Advancements in Recycled Coarse Aggregate: An overview of adhered mortar removal and strengthening treatments

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Abstract: This research paper provides a comprehensive review of pre-treatment techniques for enhancing recycled coarse aggregate (RCA) by removing adhered mortar (A-M) and strengthening A-M. The paper examines various techniques and their effects on different properties of RCA. Autogenous cleaning, ball milling treatment, acid treatment, thermal treatment, and microwave treatment were found effective for A-M removal. These techniques improved properties such as water absorption, density, and strength of RCA, but some treatments caused minor cracks. Slurry impregnation, polymer impregnation, carbonation treatment, sodium silicate impregnation, and bio-deposition treatment were discussed for A-M strengthening. These techniques enhanced the water absorption, crushing value, and strength of RCA, but polymer impregnation could decrease compressive strength of recycled aggregate concrete.

Keywords: Pre-treatment, Construction and demolition waste, Recycled aggregate, Adhered mortar, Enhancement

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Introduction

With the increase in industrialization, many countries face a significant challenge in managing construction & demolition waste (CDW). CDW is produced during building, renovation, and destruction activities [1]. Another author [2] defined CDW as encompassing an extensive variety of constituents such as construction debris, soil, steel, concrete, timber, mixed material, and bricks, from various construction activities like building construction, maintenance, renovation, site clearance, repair, and demolition. With the increase in construction activities, million tons (MT) of CDW has been produced worldwide. As per a study, CDW occupies up to 40% of the total solid waste generated worldwide [3]. It has been estimated that the U.S.A. independently generates approximately 924 MT of CDW annually. Similarly, the European union generates about 534 MT of CDW yearly [4]. Most widely used approach for the disposal of CDW is landfilling. The large deposits of CDW in landfills lead to various ecological hazards like underground water and soil pollution owing to the leaching of harmful compounds in the soil surface and groundwater [4]. However, this CDW can efficiently be utilized in concrete production, leading to sustainable construction activities, and minimizing environmental impacts. Also, with the growth of the construction industry, the consumption of concrete is also growing, making concrete a non-sustainable material [5]. Concrete, a composite material, consists of various constituents like cement, sand, coarse aggregate, and water. The aggregates in concrete occupy a significant share of 60% to 75% of its ingredients [6]. According to Tam et al. (2021), China and India account for about 40% and 10%, respectively [7]. The total global production of N.A. [8] and total global CDW generation [9] can be understood from the **Figure 1 (a) and (b),** respectively. The tend highlights the irresponsible utilization of natural resources, which contradicts the principle of sustainable development. Instead, we should focus on recycling, reusing, and reutilizing to promote a more sustainable approach. The usage of recycled aggregate (RA) sourced from CDW offers a viable alternative to NA in concrete production. Many investigations have discussed the possibility of utilization of RA in concrete [10–15]. However, the effective utilization of RA in concrete is still under question as the virgin RA in concrete is still partially used [16]. The restriction in the effective utilization of RA is the sub-standard properties of RA in reference to N.A. The RA, in its natural form, possesses inferior porosity, water absorption, and strength compared to N.A. [17,18]. The reason for these inferior properties of RA is that the old adhered mortar (A-M) stick to the aggregate, which forms a porous interfacial transition zone (ITZ) among A-M and aggregate, deteriorating RA characteristics. Mistri et al. (2020) have classified the RA into four categories depending upon the amount of A-M attached [19]. So, the consumption of RA in the development of concrete is restricted as the increased quantity of RA in concrete may lead to degrade the properties of recycled aggregate concrete (RAC) like water absorption, dry shrinkage, permeability, and strength [20,21]. Many investigations have concluded that the 100% replacement of N.A. with RA may cause a drop in compressive strength of concrete by 5% to 25% depending upon the quality of RA and water/cement (w/c) ratio [22,23]. RA is generally used in concrete with compressive strength rang not exceeding 60 MPa, flexural and split tensile greater than 4 MPa and 2 MPa, respectively [24–26].

For the effective utilization of RA in concrete many investigators have used different treatment techniques to increase the quality of RA. As per the studies, the characteristics of RA can be improved by strengthening A-M or removing A-M [27]. Removing A-M on RA can be done using various pre-treatment techniques like autogenous cleaning, ball milling, acid, thermal, and microwave treatment [7]. These pre-treatment techniques for removing A-M are classified into two categories: Physical treatment and chemical treatment. The physical treatment includes mechanical, thermal, thermos-mechanical, electrical, and water treatment. Furthermore, the chemical treatment includes acid soaking and chemico-mechanical treatment [7]. The removed A-M can be reutilized in various forms like cement, cement substitute after activation, and raw material in geo-polymer concrete as an admixture [7]. A-M can be strengthened using pre-treatment techniques like pozzolanic slurry/ polymer impregnation, accelerated carbonation, and bio-deposition treatment.

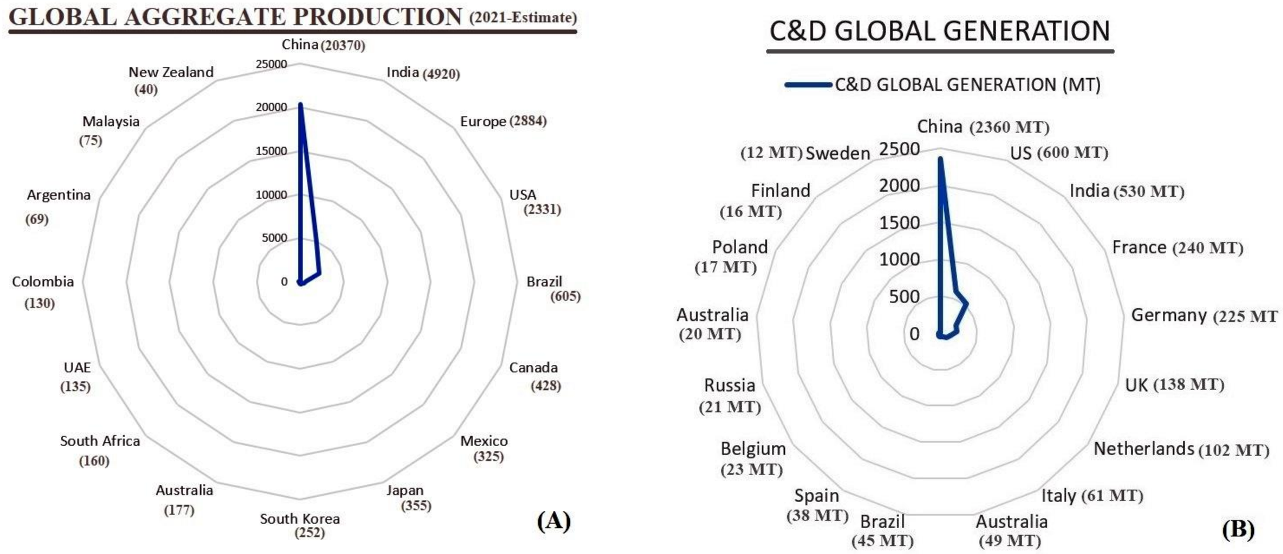

Figure 1: (a) Global production of Natural aggregate [8] **and (b) Global CDW generation** [28–34]

In this study the author has tried to review the latest literature on the various pre-treatment techniques used to enhance recycled coarse aggregate (RCA). The treatment techniques are divided into two parts: for removing A-M and for strengthening A-M. The paper also discussed the outcome of different pre-treatment methods on various parameters of RAC. Finally, after reviewing the latest available literature, this paper provides an overview of different treatment methods of RCA, considering their merits and demerits.

1. Pre-treatment techniques for the removal of adhered mortar

Using RCA in concrete, solely through manual or mechanical water cleaning the RCA from CDW, is technically insufficient due to its inability to eliminate the A-M from RCA. Many studies have shown the beneficial outcomes of the removal of A-M on various characteristics of RCA [7]. Removing A-M from the RCA surface tends to provide a smooth surface of the resulting RCA, which has its benefits in RCA concrete sequentially. The structure of A-M is highly porous; removal of A-M tends to improve RCA's porosity, density, and water absorption. It has also been seen that the RCA having less A-H tends to have better workability. This section discusses various pre-treatment techniques for removing A-M and its effect on the properties of RCA.

2.1 Autogenous cleaning

The autogenous cleaning (AC) treatment process for RCA is generally carried out to decrease the quantity of fine material adhered to the RCA. In this process, rotating mill drums are utilized to facilitate the self-collision of RCAs. This collision causes the detachment of mortar fragments attached to RCA. Based on the outcomes of Pepe et al. (2014), AC treatment improves the morphology of the RCA [35]. The water absorption of RCA after AC treatment reduced by 20-50%. The AC is also improves the tensile strength of RCA [36].

2.2 Ball milling treatment

Mechanical grinding or ball milling treatment of RCA is an effective technique for removing A-M from RCA [37]. In this method, the RCAs are subjected to grinding action using balls within a mechanical mill to eliminate the excess mortar on the aggregate [19]. Numerous research investigations have demonstrated the enhancement of RCA characteristics through the application of ball milling. Revathi et al. (2015) and Pandurangan et al. (2016) suggested that the mechanical grinding of RCA can improve RCA's wear coefficient, permeability, and E-value by 33%, 15.89%, and 31%, respectively [38,39]. Based on the study conducted by Dilbas et al. (2019), it has been determined that optimizing the drum rotation and number of steel balls in the ball milling apparatus can effectively improve the characteristics of RCA [40]. The study observed a significant improvement in the water absorption of RCA from 8.95% to 0.84%. After undergoing ball milling or mechanical grinding treatment, RCAs were determined to be suitable for the replacement of N.A. for the production of RAC [40–44]. However, ball milling, mechanical grinding, or RCA, is an effective and low-energy-consuming treatment. But during this treatment, RCAs develop minor cracks in the structure, which decreases the strength of the aggregate.

2.3 Acid treatment

Removal of A-M from the RCA surface is a complex task owing to the enduring chemical reaction for the hydration process of cement. Cement hydration occurs over a long duration as the cement constituents in the presence of water form a complex and rigid structure. However, acids ranging from strong to medium concentrations can be employed to remove the A-M from RCA [27]. Following the acid treatment of RCA, it is necessary to perform a comprehensive rinsing of RCA to remove any remaining chemicals. As per the investigation by Ouyang et al. (2023), the RCA treated with H_2SO_4 solution improves the strength, E-value, and permeability of RCA by 16.10%, 38.81%, and 28.10%, respectively, and the RCA treated with HCL immersion improved the strength, E-value, permeability of RCA by 11.51%, 20%, 12% [45]. The amount of A-M removal from the RCA depends on the acid's strength and the treatment duration [46]. While acid treatment of RCA effectively removes A-M from RCA, it necessitates a significant amount of fresh water. Moreover, the water used for rinsing the RCA during this process becomes acidic, requiring subsequent treatment before its disposal or reuse.

2.4 Thermal treatment

Thermal treatment of RCA refers to the heating of RCA to remove the excess water present in the pores and the amount of A-M. This treatment involves a series of water immersion and heating of RCA [47–49]. As reported by de Juan and Gutiérrez (2009), the process of thermal treatment is to first heat the RCA at 500℃ for two hrs., and then the RCA are immersed in water. The immediate variation in the temperature of RCA tends to break the A-M. The study's findings [39] indicated that RCA retained 11% A-M after undergoing the treatment. RCA's water absorption and specific gravity also improved by 17% and 2.4%, respectively.

2.5 Microwave treatment

Microwave treatment (MWT) of RCA is a viable method of removing A-M from RCA. As the RCA and A-M have different densities, the sensitivity of both materials toward microwaves also differs. Applying microwaves to RCA induces complex thermal stresses in A-M than in RCA, effectively detaching A-M from the RCA [50]. The success rate of MWT depends on the quantity and size of A-M attached [51]. As per various studies [52,53], the microwave treatment of RCA can remove up to 71% of A-M from RCA. This treatment can also significantly grow the compressive and flexural strength of the RCA. As per studies [54,55], the microwave treatment of RCA can improve the water absorption, apparent density, and crushing value by 28.36%, 4.44%, and 30.5%, respectively.

Table 1: Comparative analysis of adhered mortar removal of RCA

Treatment technique	Property improved	Percentage improvement	Reference
Autogenous cleaning	Water absorption	20% to 30%	[35]
	Tensile strength	Satisfactory	[36]
Ball milling treatment	Water absorption	90%	[40]
	Wear coefficient	33 %,	[38]
	Permeability	15.89%,	[38]
	E-value	31%	[38]
Acid Treatment (H_2SO_4)	Strength	16.10%	[45]
	E-value	38.81%	[45]
	Permeability	28.10%	[45]
Acid Treatment (HCl)	Strength	11.51%	[45]
	E-value	20%	[45]
	Permeability	12%	[45]
Thermal treatment	Water absorption	17%	[39]
	Specific gravity	2.4%	[39]
Microwave treatment	Water absorption	28.36%	[54]
	Apparent density	4.44%	[54]
	Crushing value	30.5%	[54]

2. Pre-treatment techniques for the strengthening of adhered mortar

RCA pre-treatment techniques for strengthening adhered mortar can be divided into three groups. The first type is surface strengthening, which involves cement slurry impregnation and polymer impregnation treatment techniques. The second category is chemical strengthening, where the strength of A-M is achieved through accelerated carbonation curing treatment and sodium silicate impregnation treatment. The third category is the biological strengthening of A-M, which is strengthened using the bio-deposition treatment technique. The subsequent discussion addresses each treatment technique's influence on RCA properties.

3.1. Slurry impregnation

Slurry impregnation is employed to enhance RCA's properties by saturating it with a highly reactive powder paste [56]. This paste enhances the saturation of the RCA surface, leading to the refinement of its microstructure. This treatment also helps to increase the bond strength among the RCA and new cement paste in concrete. The dry shrinkage of RCA was reduced by 4.46% using cement-fly ash impregnation treatment [57]. As per another study, the porosity of RCA was reduced by 23.53% and 55.29% by treating the RCA with cement slurry and pozzolanic material slurry, respectively [58]. The use of highly reactive materials in this technique confers two technical advantages. Firstly, the material's particle size is smaller than that of the cement particles, allowing it to efficiently occupy the pores within the RCA. This leads to a decrease in porosity and results in an improved external surface. Secondly, such materials exhibit a considerable surface area which enhances the hydration process of the mix [59–61].

3.2. Polymer impregnation

Polymer impregnation (Pi) is a similar technique to slurry impregnation in which the efficiency of impregnation depends upon the type of polymer material. Various silane-based emulsions and Polyvinyl alcohol (P.V.A.) are the two widely used polymers for this technique. As per a study by Kou and Poon, (2010), the density of Pi oven-dried and air-dried treated RCA improved by about 1.8% and 2%, respectively, and the water absorption improved about 61% and 74%, respectively [62]. The split tensile strength of Pi-treated RCA concrete (Pi-RAC) showed 3.24% improvement in the 28-day split tensile strength [45]. Also, the dry shrinkage of Pi-RAC was improved by 15% [62], and the dry shrinkage of silane-based Pi-RAC improved to about 9% [63]. The chloride penetration of Pi-RAC was enhanced by 30% [62]. The Pi treatment improved the water absorption and permeability of Pi-RAC effectively. However, on the other hand, it can also decrease the compressive strength of Pi-RAC by about 11% [45]. Pi modification of RCA has the capability to enhance the characteristics of RCA, but conversely, this treatment may also negatively impact the compressive strength of the concrete. The polymer particles infiltrate the cement paste and impart hydrophobic properties, hindering the hydration process. Also, the formation of hydrophobic effects the bond strength among cement paste and aggregate, further reducing the strength of the mix [27].

3.3. Carbonation treatment

Carbonation of RCA involves exposing the RCA to carbon dioxide under a controlled environment to expedite the natural carbonation process. The CO_2 reacts with the calcium hydroxide, ensuing the development of $CaCO_3$ precipitates [64]. Many studies have shown remarkable benefits of the carbonation of RCA. The carbonation treatment of RCA improved the water absorption, crushing value, and density of RCA by 23%, 7.6%, and 5.6%, respectively [65]. Another study showed an improvement of 31.5%, 15.2%, and 3.2% in the crushing value, water absorption, and density of RCA treated with carbonation [66]. The improvement in the characteristics of RCA after its carbonation is due to the development of $CaCO_3$ precipitate and additional silica gel during the treatment process [67]. This additional silica gel and $CaCO_3$ precipitate densify the microstructure of the RCA improving several properties of the mix.

3.4. Sodium silicate impregnation

Sodium silicate impregnation (SSi) treatment of RCA also possesses the ability to improve the properties of RCA significantly. SSi is almost similar to slurry impregnation and polymer impregnation treatments. The treatment commonly referred to as water glass treatment is another name of sodium silicate impregnation treatment [68]. Sodium silicate solutions are not hydrophobic as polymer solutions, so the property encasement process of this treatment is different. The RCA treated with sodium silicate impregnation treatment showed improved crushing value, water absorption and compressive strength by 16.6%, 20% and 11.82%, respectively [69]. The average improvement in the apparent density, water absorption, and crushing value of RCA treated with different sodium silicate concentrations was 2%, 10.5%, and 13.3%, respectively [70].

Furthermore, when the RCA is subjected to a sodium silicate solution, the sodium silicate ions within the pores of the RCA or attached to the surface undergo a chemical reaction with the calcium and aluminium ions found in the cement paste. The occurrence of these chemical responses leads to the development of supplementary calcium aluminate hydrates or calcium silicate hydrates, ultimately improving the characteristics of the mix [71]. Additionally, the interaction between sodium silicate and calcium hydroxide can increase the mix's alkalinity, potentially leading to a decline in its durability [27,68].

3.5. Bio-deposition treatment

Bio-deposition is a recently developer technology for the improvement of RCA. This technology works with the natural phenomenon of bacteria to produce inorganic material, which is further converted into $CaCO_3$ through several chemical reactions [72,73]. The full process of development of $CaCO_3$ can be seen in a study by [19]. RCA treated with bio-deposition treatment show an average water absorption improvement of 15.77% [74]. Another study showed an improvement in water absorption of 9% when immersed in a bacterial solution [75]. Wu et al., (2018) found the improvement of RCA after bacterial treatment as 1%, 10%, and 15% for apparent density, water absorption, and crushing value [76]. Zhao et al., (2021) found an improvement of 10% and 2% in water absorption and apparent density of RCA modified with bacterial treatment [77].

Table 2: Comparative analysis of strengthening of adhered mortar of RCA

Treatment technique	Property improved	Percentage improvement	Reference
Cement fly ash impregnation	Dry shrinkage	4.46%	[57]
Cement slurry impregnation	Porosity	23.53%	[58]
Pozzolanic slurry impregnation	Porosity	55.29%	[58]
Polymer impregnation (Oven dried)	Density	1.8%	[62]
	Water absorption	61%	[62]
Polymer impregnation (Air-dried)	Density	2%	[62]
	Water absorption	74%	[62]
Carbonation treatment	Water absorption	23%	[65]
	Crushing value	7.6%	[65]
	Apparent density	5.6%	[65]
	Apparent density	3.2%	[66]
	Water absorption	15.2%	[66]
	Crushing value	31.5%	[66]
Sodium silicate impregnation	Crushing value	16.6%	[69]
	Water absorption	20%	[69]
	Compressive strength	11.82%	[69]
	Apparent density	2%	[70]
	Water absorption	10.5%	[70]
	Crushing value	13.3%	[70]
Bio-deposition	Water absorption	15.77%	[74]
	Water absorption	9%	[75]
	Water absorption	10%	[76]
	Crushing value	15%	[76]
	Apparent density	1%	[76]
	Apparent density	2%	[77]
	Water absorption	10%	[77]

3. Conclusion

This research paper reviewed various pre-treatment techniques for enhancing recycled coarse aggregate (RCA) by removing adhered mortar (A-M) and strengthening the A-M. The techniques discussed included autogenous cleaning, ball milling treatment, acid treatment, thermal treatment, microwave treatment, slurry impregnation, polymer impregnation, carbonation treatment, sodium silicate impregnation, and bio-deposition treatment. The effects of these techniques on different properties of RCA were examined.

For the removal of A-M, Autogenous cleaning improved the morphology, water absorption, and tensile strength of RCA. Ball milling treatment improved the wear coefficient, permeability, and E-value of RCA, but minor cracks in the structure decreased the aggregate strength. Acid treatment with H_2SO_4 or HCL solutions improved RCA's strength, E-value, and permeability but required a significant amount of water and subsequent treatment for disposal or reuse. Thermal and microwave treatments also showed promising results in removing A-M and improving water absorption, apparent density, and crushing value.

Pre-treatment techniques were categorized as surface strengthening, chemical strengthening, and biological strengthening for the strengthening of adhered mortar. Slurry impregnation with cement or pozzolanic materials reduced dry shrinkage and porosity of RCA Polymer impregnation, improved density, water absorption, and split tensile strength of RCA concrete but could decrease compressive strength. Carbonation treatment and sodium silicate impregnation resulted in the formation of $CaCO_3$ and additional silica gel, enhancing water absorption, crushing value, and apparent density of RCA Bio-deposition treatment utilizing bacterial activity improved water absorption and apparent density of RCA.

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References

[1] J. Park, R. Tucker, Overcoming barriers to the reuse of construction waste material in Australia: a review of the literature, Int. J. Constr. Manag. 17 (2017) 228–237. https://doi.org/10.1080/15623599.2016.1192248.
[2] S.L. Y., T.V.W. Y., T.C. M., D. D., Mapping Approach for Examining Waste Management on Construction Sites, J. Constr. Eng. Manag. 130 (2004) 472–481. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(472).
[3] R. Jin, H. Yuan, Q. Chen, Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018, Resour. Conserv. Recycl. 140 (2019) 175–188. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.09.029.
[4] K. Chen, J. Wang, B. Yu, H. Wu, J. Zhang, Critical evaluation of construction and demolition waste and associated environmental impacts: A scientometric analysis, J. Clean. Prod. 287 (2021). https://doi.org/10.1016/j.jclepro.2020.125071.
[5] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review, Constr. Build. Mater. 68 (2014) 501–516. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.07.003.
[6] S.H. Kosmatka, W.C. Panarese, B. Kerkhoff, Design and control of concrete mixtures, Portland Cement Association Skokie, IL, 2002.
[7] V.W.Y. Tam, M. Soomro, A.C.J. Evangelista, Quality improvement of recycled concrete aggregate by removal of residual mortar: A comprehensive review of approaches adopted, Constr. Build. Mater. 288 (2021) 123066. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.123066.
[8] A. Business, Growing global aggregates sustainably, Route One. (2021). https://www.aggbusiness.com/feature/growing-global-aggregates-sustainably.
[9] B. Wang, L. Yan, Q. Fu, B. Kasal, A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete, Resour. Conserv. Recycl. 171 (2021) 105565. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105565.
[10] A. Ben Fraj, R. Idir, Concrete based on recycled aggregates – Recycling and environmental analysis: A case study of paris' region, Constr. Build. Mater. 157 (2017) 952–964.

https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.09.059.
[11] P. Gill, P. Jangra, D.K. Ashish, Non-destructive prediction of strength of geopolymer concrete employing lightweight recycled aggregates and copper slag, Energy, Ecol. Environ. (2023). https://doi.org/10.1007/s40974-023-00281-w.
[12] A.D. K., V.S. K., Effect on Permeability of Concrete Made with Successive Recycled Aggregate and Silica Fume, Urban. Challenges Emerg. Econ. (2018) 196–205. https://doi.org/doi:10.1061/9780784482032.021.
[13] P.S. Deepankar K. Ashish, Successive recycled coarse aggregate effect on mechanical behavior and microstructural characteristics of concrete, Comput. Concr. 21 (2018) 39–46.
[14] D.K.A. Preeti Saini, A Review on Recycled Concrete Aggregates, SSRG Int. J. Civ. Eng. EFES (2015) 71–75.
[15] Surender K. Verma and Deepankar K. Ashish, Mechanical behavior of concrete comprising successively recycled concrete aggregates, Adv. Concr. Constr. 5 (2017) 303–311. https://doi.org/https://doi.org/10.12989/acc.2017.5.4.303.
[16] H. Guo, C. Shi, X. Guan, J. Zhu, Y. Ding, T.-C. Ling, H. Zhang, Y. Wang, Durability of recycled aggregate concrete – A review, Cem. Concr. Compos. 89 (2018) 251–259. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2018.03.008.
[17] R. V Silva, J. de Brito, R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Constr. Build. Mater. 65 (2014) 201–217. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.04.117.
[18] Hansen T.C., Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945-1985, Mater. Struct. 19 (1986) 201–246. https://doi.org/10.1007/BF02472036.
[19] A. Mistri, S.K. Bhattacharyya, N. Dhami, A. Mukherjee, S. V Barai, A review on different treatment methods for enhancing the properties of recycled aggregates for sustainable construction materials, Constr. Build. Mater. 233 (2020) 117894. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.117894.
[20] J. Xiao, J. Li, C. Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, Cem. Concr. Res. 35 (2005) 1187–1194. https://doi.org/https://doi.org/10.1016/j.cemconres.2004.09.020.
[21] K.P. Verian, W. Ashraf, Y. Cao, Properties of recycled concrete aggregate and their influence in new concrete production, Resour. Conserv. Recycl. 133 (2018) 30–49. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.02.005.
[22] C.J. Shi, Z.J. Cao, Z.B. Xie, Research progress in the mechanical properties of recycled aggregate concrete, Mater. Rep. 30 (2016) 96–103.
[23] T. Xie, A. Gholampour, T. Ozbakkaloglu, Toward the development of sustainable concretes with recycled concrete aggregates: comprehensive review of studies on mechanical properties, J. Mater. Civ. Eng. 30 (2018) 4018211.
[24] H.-B. Le, Q.-B. Bui, Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance, Constr. Build. Mater. 257 (2020) 119522. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.119522.
[25] J. Xiao, W. Li, Y. Fan, X. Huang, An overview of study on recycled aggregate concrete in China (1996–2011), Constr. Build. Mater. 31 (2012) 364–383. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2011.12.074.
[26] K.H. Younis, K. Pilakoutas, Strength prediction model and methods for improving recycled aggregate concrete, Constr. Build. Mater. 49 (2013) 688–701. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.09.003.
[27] C. Shi, Y. Li, J. Zhang, W. Li, L. Chong, Z. Xie, Performance enhancement of recycled concrete aggregate – A review, J. Clean. Prod. 112 (2016) 466–472. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.08.057.

[28] C.P. Ginga, J.M.C. Ongpeng, M.K.M. Daly, Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production, Materials (Basel). 13 (2020). https://doi.org/10.3390/ma13132970.
[29] Eurostat, Waste Generation by Packaging Material, Packag Waste Stat. (2017).
[30] B. Eurostat, Generation of waste by waste category, hazardousness and NACE Rev. 2 activity, Dispon. En Ligne. (2016).
[31] U.S.E.P. Agency, Advancing Sustainable Materials Management: 2018 Fact Sheet, (2018).
[32] I. Ministry of Environment, Forest and Climate Change, Construction and Demolition Waste Management Rules, (2016). https://vikaspedia.in/energy/environment/waste-management/environment-ministry-notifies-construction-and-demolition-waste-management-rules-for-the-first-time.
[33] A. Aleksanin, Development of construction waste management, in: E3S Web Conf., EDP Sciences, 2019: p. 6040.
[34] K.R.A. Nunes, C.F. Mahler, Comparison of construction and demolition waste management between Brazil, European Union and USA, Waste Manag. Res. 38 (2020) 415–422.
[35] M. Pepe, R.D. Toledo Filho, E.A.B. Koenders, E. Martinelli, Alternative processing procedures for recycled aggregates in structural concrete, Constr. Build. Mater. 69 (2014) 124–132. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.06.084.
[36] M. Sadagopan, K. Malaga, A. Nagy, Improving Recycled Aggregate Quality by Mechanical Pre-Processing, Materials (Basel). 13 (2020). https://doi.org/10.3390/ma13194342.
[37] O.E. Gjorv, K. Sakai, Concrete technology for a sustainable development in the 21st century, CRC Press, 1999.
[38] P. Revathi, A.R. Ruthirapathy, K. Lavanya, Influence of Treatment Methods on the Strength and Performance Characteristics of Recycled Aggregate Concrete, J. Mater. Civ. Eng. 27 (2015) 4014168. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001128.
[39] K. Pandurangan, A. Dayanithy, S. Om Prakash, Influence of treatment methods on the bond strength of recycled aggregate concrete, Constr. Build. Mater. 120 (2016) 212–221. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.05.093.
[40] H. Dilbas, Ö. Çakır, C.D. Atiş, Experimental investigation on properties of recycled aggregate concrete with optimized Ball Milling Method, Constr. Build. Mater. 212 (2019) 716–726. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.04.007.
[41] K. Huang, T. Ding, J. Xiao, A. Singh, Modification on Recycled Aggregates and its Influence on Recycled Concrete, IOP Conf. Ser. Earth Environ. Sci. 323 (2019) 12136. https://doi.org/10.1088/1755-1315/323/1/012136.
[42] K. Yanagibashi, T. Yonezawa, K. Arakawa, M. Yamada, A new concrete recycling technique for coarse aggregate regeneration process, in: Challenges Concr. Constr. Vol. 5, Sustain. Concr. Constr. Proc. Int. Conf. Held Univ. Dundee, Scotland, UK 9–11 Sept. 2002, Thomas Telford Publishing, 2002: pp. 511–522.
[43] H. Ogawa, T. Nawa, Improving the Quality of Recycled Fine Aggregate by Selective Removal of Brittle Defects, J. Adv. Concr. Technol. 10 (2012) 395–410. https://doi.org/10.3151/jact.10.395.
[44] H.-S. Kim, J.-M. Kim, B. Kim, Quality improvement of recycled fine aggregate using steel ball with the help of acid treatment, J. Mater. Cycles Waste Manag. 20 (2018) 754–765. https://doi.org/10.1007/s10163-017-0639-8.
[45] K. Ouyang, J. Liu, S. Liu, B. Song, H. Guo, G. Li, C. Shi, Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review, Resour. Conserv. Recycl. 188 (2023) 106717. https://doi.org/https://doi.org/10.1016/j.resconrec.2022.106717.
[46] S. Ismail, M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications, Constr. Build. Mater. 44 (2013) 464–476.

https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.03.014.
[47] M. Barra de Oliveira, Estudio de la Durabilidad del Hormigón de Árido Reciclado en su aplicación como hormigón estructural, (1996).
[48] E. Vázquez, M. Barra, Hormigón de áridos reciclados: retracción, V Semin. Desnvolvimento Susatentavel Ea Reciclagem Na Constr. Civil. Com. Técnico. 206 (2002) 7–14.
[49] M.S. de Juan, P.A. Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate, Constr. Build. Mater. 23 (2009) 872–877. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2008.04.012.
[50] Q. Like, L. Yong, D. Jun, T. Pengfei, Thermal Stress Distribution and Evolution of Concrete Particles under Microwave Irradiation., J. Eng. Sci. Technol. Rev. 9 (2016).
[51] Y. Menard, K. Bru, S. Touze, A. Lemoign, J.E. Poirier, G. Ruffie, F. Bonnaudin, F. Von Der Weid, Innovative process routes for a high-quality concrete recycling, Waste Manag. 33 (2013) 1561–1565. https://doi.org/https://doi.org/10.1016/j.wasman.2013.02.006.
[52] N. Lippiatt, F. Bourgeois, Investigation of microwave-assisted concrete recycling using single-particle testing, Miner. Eng. 31 (2012) 71–81. https://doi.org/https://doi.org/10.1016/j.mineng.2011.09.017.
[53] K. Bru, S. Touzé, F. Bourgeois, N. Lippiatt, Y. Ménard, Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste, Int. J. Miner. Process. 126 (2014) 90–98. https://doi.org/https://doi.org/10.1016/j.minpro.2013.11.009.
[54] J.Z. Xiao, L. Wu, Y.H. Fan, Test on modification of recycled coarse aggregate by microwave heating, Concrete. 7 (2012) 55–57.
[55] X. Yang, Y. Liu, J. Liang, Y. Meng, H. Rong, D. Li, Y. Chen, J. Lv, Y. Jiang, Y. Liu, Straightening methods for RCA and RAC—a review, Cem. Concr. Compos. 141 (2023) 105145. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2023.105145.
[56] Z. Hongru, Z. Yuxi, M. Tao, S.S. P., Surface Treatment on Recycled Coarse Aggregates with Nanomaterials, J. Mater. Civ. Eng. 28 (2016) 4015094. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001368.
[57] J. Wang, J. Zhang, D. Cao, H. Dang, B. Ding, Comparison of recycled aggregate treatment methods on the performance for recycled concrete, Constr. Build. Mater. 234 (2020) 117366. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.117366.
[58] W.M. Shaban, J. Yang, H. Su, Q. Liu, D.C.W. Tsang, L. Wang, J. Xie, L. Li, Properties of recycled concrete aggregates strengthened by different types of pozzolan slurry, Constr. Build. Mater. 216 (2019) 632–647. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.04.231.
[59] Ö. Çakır, Ö.Ö. Sofyanlı, Influence of silica fume on mechanical and physical properties of recycled aggregate concrete, HBRC J. 11 (2015) 157–166. https://doi.org/10.1016/j.hbrcj.2014.06.002.
[60] Y. Esen, A. Kurt, Effect of High Temperature in Concrete for Different Mineral Additives and Rates, KSCE J. Civ. Eng. 22 (2018) 1288–1294. https://doi.org/10.1007/s12205-017-1224-3.
[61] R. Kurda, J. de Brito, J.D. Silvestre, Combined influence of recycled concrete aggregates and high contents of fly ash on concrete properties, Constr. Build. Mater. 157 (2017) 554–572. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.09.128.
[62] S.-C. Kou, C.-S. Poon, Properties of concrete prepared with PVA-impregnated recycled concrete aggregates, Cem. Concr. Compos. 32 (2010) 649–654. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2010.05.003.
[63] Y.-G. Zhu, S.-C. Kou, C.-S. Poon, J.-G. Dai, Q.-Y. Li, Influence of silane-based water repellent on the durability properties of recycled aggregate concrete, Cem. Concr. Compos. 35 (2013) 32–38. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2012.08.008.

[64] B. Johannesson, P. Utgenannt, Microstructural changes caused by carbonation of cement mortar, Cem. Concr. Res. 31 (2001) 925–931. https://doi.org/https://doi.org/10.1016/S0008-8846(01)00498-7.
[65] Z. Jiake, S. Caijun, L. Yake, P. Xiaoying, P. Chi-Sun, X. Zhaobin, Performance Enhancement of Recycled Concrete Aggregates through Carbonation, J. Mater. Civ. Eng. 27 (2015) 4015029. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001296.
[66] B. Lu, C. Shi, Z. Cao, M. Guo, J. Zheng, Effect of carbonated coarse recycled concrete aggregate on the properties and microstructure of recycled concrete, J. Clean. Prod. 233 (2019) 421–428. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.05.350.
[67] B. Lu, C. Shi, J. Zhang, J. Wang, Effects of carbonated hardened cement paste powder on hydration and microstructure of Portland cement, Constr. Build. Mater. 186 (2018) 699–708. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2018.07.159.
[68] X. Pan, Z. Shi, C. Shi, T.-C. Ling, N. Li, A review on concrete surface treatment Part I: Types and mechanisms, Constr. Build. Mater. 132 (2017) 578–590. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.12.025.
[69] J. Yin, A. Kang, P. Xiao, C. Kou, Y. Gong, C. Xiao, Influences of spraying sodium silicate based solution/slurry on recycled coarse aggregate, Constr. Build. Mater. 377 (2023) 130924. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2023.130924.
[70] J. Yang, Y. Guo, V.W.Y. Tam, J. Tan, A. Shen, C. Zhang, J. Zhang, Feasibility of recycled aggregates modified with a compound method involving sodium silicate and silane as permeable concrete aggregates, Constr. Build. Mater. 361 (2022) 129747. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.129747.
[71] C. Feng, B. Cui, Y. Huang, H. Guo, W. Zhang, J. Zhu, Enhancement technologies of recycled aggregate – Enhancement mechanism, influencing factors, improvement effects, technical difficulties, life cycle assessment, Constr. Build. Mater. 317 (2022) 126168. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.126168.
[72] M.S. Reddy, Biomineralization of calcium carbonates and their engineered applications: a review , Front. Microbiol. . 4 (2013). https://www.frontiersin.org/articles/10.3389/fmicb.2013.00314.
[73] N.K. Dhami, A. Mukherjee, E.L.J. Watkin, Microbial Diversity and Mineralogical-Mechanical Properties of Calcitic Cave Speleothems in Natural and in Vitro Biomineralization Conditions , Front. Microbiol. . 9 (2018). https://www.frontiersin.org/articles/10.3389/fmicb.2018.00040.
[74] A.M. Grabiec, J. Klama, D. Zawal, D. Krupa, Modification of recycled concrete aggregate by calcium carbonate biodeposition, Constr. Build. Mater. 34 (2012) 145–150. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2012.02.027.
[75] H. Sharma, S.K. Sharma, D.K. Ashish, S.K. Adhikary, G. Singh, Effect of various bio-deposition treatment techniques on recycled aggregate and recycled aggregate concrete, J. Build. Eng. 66 (2023) 105868. https://doi.org/https://doi.org/10.1016/j.jobe.2023.105868.
[76] C.-R. Wu, Y.-G. Zhu, X.-T. Zhang, S.-C. Kou, Improving the properties of recycled concrete aggregate with bio-deposition approach, Cem. Concr. Compos. 94 (2018) 248–254. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2018.09.012.
[77] Y. Zhao, L. Peng, W. Zeng, C. sun Poon, Z. Lu, Improvement in properties of concrete with modified RCA by microbial induced carbonate precipitation, Cem. Concr. Compos. 124 (2021) 104251. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2021.104251.