also, the CS of M13 was 9.96% and 18.02% higher than M1 at 7 days and 28 days and the CS of M14 was 14.56% and 32.41% higher than M1 at the respective ages. It could be observed that behaviour of hybrid fibres are better compared to single fibres and also the PF performed better in conjunction with SF in improving the CS. Such hybridization could eventually reduce the corrosion in reinforced concrete than use of single SF.

The failure of the RAC with and without fibres is shown in the Figure 11. Figure 11(a) shows the failure of RAC without fibres, figure 11(b) shows the failure of RAC with fibres, figure 11(c) shows the dispersion of PF in RAC and figure 11(d) shows the dispersion of SF in RAC. It could be observed that failure initially occurs at the corners of the specimen and prolongs to the centre of the specimen. Also, from figure 11(b) the cracks initiated at the corners were stopped by bridging the gap with fibres. In figure 11(c) agglomeration of fibres owing to its uneven dispersion ability were observed and that eventually reduces the strength of RAC, whereas in figure 10(d) hooked end SF bridges the crack and the higher tensile strength of SF eventually shows higher CS in RAC than PF.

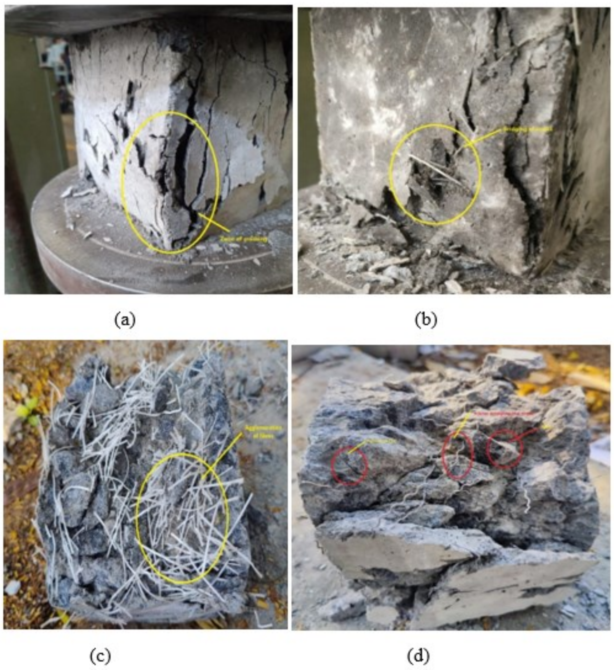


Figure 11. Failure of concrete (a) RAC (b) RAC with fibres (c) Dispersion of PF (d) Dispersion of SF

3.5. *Tensile strength*

Figure 12 shows the TS of the optimized mixes. The TS of the RAC was decreased by 20.32% at 7 days and 15.62% at 28 days compared to NAC. The decrease in the TS was due to the higher porosity of RCA and void formation in RAC upon hardening. The TS of M3 (NAC with 1.5% of SF) was 17.67% and 19.08% higher than M1 and the TS of M5 (NAC with 1% of PF) was 6.87% and 10.25% higher than M1 at 7 and 28 days. The TS of M4 (RAC with 1.5% of SF) was 11.93% and 15.30% higher than M1 at 7 days and 28 days, while the TS of M6 (RAC with 1.0% of PF) was only 7.04% and 10.91% higher than M1 at 7 days and 28 days respectively. The addition of PF increases the TS rather than the decrease as in case of CS owing to the orientation of fibres perpendicular to the loading surface of the specimen. Such orientation bridges during crack initiation and stops the crack propagation. The treatments to RCA tend to improve the TS of RAC. The TS of M7 was 5.61% higher than M2 at 7 days and 10.09% higher than M2 at 28 days and was only 15.58% lesser than M1 at 7 days and 6.15% lesser than M1 at 28 days. The enhancement in the TS was ascribed to the strengthen of ITZ subsequent from the removal of smeared cement particles. The TS of M8 was 7.04% higher than M2 at 7 days and 15.30% higher than M2 at 28 days and was only 14.28% lesser than M1 at 7 days and equivalent to M1 at 28 days. The justification for enhancement in the TS of RAC was equivalent to that of mentioned in the CS.

The RAC mix with treated RCA and fibres tends to show further enhancement in the TS. The TS of M9 was 24.56% higher than M2 at 7 days and 43.91% higher than M2 at 28 days and only 5.32% higher than M1 at 7 days and 33.53% higher than M1 at 28 days. The TS of M10 was 26.08% higher than M2 at 7 days and 45.28% higher than M2 at 28 days and only 7.22% higher than M1 at 7days and 35.14% higher than M1 at 28 days. The TS of M11 was 21.67% higher than M2 at 7 days and 37.56% higher than M2 at 28 days, while the TS of M11 was 1.70% higher than M1 at 7 days and 26.03% higher than M1 at 28 days. The TS of M12 was 22.43% higher than M2 at 7 days and 38.61% higher than M2 at 28 days, while the TS of M12 was 2.94% higher than M1 at 7 days and 27.24% higher than M1 at 28 days. The addition of hybrid fibres tend to further increase the TS of RAC. The TS of M13 was 29.48% higher than M2 at 7 days and 46.67% higher than M2 at 28 days, while the TS of M13 was 11.49% higher than M1 at 7 days and 36.80% higher than M1 at 28 days. Also, the TS of M14 was 35.64% higher than M2 at 7 days and 57.09% higher than M2 at 28 days, while the TS of M14 was 19.23% higher than M1 at 7 days and 49.14% higher than M1 at 28 days. It could be observed that behaviour of hybrid fibres are better compared to single fibres and also the PF performed better in conjunction with SF in improving the TS.

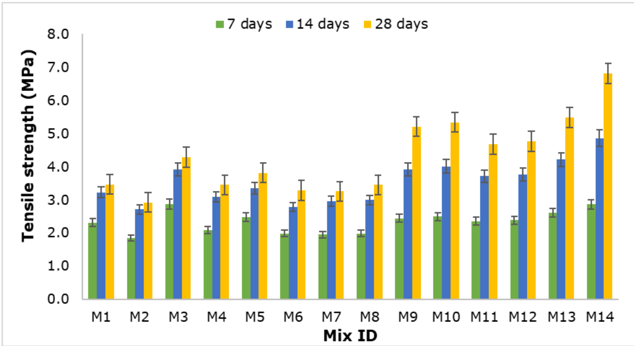


Figure 12. Tensile strength of optimized mixes

3.6. *Elastic modulus*

Figure 13 shows the EM of the optimized concrete mixes. The EM of the RAC was reduced by 20.04% at 7 days and 8.58% at 28 days compared to NAC. The reduction in the EM is owing to the reduction in the stiffness of the adherence. Since stiffness is directly proportional to the EM, reduction in the stiffness ensued through the smeared cement particles on RCA reduces the EM of RAC (Sivamani *et al.* 2021, Sivamani *et al.* 2021b). The EM of M3 (NAC with

1.5% of SF) was 1.39% and 8.02% higher than M1 at 7 and 28 days while the EM of M5 (NAC with 1% of PF) was 2.03% and 4.77% lesser than M1 at 7 and 28 days. The EM of M4 (RAC with 1.5% of SF) and M6 (RAC with 1% of PF) was 13.34% and 17.05% higher at 7 days and 1.55% and 2.78% higher at 28 days respectively. The treatments to RCA tend to improve the EM of RAC. The EM of M7 was 3.52% higher than M2 at 7 days and 6.65% higher than M2 at 28 days, while the EM of M7 was 17.12% lower than M1 at 7 days and 2.07% lower than M1 at 28 days. The enhancement in the EM was attributed to the enhancement in the stiffness of RCA through treatments to RCA by removal of smeared mortar on it. The EM of M8 was 5.35% higher than M2 at 7 days and 8.51% higher than M2 at 28 days and was only 12.75% lesser than M1 at 7 days and equivalent to M1 at 28 days. The enhancement in the EM was attributed to the enhancement in the stiffness of RCA through treatments to RCA by coating of smeared mortar on it.

The RAC mix with treated RCA and fibres tends to show further enhancement in the EM. The EM of M9 and M10 was 9.06% and 12.85% higher than M1 at 28 days and 16.87% and 20.33% higher than M2 at 28 days. However, the EM of M11 and M12 was 12.23% and 7.39% lesser than M2 at 7 days and only 1.09% and 2.33% lesser than M2 at 28 days. The addition of hybrid fibres tend to further increase the EM of RAC. The EM of M13 was 10.73% higher than M2 at 7 days and 23.03% higher than M2 at 28 days. Similarly, the EM of M14 was 15.79% higher than M2 at 7 days and 24.84% higher than M2 at 28 days. Also, the EM of M13 was only 0.85% higher than M1 at 7 days and 15.76% higher than M1 at 28 days and the EM of M14 was 4.68% higher than M1 at 7 days and 17.78% higher than M1 at 28 days.

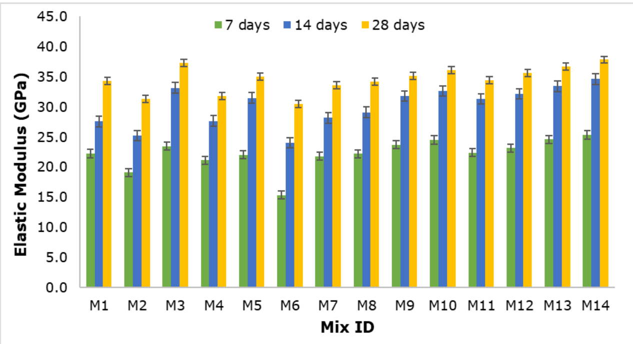


Figure 13. Elastic modulus of optimized mixes

3.7. Water absorption

Figure 14 shows the WA of the optimized mixes. The WA of M2 (100% RCA) was increased by 26.38% at 7 days and 16.19% at 28 days. The increase in the WA of RAC was due to the increase in the WA of RCA owing to the smeared cement particles on it. The WA of M3 was lowered by 7.77% at 7 days and 12.93% at 28 days, while the WA of M5 was lowered by only 2.32% at 7 days and 7.78% at 28 days. The WA of M4 was increased by 17.44% at 7 days compared to M2 and lowered by 5.21% compared to M2 at 28 days. The WA of M4 was increased by 39.21% and 11.58% compared to M1 at 7 days and 28 days. The WA of M6 was increased by 23.20% at 7 days and 1.87% at 28 days compared to M2 at 28 days. The WA of M6 was increased by 43.46% and 2.46% compared to M1 at 7 days and 28 days. The decrease in the WA with addition of fibres attributes to the bridging effect of fibres in the micro-voids in the cement matrix. Also, the reduction in the shrinkage cracking due to addition of fibres contribute to decrease in the WA. The WA of M7 was lowered by 11.02% at 7 days and 11.02% at 28 days compared to M2, while the WA of M8 was lowered by 14.78% at 7 days and 17.52% at 28 days. The reduction in the former case was attributed to the disintegration of cement particles on RCA due to acid impregnation, while in latter case precipitated $CaCO_3$ seals the micro-voids on the RCA. The results are much better with carbonation than acid impregnation as carbonation lids the micro-voids on the smeared mortar on the RCA while the acid impregnation removes the smeared mortar and that does not ensure the complete removal.

The resistance of RAC mixes with fibre and treated RCA to water was still more efficient than the RAC with untreated RCA. The WA of M8 was 24.71% lower than M2 at 7 days and 28.39% lower than M2 at 28 days. The WA of M9 was 29.91% lower than M2 at 7 days and 33.26% lower than M2 at 28 days. The behaviour was reversal with the PF owing to its agglomeration effect. The WA of M11 was increased by 6.80% at 7 days and reduced by only 0.97% at 28 days, but the WA of M12 was lowered by only 0.26% at 7 days and 6.49% at 28 days. The addition of hybrid fibres tend to show effect on the WA as the percentage of PF was reduced and the agglomeration effect was reduced upon conjunction with SF in the concrete. The WA of M13 and M14 was lowered by 31.65% at 7 days and 36.92% at 28 days and 35.37% at 7 days and 39.40% at 28 days.

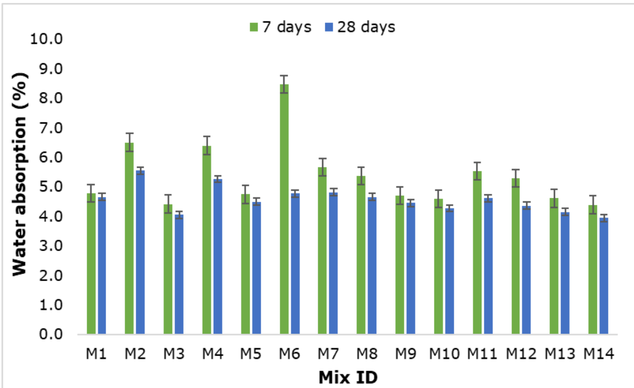


Figure 14. Water absorption of optimized mixes

4. Conclusions

The research study on the suitable utilization of dumped construction wastes through treatment with acids and CO_2 was performed to evaluate its mechanical properties and water absorption. The following conclusions upon research were presented as follows:-

1. The characteristics of RCA was substandard owing to its higher porousness and upon treatment, the water absorption tend to reduce. Compared to acid treatment, carbonation treatment reduces the water absorption of RCA greatly as it seals the micro-cracks rather than removal of cement mortar on it.

2. The acid impregnation and carbonation to RCA reduced the water absorption by 30.14% and 40.03% and enhanced the strength of RAC by 12.86% and 16.30%.
3. The addition of SF tend to enhance the strength of RAC while PF reduces the strength owing to its agglomeration effect. The addition of SF enhanced the strength of RAC by 15.36% while the addition of PF reduced the strength by 5.50%.
4. With 1% SF, the tensile strength of RAC with treated RCA was enhanced by 45.31% while the mix with hybrid fibre and treated RCA show up to 57.12% strength improvement compared to RAC.
5. The water absorption of RAC was lowered with the use of treated RCA and fibres and the maximum was observed in the mix with carbonation treated RCA and hybrid fibres.
6. The concept of hybrid fibre RAC pose suggestions on sustainable concrete with better corrosion resistance and reduced self-weight compared to single SF mixes.

5. Conflicts of Interest

The authors have declared no conflict of interest

6. Data Availability Statement

The data that support the findings of this study are available within the study and can be collected from the corresponding author upon request.

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