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Geopolymer concrete incorporating recycled aggregates: A comprehensive review

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ABSTRACT

Several industrial by-products are extensively used again as a supplementary cementitious material or aggregates in the interest to reduce environmental footprints in terms of energy depletion, pollution, waste disposition, resource depletion, and global warming related with conventional cement. A remarkable quantity of industrial scrap materials, primarily designated as construction and demolition waste from the construction industry, has transformed into crucial apprehension of governments. In the recent past, substantial explorations have been accomplished to appreciate the distinct characteristics of concrete, employing recycled aggregates from construction and demolition waste. Geopolymer composite is a new cementitious material, and it appears to be a potential replacement for conventional cement concrete. This paper summarises the previous research concerning the utilisation of recycled aggregate as a partial or complete supplants for conventional aggregates in geopolymer concrete. The influence of recycled aggregate addition on the fresh and hardened properties of geopolymer concrete is comprehensively reviewed in this paper. The studies suggest significant improvement in the workability on addition of recycled aggregates to geopolymer concrete. However, the addition results in increased water absorption and sorptivity.

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Nomenclature

Abbreviations

GRAC	Geopolymer Recycled Aggregate Concrete
C&D	Construction and Demolition
OPC	Ordinary Portland cement
NAC	Normal/natural Aggregate Concrete
RA	Recycled Aggregates
RAC	Recycled Aggregate Concrete
FA	Fly Ash
SEM	Scanning Electron Microscopy
MK	Metakaolin
SSD	Saturated Surface Dry
RCLA	Recycled Lightweight Concrete Aggregate
RGCA	Recycled Geopolymer-Concrete Aggregates
TCLP	Toxicity Characteristic Leaching Procedure
PCC	Portland Cement Concrete
IST	Initial Setting Time
GGBFS	Ground Granulated Blast Furnace Slag
ITZ	Interfacial Transition Zone
C-S-H	Calcium Silicate Hydrate
GNAC	Geopolymer Natural Aggregate Concrete
NaOH	Sodium Hydroxide
CO_2	Carbon dioxide
3D	3 Dimensional
XRF	X-Ray Fluorescence
XRD	X-Ray Diffraction
HCF	High Calcium Fly ash
UNEP	United Nations Environmental Programme
MPa	Mega Pascal
RCP	Rapid Chloride Penetration
OITZ	Old Interfacial Transition Zone
Nano-SiO_2	Nano Silica
FST	Final Setting Time

1. Introduction

Cement concrete is contemplated as the second most exhausting material after drinkable water. It was appraised that the world utilises thirty billion tons of concrete every year (York and Europe, 2021). The vital and costly ingredient of concrete is cement, which is the binding material. Cement production reckons for almost 5–7% of the global carbon dioxide (CO_2) emission, as manufacturing one ton of cement (OPC) liberates one ton of carbon dioxide. This situation will be alarming, and hence there is an urgent need to minimise the CO_2 emissions from cement industries (Sharma et al., 2017; Singh and Middendorf, 2020).

Several industrial by-products are extensively utilised to replace the Portland cement partially or fully to diminish the discharge of greenhouse gases associated with the cement manufacture. Commonly used by-products are fly ash (Mehra et al., 2016); condensed silica fume (Vaibhav et al., 2019), blast furnace slag (Zawrah et al., 2016), ferrochrome slag (Nath, 2018), copper slag, steel scrap, jarosite (Mehra et al., 2016), stone wastes (Kumar et al., 2016; Kumar et al., 2018), copper tailings, brick waste, tire ash (Thomas and Gupta, 2016), etc., and some of the farming residues like palm oil fuel ash (Ul Islam et al., 2016), bagasse ash, corn cob ash (Charitha et al., 2021), elephant grass ash, wood waste ash (Arunkumar et al., 2022), coconut shell & fibers (Alyousef et al., 2020), rice husk ash (Siddika et al., 2021; Siddika et al., 2018), tobacco waste, etc. have been established competent as supplement or replenishment to cement and aggregates (Arunkumar et al., 2022; Alyousef et al., 2020; Siddika et al., 2021; Siddika et al., 2018).

In recent years, geopolymer binder appears to be a alternative to conventional cement concrete. The title ‘geopolymer’ was designated by Joseph Davidovits in 1978 for an amorphous alkali aluminosilicate or alkali-activated cement (Davidovits, 1991; Davidovits, 1989; Younis et al., 2020). The term ‘geo’ stands for geological or industrial materials like FA, blast furnace slag, silica fume etc. whereas the term ‘polymer’ stands for a chain of molecules derived from the same unit (Younis et al., 2020). Geopolymers are alternative cementitious materials generated by the reaction of an alkaline activator (potassium hydroxide, sodium hydroxide, or sodium silicate/carbonates soluble in water) polymerising the aluminosilicate binder material (silica fume, fly ash, metakaolin, blast furnace slag, iron slag, rice husk ash, high calcium wood ash, waste glass, red mud, copper mine tailings, etc.) (Duxson et al., 2007; Assaedi et al., 2019; Hassan et al., 2019).

During the chemical reaction, the liquefied Al_2O_3 and SiO_2 encounter geopolymerization to manifest a three-dimensional amorphous aluminosilicate matrix that exhibits strength corresponding to or superior to the OPC concrete. The process of preparation of geopolymer concrete is given in Fig. 1a. Silva et al. (Silva et al., 2007) explained the operation of geopolymerization into three stages. In the first stage, dissipation of oxide minerals from the origin materials (usually silica and alumina) is occurred with the help of extremely alkaline environments. Hauling/acclimatisation of liquefied oxide minerals succeeded by coagulation take place in the second stage. Poly-condensation to manifest 3D matrix of silico-aluminates structures is the final stage (Part et al., 2015; Cui et al., 2020).

In recent years, studies are being carried out to find alternative binder materials also as the demand for materials like fly ash and GGBFS has increased tremendously. Arunkumar et al. (Arunkumar et al., 2022; Arunkumar et al., 2021) carried out an experimental study to explore the potential of low calcium wood ash as a replacement for fly ash in geopolymer concrete. The experimental results showed the optimum content of waste wood ash as 30% of the total binder material at which maximum compressive strength and flexural strength were attained (Arunkumar et al., 2021). A similar study was done on GGBFS based geopolymer concrete using bio-medical waste ash (Shah et al., 2020). The experiment was done up to an ash content of 10%. The results showed an increase in compressive strength with increase in bio-waste medical ash. Similar trend was also reported by Kumar et al. (Kumar et al., 2021; Kumar et al., 2020) and Arunacha-

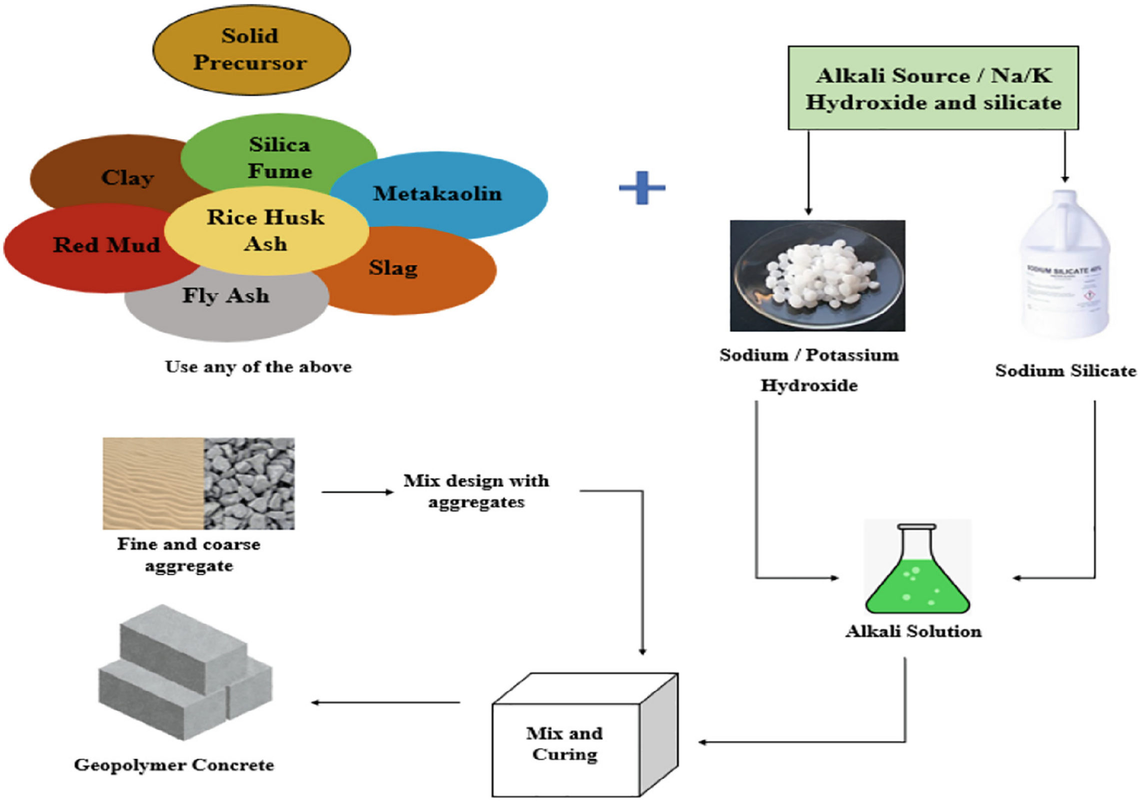


Fig. 1a. Production of geopolymer concrete.

Fig. 1b. The preparation procedure of recycled aggregates (Xie et al., 2019; Xie et al., 2019).

lam et al. (Arunachalam et al., 2021). In order to develop green geopolymer concrete, Arunkumar et al. (Arunkumar et al., 2021) carried out an experimental study using waste wood ash as a replacement for fly ash and waste rubber as fibres to improve the properties like ductility, impact energy and energy absorption. With the technological revolution in distinct disciplines, innumerable and heterogeneous solid waste materials have been initiated by commercial, farming, mining, and domiciliary ventures. According to the “Global Waste Management Outlook” devised by United Nations Environmental Programme (UNEP) and International Solid Waste Association (ISWA), the annual quantity of municipal solid leftover is approximately 2 billion tons. In contrast, the amount of solid urban leftover initiated by sectors such as business, domestic, construction, and other production units redress seven to ten billion tons of waste per annum (Siddika et al., 2019; Turkyilmaz et al., 2019; Global Waste Management Outlook, n.d.; Islam et al., 2021). By the year 2025, the amount is expected to become 19 billion tons every year. The land demand for discarding these leftover/scrap materials is a severe concern for civil and environmental engineers (Richardson et al., 2012; Al-Mutairi et al., 2010; Pappu et al., 2007).

Effective reuse of some of these by-products yields a handful of rewards, including superior strength and durability characteristics, scaling down in construction toll by economising cement and virgin aggregates along with habitat helpfulness like depletion in carbon dioxide emission and the effortless disposal of the contaminating waste materials (Xie et al., 2019; Arunkumar et al., 2021; Arunkumar et al., 2021; Arunkumar et al., 2021). Cement concrete is regarded as one of the major non-sustainable composite materials partially by reason of the consumption of a large quantity of virgin aggregates. Concrete has a crucial task in the economic furtherance of the world. The contemporary annual handling of concrete is roughly thirty billion metric tons. With this escalation in the outlay of ingestion of concrete, it is presumed that the insistence for virgin aggregates will be magnified in the succeeding two to three decades. Thus, the concrete industry ingests abundant quantities of virgin supplies that seeds sizeable environmental, energy, and economic deprivation as it campaigns 50% primal matter, 40% of net energy, in addition to bringing about 50% of the aggregate waste (Oikonomou, 2005; Behera et al., 2014).

A sizeable quantity of manufacturing waste is fashioned by the building industry, chiefly designated as construction & demolition waste (C&D waste) which has transformed into a major apprehension of administrations and construction corporations (Jin et al., 2019; Ferronato et al., 2019). In the recent past, substantial explorations have been accomplished to appreciate the distinct attributes of concrete employing recycled aggregates (RA) from construction and demolition waste. The preparation of recycled aggregate is given in Fig. 1b, the image showing coarse, medium, and fine RA is given in Fig. 2. The morphology of natural (irregular with precipitous edges) and RA (proportionately round sides) is shown in Fig. 3. Various researchers have designated that RA could, fortunately, be reserved as supplant for virgin aggregates to produce concrete, assigning the competent achievements of conventional structural concrete (Kalinowska-Wichrowska and Suescum-Morales, 2020; Tan et al., 2020). Nowadays, recycled aggregate concrete (RAC) is essentially utilised for both structural and non-structural applications. It has been confirmed that its employment is feasible both commercially and technically (Behera et al., 2014; Limbachiya et al., 2012; Robayo-Salazar et al., 2017). A typical XRD graph of sieved C & D waste powder is shown in figure, which confirms the presence of Quartz (SiO_2) and Calcite ($CaCO_3$) as primary composition in addition to other silicates and aluminosilicates.Fig. 4.

This paper presents a comprehensive assessment of the current trends in geopolymer concrete containing recycled aggregates from C&D waste as a restricted/complete replacement for virgin aggregates. This paper includes the properties of these materials and their outturning on distinct characteristics of fresh and hardened concrete (mechanical properties, durability, etc.). It is expected that this evaluation aids in tapering the aperture between academic/elementary researches and the construction industry.

2. Methodology adopted for review

The present review aims to find the effect of aggregate replacement using recycled aggregates on the properties of geopolymer concrete. For this purpose, the following research questions were formulated to address the primary aim of the present review.

1) How does geopolymer concrete differ from conventional concrete in its physical and chemical properties?
2) What are the fresh and hardened properties of geopolymer concrete?
3) How can the behaviour of geopolymer concrete be affected by the inclusion of recycled aggregate?
4) Why does recycled aggregate geopolymer concrete have less industrial acceptance than conventional recycled aggregate concrete?
5) What are the possible ways to improve the acceptance of recycled aggregate concrete in the construction industry?

The methodology adopted in the present study involves collecting literature, screening based on their relevance to the primary aim of the review and critical assessment of the collected literature. The initial level of literature collection included the articles related to geopolymer concrete. At the initial level, the literature collection was accomplished using the appropriate keywords such as 'geopolymer concrete', 'recycled aggregate', 'construction and demolition waste'. This accounted for around 5000 articles together. The databases like Google Scholar, Science Direct etc., were utilised for the literature collection. The search was again refined by using the specific keywords 'geopolymer recycled aggregate concrete', and 'recycled geopolymer concrete aggregate', In this stage, 1073 articles were obtained. The literature was further screened by restricting only peer-reviewed articles, technical notes, textbooks and international standards, reducing the number of articles to 820.

The methodology adopted for the review is as shown in Fig. 5. Further screening of the literature was done based on the following criteria.

- Exclusion of articles not related to properties of geopolymer concrete.
- Exclusion of articles not directly related to the primary aim of this present review like articles discussing cement replacement.

The content was meticulously reviewed, and the articles were gone through one by one. After careful evaluation, 112 peer-reviewed articles which are highly relevant to the study were selected to bring out a detailed study on the effect of replacing conventional aggregate with recycled aggregate in geopolymer concrete.

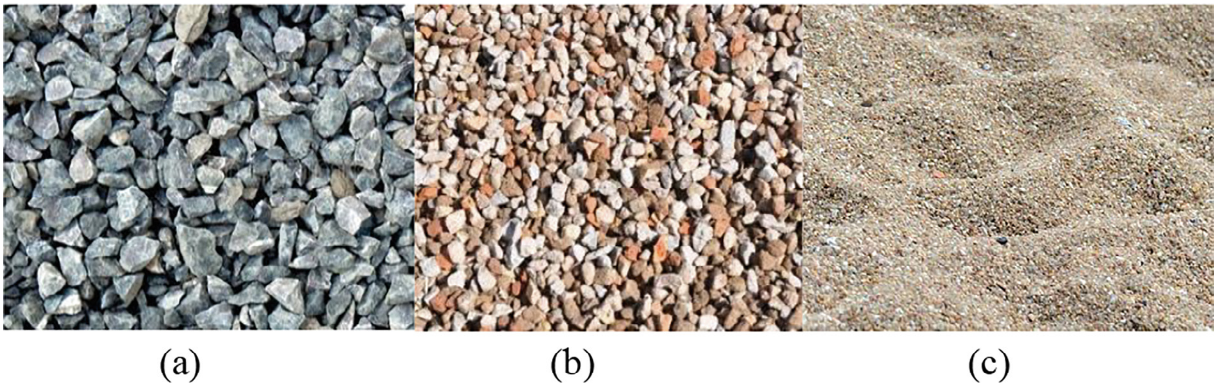


Fig. 2. Coarse (a), medium (b), and fine (c) recycled aggregates.

(a) Natural aggregate (maximum size of 9.5 mm)

(b) Natural aggregate (maximum size of 19 mm)

(c) Recycled aggregate (maximum size of 9.5 mm)

(d) Recycled aggregate (maximum size of 19 mm)

Fig. 3. Comparing the morphology of fine and coarse aggregates used in concrete (Hu et al., 2019).

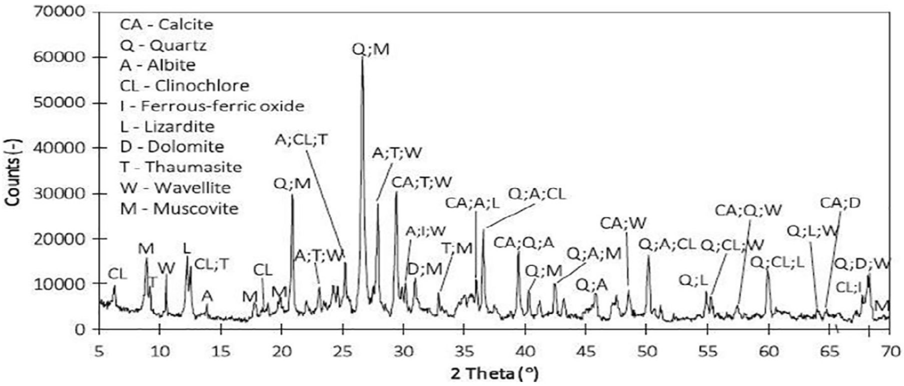


Fig. 4. XRD model of sieved C&D waste powder, d < 63 mm (Bassani et al., 2019).

3. Characterisation of recycled aggregates

X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) are generally used for the oxide and mineralogical analysis samples. After examining XRF of the construction and demolition samples, Bassani et al. (Bassani et al., 2019) stated that the material principally constitutes of silicon, calcium, aluminium, and iron oxides along with notable quantities of alkaline and alkaline-earth oxides, MgO and K_2O in particular, and insignificant quantities of transition metal oxides (*Figure-4*). XRD manifests Quartz and Calcite's existence and other silicates, such as Lizardite, thaumasite, and aluminosilicates (Albite, Clinochlore, Wavellite, and Muscovite. Ren and Zhang (Ren and Zhang, 2016) observed that the waste concrete fines predominantly consist of silica (57.3%), calcium oxides (17.5%), aluminium (6.57%), as given in Table 1.

4. General overview on the use of recycled aggregates in cement concrete

Worldwide, the C&D waste generation is rapidly increasing with the growth of urbanisation and industrialisation. European Union and the United States produce around 850–890 million tons and 450–530 million tons of C&D waste , respectively, per annum (Tam et al., 2018; Villoria Sáez and Osmani, 2019). The global C&D waste accounts for 30–40% of the total solid waste. As per the statistics by the building material promotion council, India generates 140–150 million tons annually (Tam et al., 2018), while recycling is less than 10%. Demolition of concrete structure produces around 0.61 m^3/m^2 of concrete and 0.0723 m^3/m^2 brick waste. Additionally, during the construction of a new concrete structure, around 1–4% of concrete and 3–12% of bricks are wasted (Saha et al., 2021; Thomas et al., 2015). Therefore, this huge amount of waste is needed to be properly managed for environmental safety, and researchers found recycling them into concrete construction is one of the economical and eco-friendly methods. As the C&D waste contains mostly solid and inert materials, it is suitable to be used as supplementary inert materials, like aggregates in concrete.

The process of production, managing, and recycling of aggregates from C&Dwaste to concrete production is shown in Fig. 6 (inputs from (Le and Bui, 2020). The application of recycled aggregates in the construction was first initiated in Europe after World War II (Tam et al., 2018). Initially, the demolished concrete was typically used for constructing pavement layers. Nowadays, recycled aggregate use in concrete production increases worldwide as a result of its reliable

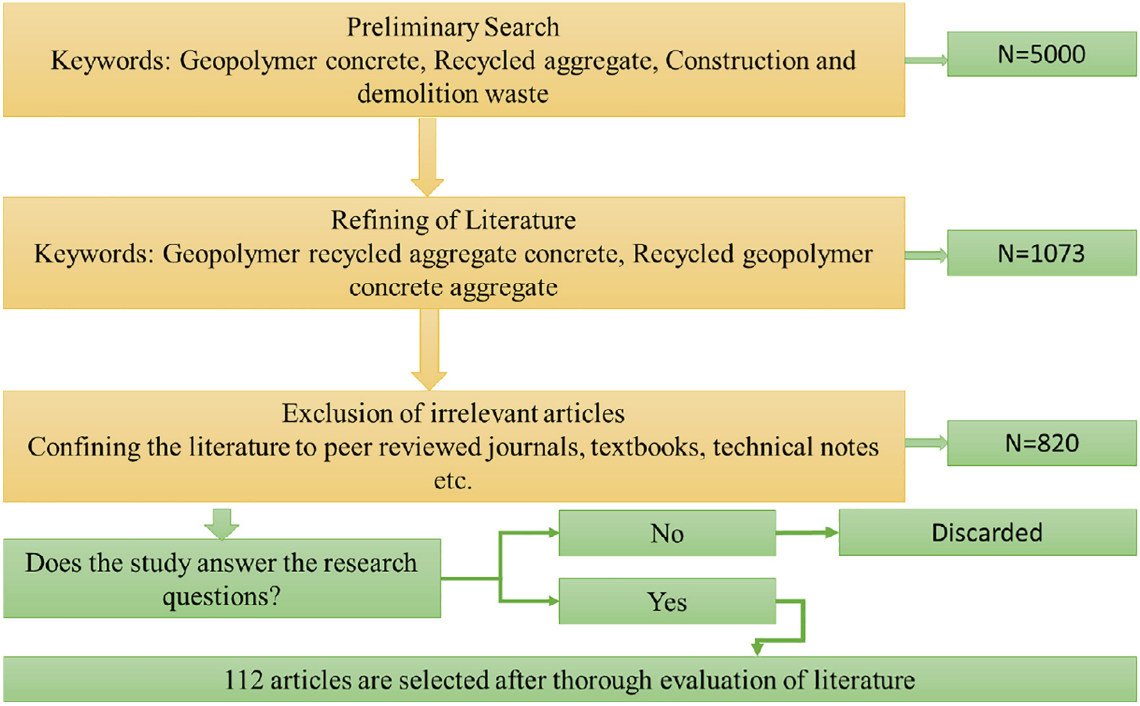


Fig. 5. Methodology adopted for the review.

Table 1
Chemical composition of recycled and natural aggregate.

	Recycled aggregate				Natural aggregate	
Chemical compounds (%)	(Bassani et al., 2019)	(Ren and Zhang, 2016)	(Robayo-Salazar et al., 2017)	(Ren and Zhang, 2018)	(Al-Zahraa et al., 2010)	(Zhang et al., 2019)
SiO_2	46.1	57.3	56.21	40.1	55.57	68.07
CaO	16.4	17.5	15.37	20.6	13.33	3.48
Al_2O_3	13.2	6.57	10.68	9.60	0.77	15.85
Fe_2O_3	8.52	2.12	10.39	3.50	0.37	2.8
MgO	7.62	1.71	3.35	2.10	9.59	1.1
SO_2	4.02	0.77	–	–	–	–
K_2O	2.33	1.68	0.36	2.30	0.09	1.67
TiO_2	0.84	–	0.24	–	0.01	0.44
Na_2O	–	4.53	2.08	1.70	0.14	4.71

performance, ensuring sustainability and reducing landfill problems. Besides, partial replacement of conventional quarry aggregates by recycled aggregates can reduce energy consumption as well as CO_2 emission by around 46% (Tam et al., 2018). Accelerated urbanization increases the demand for conventional construction materials specifically aggregates (Siddika et al., 2021; Su et al., 2021). For instance, the global aggregate production rate was 26 billion tons in 2012 and 40 billion tons in 2014. Besides, the rate crosses around 55 billion tons at present (Tam et al., 2018; Makul et al., 2021). As the demolished concrete can be effectively recycled as aggregates, the exploitation of natural resources for aggregates can be curtailed. However, the sustainability and performance of recycled aggregate concrete are governed by the preparation and pretreatment of demolished aggregates (Le and Bui, 2020).

There are several techniques for preparing recycled aggregates from the demolished concrete: manual hand hammering, mechanical engines, or blasting techniques (Siddika et al., 2021). Considering the economy, fewer sorting concerns and time effectiveness, the mechanical method of separating aggregate from demolished concrete is recommended. However, the collected aggregates must be pretreated to clean the contaminations, loose materials, and organic components. Commonly adopted pretreatments are crushing, sieving, and watering. The concrete mixture can be designed depending on the fineness, water absorption, and crushing strength of the recycled aggregates.

Up to the present date, there are few review papers on the properties of concrete made with RA (Rana et al., 2016; Rattanachu et al., 2020; Makul et al., 2021; Le and Bui, 2020; Siddika et al., 2021), while there are no reviews so far (to the best of knowledge) on the properties of geopolymer recycled aggregate concrete. The available review papers include a significant research database and explain the impacts of adding recycled aggregates on fresh and hardened properties of concrete. According to these studies, the general trend of using recycled aggregates in cement concrete is satisfactory for low-grade concrete to high-strength structural concrete. However, there is a wide disparity and contradictions on the resulting strength of RCA. The grade of control concrete and quality of recycled aggregates are major factors of varying compressive strength of RAC. Typically, M20-M50 grade concrete can be developed using RA, depending upon the mixture design and content of RA (Rana et al., 2016; Rattanachu et al., 2020; Makul et al., 2021; Le and Bui, 2020; Siddika et al., 2021). The variation in the compressive strength for similar mix-designed RAC is primarily

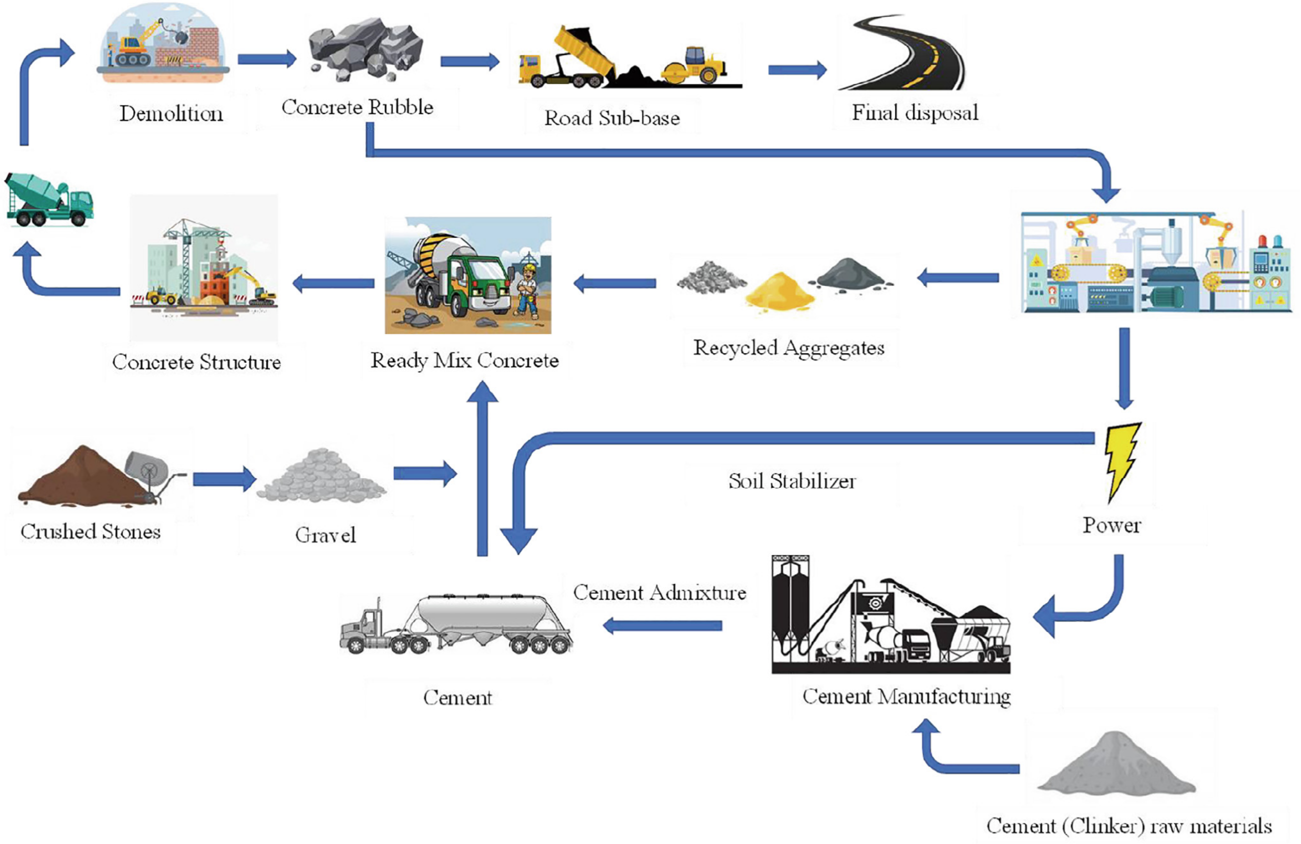


Fig. 6. Process of production and recycling of building's C&D wastes as recycled aggregates.

caused by reason of the variation in source, age, and water absorption of RA, which needs to be considered while using RAC.

Depending upon the density, particle size, and water absorption of RA, the class of RA, can be estimated. Typically, less than 6% water absorption is recommended for class 1 type RA (Saha et al., 2021). Due to the presence of hardened products in the recycled fine aggregate, they cannot wholly take part in the pozzolanic reaction. Thus, it acts as a filler in concrete. Therefore, the pore refinement occurs, and the microstructure of the concrete is found to be improved up to an optimum replacement level of 30% in RAC (Siddika et al., 2021). On the other hand, the recycled coarse aggregates contribute to the volume and imparts strength by transferring load through the improved bond developed between the paste and aggregates. The strength of the bond between RA and cement paste varies with the mixture characteristics such as water-cement ratio, binder content, designed grade of concrete etc. As the RA absorbs more water than normal aggregates, a compact and strong interfacial transition zone is developed because of the water exchange between dry aggregates and cement paste (Siddika et al., 2021). This helps to improve the strength and durability of the concrete. On the other hand, excessive water absorption can hinder workability and lead to hydration problems, cause reduction in the compressive strength (Siddika et al., 2021; Xiao et al., 2012). Thus, pre-saturated RA is recommended for use in RAC. With the saturated RA, the workability of RAC can be improved. However, shrinkage of concrete can be increased as a result of the evaporation of free moisture after hardening, thus resulting in RAC's strength reduction. Moreover, the strength of RAC is also influenced by the strength of RA. The lower strength of RA, depending on the age and source of RA results in a significant reduction in the strength of RAC.

RA may contain old mortar attached to it, depending on its source. As a result, RAC develops a complicated interfacial transition zones, one between the old mortar and RA and the another between the new mortar and RA (Omary et al., 2016). Moreover, if the aggregate is replaced partially, another type of interfacial transition zone is also developed between the new aggregate and new mortar. This disparity in the microstructure of RAC, which affects its strength, limits its application in structural members. Furthermore, the RA contains microcracks and pores. With the increasing amount of recycled aggregates in RAC, the porosity and non-uniformity in microstructure are increased, thus reducing the durability and limiting the long-term serviceability (Gabr et al., 2011). Therefore, the classification of RA is needed for the suitable grade of concrete.

With the increasing knowledge and research database on the use of RA, the application of RAC in construction is increasing rapidly. For example, Tam et al. (Tam et al., 2018) reported that the European Union produces around 2000 million tons of aggregates for concrete construction, producing around 190–200 million tons of recycled aggregates. Among the total production, 20% of RAs are used in the road construction, and 80% are used in the building construction. Besides, in the United States, 6% of RA is being used in new concrete. Based on the research data and field applications of RAC, there are several guidelines and standards proposed and being developed to maintain the quality and standards of RA (Tam et al., 2018; Gonçalves and Brito, 2010; Bernal et al., 2011). Based on the Australian guidelines, RA with a density above 2100 kg/m^3, water absorption less than 6%, and contaminants less than 1%, can be classified as class 1A type aggregates and can be used up to 30% of aggregates volume in new concrete to achieve 40 MPa strength in 28 days. Besides, for 25 MPa concrete, the class 1B RA (density $>$ 1800 kg/m^3 and water absorption less than 8%) can be used up to an aggregate replacement level of 100% in concrete. However, in Europe, China, and Asian standards, the water absorption of RA is margined up to 10% (Tam et al., 2018; Gonçalves and Brito, 2010; Bernal et al., 2011). Water absorption, density, and impurity content are the main controlling parameters considered in all the standards for optimum content of RA. Therefore, by controlling these parameters, the class of RA can be maintained to achieve a consistent performance of RAC. The details of these parameters are summarized in Fig. 6, the summary of the recycling process is mentioned in Fig. 7.

Despite having significant research data and guidelines on the use of RA in structural concrete, there are some barriers to recycling and reusing RA. The main barriers are the limiting availability of standards for all exposure conditions, supply and availability limit, customer's perception, distance from the suppliers, and long term serviceability limitation of RAC. By providing routine information from the construction sectors about the potential impacts of RAC, the acceptability of RA can be increased. Besides, with the increasing training and awareness on the use of RA in concrete at the local construction level, the supply and reuse of RA at the local level will be increased. This will enhance sustainability in the construction at the source generation level and leads to reduce the cost of the transportation. Moreover, the recycling of RA in RAC is an ecofriendly method of handling construction waste, thereby reducing landfill problems and emissions.

5. Influence on fresh properties

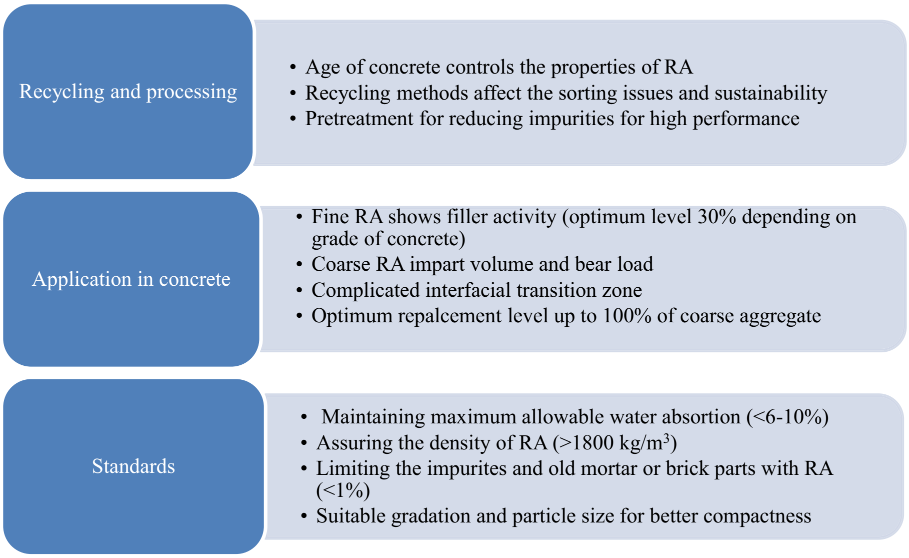
The influence of recycled aggregates on the fresh properties of geopolymer concrete are discussed below.

1.1. Workability

Fresh blends of geopolymer composites exhibit high cohesion and viscous attributes, reducing slump upon an increase with the content of GGBFS. This can be accredited to the excessive amount of calcium ions liquefied from GGBFS and its quick reaction with the alkali activator to precipitate as calcium silicate hydrate (Nuaklong et al., 2016). The RA being more porous than the NA due to the presence of attached mortar, absorbs more water during the mixing process, thereby reducing the workability. In order to eliminate this problem, many researchers have proposed the use of pre-soaked aggregates in surface saturated dry condition(SSD). The workability of concrete with recycled aggregates in the SSD condition is enhanced with increasing RA content, as a result of more unbound water in SSD circumstances than the NA (Behera et al., 2014; Hu et al., 2019). Nuaklong et al. (Arora et al., 2021) conducted a similar study on fly ash-based geopolymer concrete with recycled aggregates in SSD condition. The results showed an increase in the slump of the mix owing to the larger pore volume and water in recycled aggregates(in SSD) compared to conventional aggregates. However, Saloni et al. (Nuaklong et al., 2018) inferred that the inclusion of RCA in geopolymer concrete reduces workability as RCA results in an increase in harshness. Xie et al. (Xie et al., 2019) also stated that the GRAC imparts a higher slump than the OPC concrete for the same water to binder ratio (w/b). Increasing the amount of GGBFS and decreasing the w/b can reduce the slump value of GRAC. Nuaklong et al. (Nuaklong et al., 2018) utilized metakaolin as a substitution for high calcium fly ash (HCF) in geopolymer binders. The measured slump flow values for the GNAC were within the range of 398–510 mm, while that of GRAC was in the range of 473–697 mm. GRAC was approximately16 –26.8% superior to GNAC. The excessive fineness and angular structure of the MK tend to decrease the slump flow with an increase in the metakaolin content (fly ash particles are spherical in shape). Besides, replacement of fly ash with MK, the fly ash at 0%, 10%, 20%, and 30%, the slump flows were 697, 609, 546, and 473 mm, correspondingly. Table 2 shows the effects of RA on the workability of GRAC, revealed in various former investigations.

1.2. Setting time, segregation, and bleeding

It was observed by Ren and Zhang (Posi et al., 2016) that the initial setting time (IST) deviates from 21 to 151 min. It is influenced by the binder to aggregate ratio, NaOH aggregation from sodium silicate solution to NaOH solution mass, and the aggregate category. It was deduced from the former investigations that the IST of concrete incorporating RA is much shorter than that containing NA. The RA absorbs more water than the NA as the facet of the RA is more pervious and irregular compared to natural aggregates. The mixing process of RA leads to the formation of fresh broken surfaces, which absorb more water (Ren and Zhang, 2016). Hu et al. (Hu et al., 2019) reported that the initial setting time of GRAC marginally was enhanced with increasing content of RA (SSD), which can be justified by the presence of an excessive quantity of free water. Furthermore, soluble sugars/organic substances in RA have impending consequences on the setting as well as the hardening of geopolymer matrices. Xie et al. (Xie et al., 2019) observed that the GRAC had much shorter IST and FST in contrast with the virgin concrete (NC) and RA concrete (RC). The maximum initial and final setting times of GRAC was 33–78 min, approximately10%



Recycling and processing

- Age of concrete controls the properties of RA
- Recycling methods affect the sorting issues and sustainability
- Pretreatment for reducing impurities for high performance

Application in concrete

- Fine RA shows filler activity (optimum level 30% depending on grade of concrete)
- Coarse RA impart volume and bear load
- Complicated interfacial transition zone
- Optimum repalcement level up to 100% of coarse aggregate

Standards

- Maintaining maximum allowable water absorption (<6-10%)
- Assuring the density of RA (>1800 kg/m^3)
- Limiting the impurites and old mortar or brick parts with RA (<1%)
- Suitable gradation and particle size for better compactness

Fig. 7. Summary of main parameters for recycling, processing, and application of RA in concrete.

Table 2
Effect of RA on the workability of GRAC.

Ref.	Binder base material	Influence on the workability
(Nuaklong et al., 2020)	FA and Nano-SiO_2	The usage of nano-SiO_2 led to magnifying the workability of GC containing RA.
(Hu et al., 2019)	FA and GGBFS	The workability of the GC blends displayed a moderately increasing trend due to the increased renewal magnitude of RA
(Oikonomou, 2005)	FA	The use of saturated surface dry RCA ameliorated workability due to the enormous volume of pore and water at the saturated surface dry environment.
(Xie et al., 2019)	GGBS and MK	The slump value increased due to an increase in the recycled aggregate content in the GC samples.
(Xie et al., 2019)	FA and GGBS	The slump value declined with an escalation in the quota of recycled aggregate.
(Ren and Zhang, 2019)	Rice husk ash and Nano-SiO_2	The workability of control geopolymer concrete was about 14% higher than natural concrete.

of the setting times of NC and RC because the response of geopolymer was expeditious. The setting time of geopolymer can be dropped by 90% in contrast to the hydration of the cement mixture. When metakaolin was replaced for fly ash with the same level, the IST and FST were found to be increased approximately by 25% and 15%, correspondingly. Hu et al. (Hu et al., 2019) reported that no segregation or bleeding could be inferred in the geopolymer recycled aggregate concrete mixtures during mixing, casting, and compacting pocesses. Table 3 shows the influences of RA on the setting time, bleeding and segregation of geopolymer concrete, revealed in various former investigations.

6. Influence on hardened properties of concrete

The replacement of conventional aggregates using RA significantly influences the hardened properties of concrete such as density, compressive strength, tensile strength etc. This section discusses the effect of RA on these specified properties.

2.1. Density

The use of recycled aggregates minimizes the density of concrete, owing to the reduced density of the recycled aggregates compared with conventional aggregates. Hu et al. (Hu et al., 2019) stated a reduction in the density of RA used concrete by 4–8% (varying from 2165-2432 kg/m^3) compared to the reference concrete containing natural aggregates. Nuaklong et al. (Arora et al., 2021) stated that the density was reduced by 6–10% (varying from 2160-2210 kg/m^3 when RCA was incorporated in the concrete. Nuaklong et al. (Arora et al., 2021) noted that the dry-rodded density of the geopolymer RA mortar was 29% lower than that of the control mortar with NA. The drop in the dry bulk density fluctuated from 2.5 to 8.0% for the geopolymer mortar incorporated with RA compared to the NA used specimens. The dry bulk density of the control specimen was 1.84 g/cm^3. The density of specimens containing 25, 50, 75, and 100% RA was 1.95, 1.92, 1.88, and 1.84 g/cm^{3,} respectively. Posi et al. (Sata et al., 2013) prepared lightweight concrete blocks using recycled lightweight concrete aggregate (RLCA). The fly ash supplants for OPC at the level of 0, 5, 10, and 15% by weight effectively curtailed the density of the concrete block. For lightweight concrete applications with low strength requirements (density of 1300 kg/m^3 and compressive strength of 4.5 MPa), mixture with no OPC (cured at 25 °C) was found to be adequate. The inclusion of OPC and temperature curing to some extent enriched the density and the strength development. Concrete having 1400 kg/m^3 density and 14.5 MPa of strength was acquired at the optimum OPC replacement of 10% and at optimum temperature curing of 60 °C. Table 4 indicates the effects of RA on the density of geopolymer concrete, revealed in various investigations.

2.2. Compressive strength and resistance to surface abrasion

Earlier studies have shown that replacing OPC with fly ash or GGBS increases the compressive strength of the RA used concrete. Xie et al. (Xie et al., 2019; Xie et al., 2019) mentioned that the compressive strength of GRAC escalated with an increase in the GGBS content, in the order of 50% and 180% higher in contrast with the OPC concrete when the amount of GGBS was 50% and 75%, correspondingly. Ren and Zhang (Pappu et al., 2007; Saraswathy and Song, 2007; Villoria Sáez and Osmani, 2019) observed that the highly porous paste/mortar attached to the recycled aggregates could ingest the alkaline solution directing to geopolymerization of the original ITZ, which ameliorates the constitution of RA and exceed the robustness of the geopolymer concrete. Fig. 8 shows the grain size distribution of class F fly ash, waste concrete fines, fine and coarse recycled aggregates, and fine and coarse natural aggregates. From the Fig. 8, it is evident that recycled coarse aggregate can be produced similar to the natural coarse aggregates. In the similar manner, the grain size distribution of recycled fine aggregated have comparable to the natural fine aggregates. Arulrajah et al. (Athira et al., 2021) stated that the construction and demolition aggregates stabilized by calcium carbonate residue with 5% slag could improve the strength properties for pavement base as well as sub-base applications. Ren and Zhang (Posi et al., 2016) carried out study on the compressive strength of GPC with RA and that with NA at room temperature and curing temperature of 35 °C. The results showed better performance of RA based GPC as compared to NA based PC at both temperatures. Higher temperature speeds up the geopolymerization activity and steer to enhanced robustness of the geopolymer concrete. However, the type of source materials influences on the selection of curing method. For example, ambient curing is beneficial for slag based alkali activated binder whereas heat is suitable for fly ash based geopolymer concrete (Mesgari et al., 2020). Nuaklong et al. (Nuaklong et al., 2018; Nuaklong et al., 2020) noted an enhancement in the mechanical properties with increasing amount OPC replaced for high calcium fly ash, as the compressive strengths of

Table 3
Consequence of RA on the setting time, bleeding and segregation of GRAC.

Ref.	Precursors	Replacement level	Results on the setting time of GC
(Hu et al., 2019)	FA and GGBFS	0, 50, and 100%	Using recycled aggregates over natural aggregate led to a slight increase in the initial and final setting times.
(Xie et al., 2019)	FA and GGBS	0, 25, 50, 75, and 100%	The water depletion can escalate the condensation activity in the geopolymer concrete, accordingly narrowing down the setting time.
(Hu et al., 2019)	FA and GGBFS	0, 50, and 100%	No bleeding or segregation occurred in the blends in the course of mixing, casting, and compacting.

Table 4
Influence of RA on the density of GRAC.

Ref.	Substitution level	Influence on the density of GC
(Hu et al., 2019)	0, 50, and 100%	The Utilization of recycled aggregate minimized the density by 4–8%.
(Arulrajah et al., 2016)	0 and 100%	The use of recycled aggregate diminished the density of GC samples.
(Oikonomou, 2005)	0 and 100%	The density was decreased by 6–10% (2210–2160 kg/m^3)

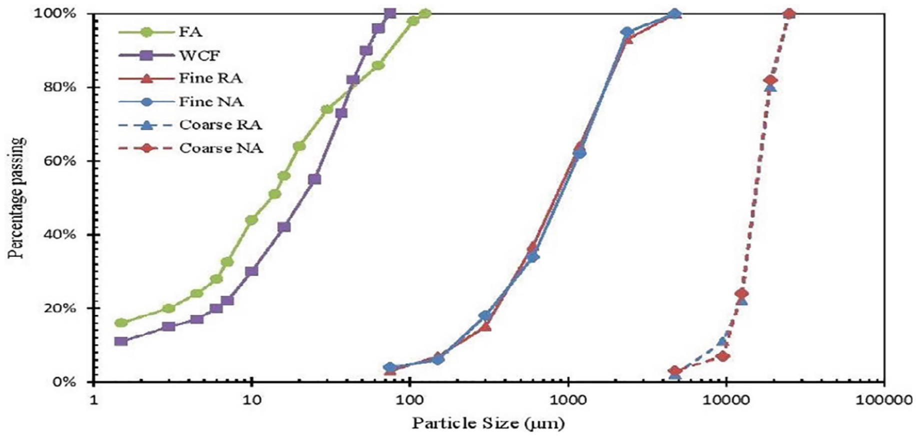


Fig. 8. Particle size distribution of geopolymer ingredients (Posi et al., 2016).

36.2, 38.6, and 48.7 MPa was achieved (in contrast with the 32.9 MPa of control GRAC) with the inclusion of 5%, 10%, and 15% OPC respectively. When nano-SiO$_2$ partially restored the high calcium fly ash in the GRAC from 1 to 3%, the compressive strength was increased to 39.6, 42.6, and 31.6 MPa, respectively. Conversely, a declining trend of compressive strength was reported for RCA incorporated geopolymer concrete by Saloni et al. (Nuaklong et al., 2018). This reduction can be attributed to the inferior properties of RCA and increased water absorption as compared to natural aggregate. The main factor influencing this reduction in strength is the weak ITZ between old mortar and new matrix. Similar trend was also stated by Mesgari et al. (Ganesh and Muthukannan, 2019).

The abrasion resistance is normally dispensed in terms of average weight loss after the specified abrasion cycles. It can be strongly correlated with the compressive strength and aggregate matrix interfacial bond of the concrete. Nuaklong et al. (Arora et al., 2021) inferred that the weight loss of control specimens (geopolymer mixture containing limestone aggregates) with sodium hydroxide aggregations of 8 M, 12 M, and 16 M were 1.24, 0.92, and 1.16 g, respectively, while that of geopolymer recycled aggregate concrete were 1.45, 0.92 and 1.53 g respectively. The geopolymer concrete containing limestone aggregates was highly impervious to abrasion in contrast with the GRAC. A similar study on fly ash based geopolymer concrete was done by Ganesh and Muthukannan (Koushkbaghi et al., 2019). In the study, geopolymer concrete was cast for different molarities and cured under two regimes. The specimens were then exposed to elevated temperature and tested for its compressive strength. The results showed better performance for oven-cured specimens as compared to ambient cured specimens. Nuaklong et al. (Nuaklong et al., 2020) explained that the increment in the amount of OPC in the geopolymer concrete, guided to a positive decline in the mass depletion of the GRAC. The mixture containing 15% OPC manifested an exceptional surface abrasion resistance offering 36% curtailment in the weight dropping compared to that of the GRAC without OPC. Nuaklong et al. (Nuaklong et al., 2018) mentioned that the GRAC specimens containing 10–30% metakaolin (substituted for fly ash) had high resistant to surface abrasion. The weight loss for the GRAC without metakaolin was 3.32 g, whereas the mass loss of specimens containing 10, 20, and 30% metakaolin loss was 2.01, 1.75, and 1.47 g, respectively (reductions of 39, 45, and 55% when compared with GRAC). Table 5 shows the influence of RA on the compressive strength of GRAC, studied by various researchers.

2.3. Flexural strength, split tensile strength and toughness

Flexural strength and splitting tensile strength are reduced with the increase in the quantity of RA by reason of the inadequate bonding strength between RA and the geopolymer matrix. It was noted that the insertion of 30% GGBFS increased the tensile strength by 1.87 MPa, and the flexural strength by 64% and 92% for the mixtures containing 50% and 100% recycled aggregates, respectively (Hu et al., 2019). Mohammadinia et al. (Zhu et al., 2020) studied the strength of geopolymer with C&D aggregates (treated at 40 °C temperature and cured in the moisture chamber for seven days) and found marginal changes in the strength. Akbarnezhad et al. (Shaikh, 2016) and Mesgari et al. (Ganesh and Muthukannan, 2019) explored the characteristics of the scrap aggregates of the geopolymer concrete (RGCA) to prepare new recycled aggregate geopolymer concrete (GRAC). It was mentioned that 50% and 100% substitution of natural coarse aggregates (NA) with RGCA resulted in about 8.2% and 15.2% drop in the median flexural strength of GRAC specimens compared with the control geopolymer concrete. In addition, 20% replacement of NA with RGCA has exhibited an insignificant dissimilarity of 0.4% in the median flexural strength of geopolymer concrete specimens. Xie et al. (Xie et al., 2019; Xie et al., 2019) observed an enhancement in the toughness with the increase in the curing period. The toughness of GGBS/metakaolin based geopolymer specimens diminished with the increase in the recycled aggregate content by reason of the high deformation caused by the higher amount of RA under the same loading. Table 6 communicates the effects of RA on the flexural and splitting strength of geopolymer concrete, reported in various investigations.

2.4. Water absorption and sorptivity

Elchalakani and Elgaali (2012) witnessed that the quality of the RA obtained from the construction waste is superior to that of the demo-

Table 5
Influence of RA on the compressive strength of GRAC.

Ref.	Precursors	Test outcomes
(Nuaklong et al., 2020)	Nano-SiO_2	The compressive strength of GC with 1, 2, and 3% Nano-SiO_2 were 39.6, 42.6, and 31.6 MPa, in succession, in contrast with the 32.9 MPa of the reference specimens
(Akbarnezhad et al., 2015)	MK	Slight curtailment in the compressive strength of GC incorporating 30% RCA.
(Hu et al., 2019)	FA and GGBFS	The recycled aggregate negatively influenced the compressive strength, which curtailed with an escalation in the quantity of recycled aggregate.
(Arulrajah et al., 2016)	FA	The use of recycled aggregate in the pervious GC resulted in reducing the compressive strength.
(Shaikh, 2016)	FA and GGBFS	The compressive strength value was similar to the replacement level 20% of recycled aggregates then reduced when increased replacement level up to 100%.
(Ganesh and Muthukannan, 2019)	FA, MK, and GGBFS	The compressive strength decreased gradually due to an escalation in the replacement level of recycled geopolymer aggregate.
(Xie et al., 2019)	GGBS and MK	The recycled aggregate level led to a decline in the compressive strength of geopolymer concrete.
(Mohammadinia et al., 2016)	FA	The compressive strength has decreased due to the escalation of the recycled aggregates content from 0 to 50%.

Table 6
Influence of RA on the water absorption and sorptivity of GRAC.

Ref.	Replacement level	Influence on the flexural and splitting strength
(Ojha and Gupta, 2020)	0, 20, 50, 80, and 100%	Recycle geopolymer aggregates mortar exhibits a lower depletion rate in the flexural strength than natural aggregate mortar specimen
(Ganesh and Muthukannan, 2019)	0, 20, 50, and 100%	The flexural strength slightly decreased due to the increase in the content of recycled geopolymer aggregates.
(Tan et al., 2020)	0, 10, 25, 40, and 50%	The flexural strength was increased due to the increase in the slag content in the GC mixtures.
(Panizza et al., 2020)	0 and 25%	The flexural strength of geopolymer concrete was affected by the recycled aggregates and was lower value than that of conventional aggregates
(Arulrajah et al., 2016)	0 and 100%	The use of recycled aggregate in the previous GC resulted in a reduction in the splitting tensile strength
(Panizza et al., 2018)	0, 50, and 100%	The splitting tensile strength was 5 to 10% of the compressive strength of GC specimens.
(Ren and Zhang, 2019)	0 and 100%	The splitting tensile strength of geopolymer concrete decreased when virgin lime-stones renewed by recycled aggregates

lition waste because of the reduced water absorption of the the former (1.03%) than latter (5.2%). It is by reason of cracks and fissures during its manufacturing process. Increasing the water absorption adversely affects workability of fresh concrete mixture and other properties (Posi et al., 2013). Replacement of fly ash with GGBFS leads to a reduced water absorption and water sorptivity accredited to the formation of denser calcium alumino-silicate hydrate gels (Jin et al., 2019). It was observed by Nuaklong et al. (Nuaklong et al., 2018) that the use of 5, 10, and 15% of OPC in a geopolymer concrete assisted in reducing the porosity by 2, 7, and 30%. The rate of water absorption by reduced by 10%, 12% and 33% in succession, on account of the impenetrable microstructure of C-A-S-H type gel in contrast with the fly ash, formed geopolymer. Increasing the quantity of metakaolin can remarkably refine the transport characteristics of the geopolymer concrete specimens. The partial replacement of 10, 20, and 30% fly ash with MK notably brought down the water absorption to 5.31%, 4.63%, and 4.58%, correspondingly. In comparison with the 10.31% water absorption of the unblended concrete specimens, while bringing down the sorptivity values to 71.4, 84.4, and 85.3% lower than the control GRAC specimens having 0% MK. The better sorptivity development for GRAC specimens containing MK would perforate the old cracks, voids, and ITZ of the porous RA, strengthening them and leading to a remarkable enhancement in the performance of GRAC (Nuaklong et al., 2018). Table 7 communicates the effects of RA on the water engrossment and sorptivity of geopolymer concrete specimens, revealed in various investigations.

2.5. Elastic modulus

The deformation resistance of the recycled aggregates is comparatively low in comparison with the natural aggregates. The creation of micro-cracks in the RA during the crushing of the C&D waste could be the reason for the reduced elastic modulus of RA used concrete (Mohammadinia et al., 2016). Hu et al. stated (Hu et al., 2019) that there was a reduction of 20% and 40% in the elastic modulus when the recycled aggregates were used as substitutes at the level of 50% and 100%, respectively. Xie et al. (Xie et al., 2019; Xie et al., 2019) studied the behaviour of the GGBS-metakaolin based geopolymer spec-

Table 7
Influence of RA on the water absorption and sorptivity of GRAC.

Ref.	Precursor used	Influence on GRAC
(Nuaklong et al., 2020)	FA and Nano-SiO_2	The use of FA instead of OPC by 5–15% can enhance the water absorption and sorptivity of GC containing RA.
(Akbarnezhad et al., 2015)	MK	The water absorption of GC increased by about 23% due to the increase in the quota of RCA from 0% to 30%.
(Hu et al., 2019)	FA and GGBFS	The water absorption rate was enhanced owing to an expansion in the content of recycled aggregate.
(Wang et al., 2020)	0, 30, and 70%	The water absorption moderately escalated with the surge in the quantity of aggregate/ash ratios.
(Oikonomou, 2005)	FA	The use of RCA in fly ash-based geopolymer concrete exhibited excessive water absorption and permeable voids.
(Ojha and Gupta, 2020)	MK	The employment of recycled geopolymer aggregates in geopolymer mortar increases the water absorption rate and its coefficient.

Table 8
Influence of RA on the modulus of elasticity of GRAC.

Ref.	Replacement level	Influence on GRAC
(Wang et al., 2020)	0, 30, and 70%	The modulus of elasticity of lightweight concrete exhibited an indistinguishable fashion to the mechanical properties.
(Shaikh, 2016)	0, 20, 40, 60, 80, and 100%	The MOE of GC decreased gradually due to the use of recycled coarse aggregate.
(Al Mamun and Islam, 2017)	0, 20, 40, 60, 80, and 100%	The MOE of geopolymer recycled aggregate concrete moderately enhanced and then decreased as the curing temperature was enhanced.
(Ganesh and Muthukannan, 2019)	0, 20, 50, and 100%	The MOE slightly decreased due to the increased replacement level of recycling geopolymer aggregates
(Xie et al., 2019)	0, 25, 50, 75, and 100%	The MOE of RAC was much lower in comparison with that of natural concrete. Increasing the quota of RAC results in a decrease in the MOE of geopolymer concrete
(Xie et al., 2019)	0, 50, and 100%	The MOE decreased significantly due to an increase in the content of recycled aggregates.
(Mohammadinia et al., 2016)	0, 15, 30, and 50%	The MOE decreased with an enhancement in the recycled aggregate content.

imens that replaced the OPC paste in the RA concretes. GGBS/metakaolin ratios were considered 1:1 and 7:3. It was perceived that the elastic modulus of geopolymer concrete containing GGBS-metakaolin remarkably decreased with the increase in RA content and was lower in comparison with that of virgin aggregate used concrete. Akbarnezhad et al. (Shaikh, 2016) and Mesgari et al. (Ganesh and Muthukannan, 2019) observed an 8.6% average enhancement in the modulus of elasticity of GRAC incorporating 20% coarse RGCA in contrast with the geopolymer concrete, and about 2.8% and 10.7% curtailment in the modulus of elasticity with coarse GRAC fragments of 50% and 100%, in succession. The effects of RA reported in the previous research investigations are given in Table 8.

2.6. Chloride ion penetration

Earlier studies have reported higher chloride penetration depth for the RA concrete in comparison with the conventional concrete because of the easier pore path on the attached mortar on the facet of the recycled aggregates for the transport of the aggressive chloride ions. The test set up for the chloride penetration test is shown in Fig. 9 (Nuaklong et al., 2020). The chloride depth penetration for RA used geopolymer concrete was found within the specified limits. Nuaklong et al. (Arora et al., 2021) and Mamun and Shafiqul (Elchalakani and Elgaali, 2012) reported the chloride penetration depth of concrete submerged in a 3% NaCl blend for 120 days. The depth of penetration of geopolymer concrete having limestone aggregates and recycled concrete aggregates at 120 days was 21.5 mm and 20.9 mm, respectively. Elchalakani et al. (Elchalakani et al., 2017; Alabi and Mahachi, 2021) observed the RCP resistance was 671 Coulombs (in the Gulf region, RCP should be less than 1,000C) for the concrete specimens where 90% Portland cement was substituted by GGBFS, and 100% natural aggregate was substituted with recycled aggregates. Nuaklong et al. (Nuaklong et al., 2020) noticed a notably lower depth of chloride penetration when the 5–15% OPC was blended with GRAC. The depth of chloride penetration for GRAC concrete specimens containing 5–15% OPC at 120 days saturation term was 13.2, 11.5, and 9.4 mm, in succession, while that of control GRAC was 20.6 mm. The effects of RA on the chloride perforation of geopolymer concrete stated in various investigations are given in Table 9.

2.7. Sulfuric acid resistance

The chemical reaction between calcium (Ca) compounds in cement binder and sulfuric/hydrochloric acid prompts rupture and deterioration in cement binder structure as a consequence of the generated tensile stresses. Geopolymer matrix is usually highly resistant to sulfuric acid because of the reduced water ingression and low calcium (Ca) occupancy which generates slightly dissolvable compounds (Nuaklong et al., 2019). It was reported by Nuaklong et al. (Ren and Zhang, 2019; Sanusi et al., 2011) that the impedance to acid attack

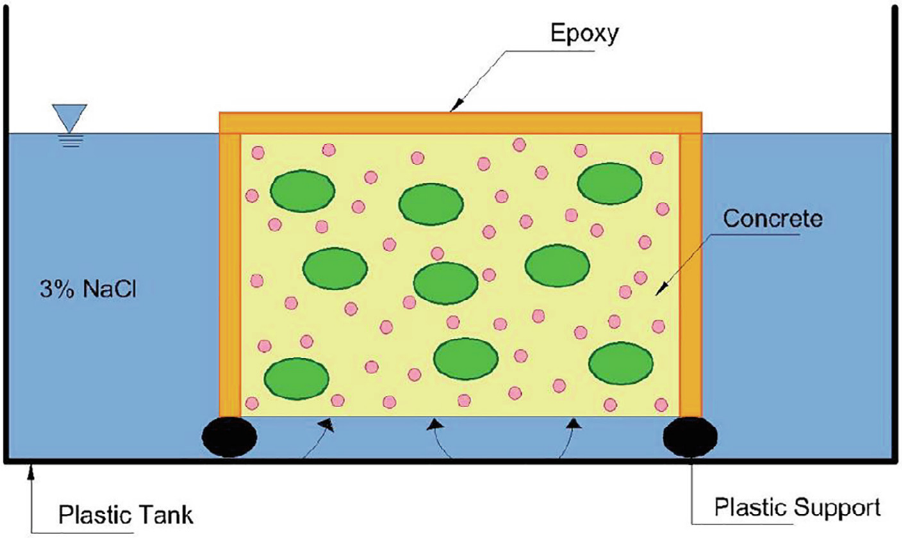


Fig. 9. Test setup for chloride penetration into concrete.

Table 9
Effect of RA on the effect of chloride penetration.

Ref.	Replacement level	Precursor	Effect on the chloride ion penetration of GC
(Akbarnezhad et al., 2015)	0, 10, 20, and 30%	MK	The increase of the RCA percentages led to an increase in the chloride ion penetration
(Nuaklong et al., 2020)	FA and Nano-SiO_2	MK	Enhancement in the immunity to chloride penetration due to an increase in the substitution level of cement with FA from 5% to 15%.
(Oikonomou, 2005)	0 and 100%	FA	RCA concrete consistently exhibited reduced strength and immunity to chloride, frost, and sulfate attack compared to the reference specimen.
(Fernando and Said, 2011)	0 and 100%	FA and RHA	RCA concrete exhibited improved immunity to chloride ion penetration.
(Mohammadinia et al., 2016)	0, 15, 30, and 50%	FA	The Chloride ion penetration depth increased from 11 to 25 mm on account of the replacement of natural aggregates by 50% of recycled aggregates in the GC mixtures.

enhanced with the increment in sodium hydroxide concentration. The geopolymer specimens containing recycled aggregates exhibited less resistance to acid attack when compared with the geopolymer limestone aggregate concrete specimens. The reaction between an acid and the calcium compounds present in the attached cement mortar surrounding the recycled aggregates follows the deterioration of the concrete (Fig. 10).

Nuaklong et al. (Ganesh and Muthukannan, 2019) noted that the geopolymer matrices exhibited an insignificant change in the weight after 28 days susceptibility to 3% sulfuric acid, which notably lessened after 56 days of immersion. Poor resistance to acid attack resulted from the generation of C-A-S-H gel arising from the inclusion of OPC in fly ash based geopolymer. The mixtures blended with 5, 10, and 15% OPC exhibited weight loss of 25, 22.4, and 22.6% in succession (84 days) in comparison with the 19.3% loss of the reference specimens. While the weight loss for the GRAC mixture specimens (120 days) containing 1, 2 and 3% nano-SiO_2 were 31, 32.5 and 30.3%, respectively in contrast with the 28.7% loss for the reference specimen. The reduction in sulphuric acid resistance for GRAC can be attributed to high water absorption capacity, permeable voids and sorptivity of RA as compared to NA. Moreover, the calcium compounds present in RA and the attached mortar may react with the acid solution resulting in further deterioration of the concrete. The effects of RA on the resistance to sulfate and acid attack of geopolymer concrete, revealed in various investigations, are exhibited in Table 10.

2.8. Toxicity characteristic leaching procedure (TCLP)

This procedure is employed to regulate the release of the prospective precarious heavy metals and other ingredients of possible apprehension from the geopolymer matrices and be aware of whether the material should be designated as dangerous or non-hazardous. Sanusi et al. (Sanusi et al., 2016) investigated toxicity characteristics of coal fly ash based geopolymer concrete with virgin aggregates as per Netherlands normalization institute standard (EA NEN 7371, 2005) and the peak cluster of three elements, As-arsenic, Cr-chromium, and Se-selenium were detected. The maximum leach out was measured for As with a concentration of 13 mg/kg). Replacing coarse aggregates with recycled concrete aggregates (RCA) leads to a gradual reduction in the arsenic concentration. The arsenic concentration was reduced to 10 mg/kg and 9 mg/kg when the RCA was replaced for 10% and 50%, correspondingly. Sanusi et al. (Komnitsas, 2016) conducted TCLP test as per EPA method 1311 and found out that most of the ingredients of possible apprehension were not leached at levels above the EPA soil screening levels or the TCLP governing thresholds. Silver, lead, and cadmium leached at levels just about the exposure curb (roughly one ppb) of the ICP-MS gauge employed in elemental exposition. Komnitsas (Alanazi, 2022) observed that the predicted leaching of precarious ingredients, chiefly heavy metals, from the generated specimens was very moderate, given that their degree of solubilization from the inceptive raw materials is minor.

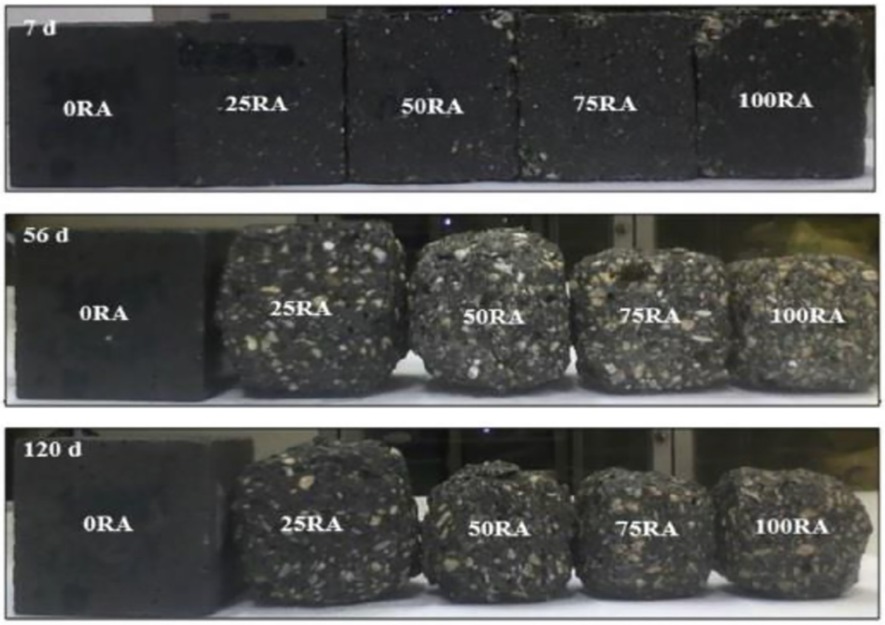


Fig. 10. Geopolymer-recycled aggregate mortar samples after 7, 56, and 120 days of vulnerability to the acid solution (Fernando and Said, 2011).

Table 10
Influence of RA on the sulfate and acid attack resistance.

Ref.	Replacement level	Effect on the sulfate and acid resistance of GC
(Hu et al., 2019)	0, 50, and 100%	The employment of recycled aggregate alternatively for natural aggregates in GC has a similar effect on sulfate and acid resistance.
(Nuaklong et al., 2020)	FA and Nano-SiO_2	Using FA as cement replacement by 5–15% improved the concrete durability against the sulfuric acid for the recycled aggregate geopolymer concrete.
(Oikonomou, 2005)	0 and 100%	The high sulfuric acid resistance of the geopolymer matrix may be due to the reduced water engrossment and lower volume calcium (Ca), initiating fewer soluble compounds.
(Sanusi et al., 2011)	0, 25, 50, 75, and 100%	The rate of deterioration increased due to an enhancement in the quota of the recycled aggregates.

2.9. Microstructure studies

There are three phases in the conventional concrete (virgin aggregate, ITZ, and hydrated cement) and five phases in the recycled aggregate concrete (virgin aggregate, old ITZ, old cement paste, new ITZ, and new cement paste). The new ITZ is very important in RA used concrete owing to its contribution to the failure mechanism. Fig. 11 shows the ITZ of conventional concrete and recycled aggregate concrete. Despite the great attention given to geopolymer concrete, the studies on it microstructural properties are very less in number. Similar to OPC concrete, geopolymer concrete also has three phases- aggregate, ITZ and geopolymer matrix. Alanazi (Liu et al., 2016)conducted a study to explore the microstructural characteristics of geopolymer concrete. The results showed that the geopolymer concrete had better ITZ characteristics as compared to the conventional concrete which might be due to the better bonding of geopolymer matrix with the aggregates. Fig. 12 shows the ITZ in geopolymer concrete produced from RA and virgin aggregates and the new ITZ between virgin aggregates and geopolymer cementitious material (Pawluczuk et al., 2021; Ouda and Gharieb, 2020). The microstructure of geopolymer concrete incorporating natural aggregates and recycled aggregates was investigated by Hu et al. (Hu et al., 2019). The geopolymer matrix without GGBFS exhibited a non-uniform structure, multiplicity of porosity, and was observed with many defects. With an enhancement in the GGBFS content, pore composition was improved because of the formation of a dense structure. As the mild portion is in the ITZ connecting the aggregate and the matrix, cracks in the shared boundary are then enlarged to the matrix (Fig. 13. Ouda and Gharieb (Thaarrini et al., 2016) witnessed a denser and impermeable microstructure for the geopolymer matrix (incorporating brick waste and 5–30% of calcined-dolomite concrete powder) unveiled to 800 °C for two h at five °C/min. An enhancement in the quantity of RA reduced the formation of the cracks in the geopolymer blend. The continued geopolymerization improved the crack reduction on the escalation of the curing interval from 7 to 28 days, creating a very strong matrix preventing the crack propagation through it (Xie et al., 2019; Xie et al., 2019).

The cost comparison between conventional concrete and geopolymer concrete was done by Thaarrini and Dhivya (Wang et al., 2020). The materials used for the conventional concrete were cement, fine aggregate, coarse aggregate and superplasticiser. For GPC, the materials used were bottom ash, GGBFS, river sand, foundry sand, coarse aggregate, NaOH flakes, Na_2SiO_3 solution. For the production of 1 m^3 of M30 grade concrete, the cost for GPC was around 1.7% greater than the conventional concrete whereas for M50 concrete, the savings was around 11%. Thus, geopolymer concretes will be economically beneficial for higher grades of concrete.

7. Future aspects

Based on the comprehensive review adopted in the study, essential research gaps are identified, and directions for future research studies are listed below for effective use of recycled aggregate based geopolymer concrete in the construction industry. The directions for future research are listed below.

The properties of aggregates influence the properties of concrete significantly. RCA mainly consists of normal aggregates, attached mortar and an interface between them. The properties will be different for GPC with treated and GPC with untreated RCA. The pre-treatment can be done either by removing the old mortar or by surface treatment [112]. Many methods, including thermal treatment, mechanical treatment, chemical treatment, and water cleaning techniques, are used to remove the weak mortar attached to the aggregate. Besides, a combination of any two treatments, such as thermo-mechanical treatment, chemical–mechanical treatment, is also adopted. Thermal treatment includes traditional heating or microwave heating method. In the traditional treatment method, RCA is heated, and due to the difference in

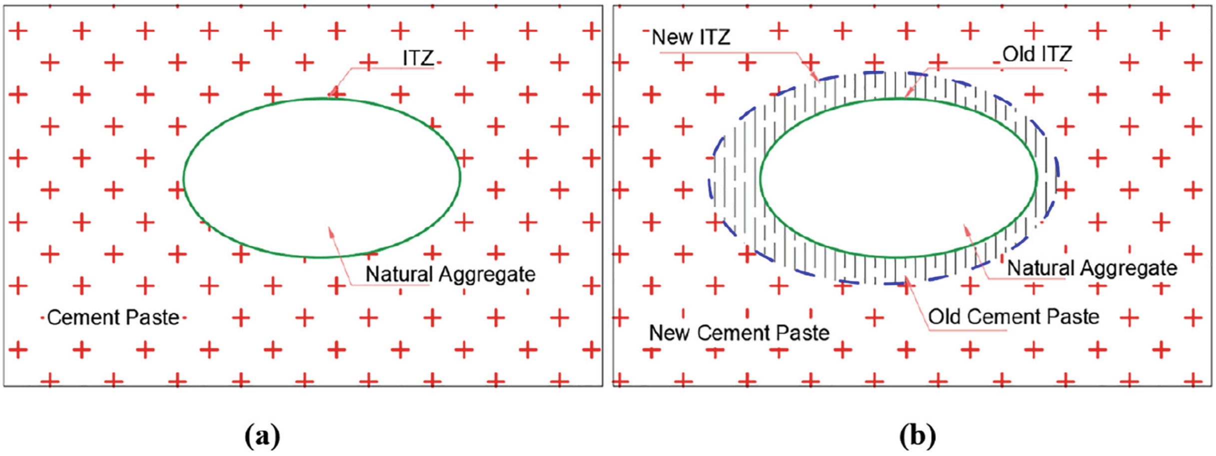


Fig. 11. Constitutive phases. (a) conventional concrete; (b) recycled aggregate concrete.

Fig. 12. The ITZ in geopolymer concrete generated from RA (a) and NA (b), where A represents the contemporary interfacial transition zones connecting natural aggregate and geopolymer (Ren and Zhang, 2016).

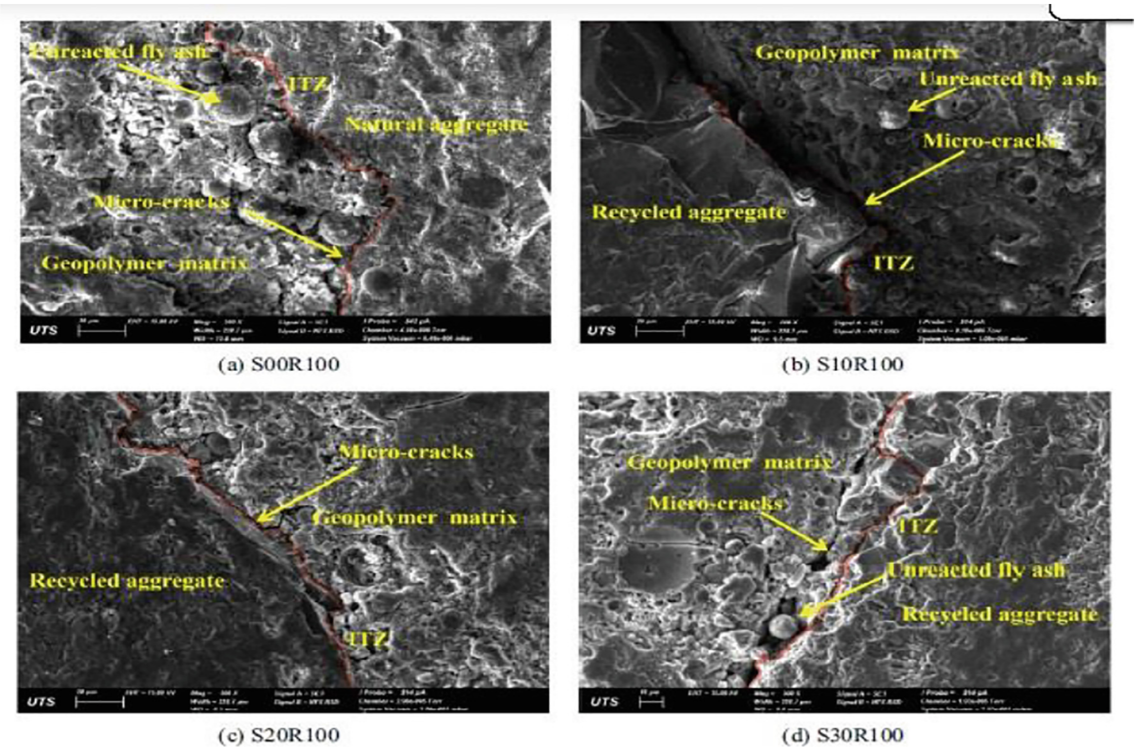


Fig. 13. Microstructure of geopolymer blends incorporating recycled coarse aggregates, where S is GGBFS and R is recycled aggregates (Hu et al., 2019).

thermal expansion between aggregate and mortar, the weak mortar can be separated. Similarly, in microwave heating, this separation of adhered mortar from normal aggregate is achieved because of the difference in electromagnetic properties of aggregate and mortar. Different pre-treatment methods are available and will have different impacts on the properties of concrete. Hence, in-depth studies need to be done on these methods to find the most suitable treatment methods.

It is anticipated that the emerging utilization of geopolymer as an alternative for Portland cement concrete will escort to a corresponding escalation in the quantity of geopolymer debris in the future. Accessible literature is on the use of PCC demolition waste in normal concrete and geopolymer concrete. There is forthwith a proficiency gap on the reuse of geopolymer demolition waste in Portland cement concrete as well as in geopolymer concrete.

A handful of investigations supposed that the OPC concrete incorporating nano-SiO_2 acquires higher early compressive strength in contrast with the traditional concrete due to the remarkable capability of the nano-particle in the curtailment of porosity, making the concrete impenetrable and robust. An investigation on the GRAC containing a combination of OPC and nano-SiO_2 (0.25–1%) in varying percentages can be a breakthrough in the GRAC research.

The investigation is needed on the suitable mix design procedure, structural performance, and durability of GRAC influencing collaborative usage of metakaolin and GGBS. As per the available works of literature, only the workability, compressive strength properties, stress–strain relation, elastic modulus, Poisson's ratio, toughness, and failure mode of GGBS/metakaolin based GRAC is investigated. The utilization of the one-part geopolymer with multiple raw materials and RCA will also need to be looked at in terms of the optimal mix and coordination mechanism.

Various researchers reported that the incorporation of MK magnifies the mechanical properties and durability of concrete on account of its high pozzolanic susceptibility and filling effects. As per the available literature, the research on workability, strength, water absorption, acid attack, and chloride ion penetration are available on high calcium fly ash (HCF) combined with MK. An appropriate study can be conducted on the characteristics of high strength GRAC along with the sulfate attack, corrosion potentials of steel reinforcements, carbonation resistance, and microstructure properties.

The durability of GRAC needs studied on material as well as structural aspects. The introduction of proper quality standards is essential for prospective applications.

8. Summary and conclusion

This review paper comprehends the scientific insights with reference to the use of recycled aggregate from construction and demolition waste in geopolymer concrete and outlines its influence on the different properties of geopolymer recycled aggregates used in concrete. Recycled aggregates are gaining popularity to be used as a construction material and contribute to the sustainable development in the construction industry. The following conclusions can be drawn.

Recycled aggregates in saturated surface dry condition improve the workability of geopolymer concrete. Workability of concrete is increased with increase in the amount of recycled aggregates.

The compressive strength of GRAC is found higher than OPC concrete, and it increases with the increase in slag content.

The microstructure studies on geopolymer concrete reported better ITZ characteristics as compared to conventional concrete.

High volume fly ash blended with 5–15% OPC and metakaolin is more resistant to surface abrasion.

The water absorption and sorptivity of GRAC are increased with the increase in the amount of RA, mainly by reason of the higher absorption value of recycled aggregates caused by the cracks and fissures during its manufacturing process.

Geopolymer concrete is highly immune to sulfuric acid. At the same time, the GRAC (normal or blended) is less resistant to acid attack because of the reaction between acid and the calcium compounds present in the attached cement mortar, surrounding the recycled aggregates.

The chloride penetration for geopolymer concrete containing recycled aggregates was found within the specified limits. Thus, more concentrated research needs to be administered in this area for the well-organized use of recycled aggregates in geopolymer concrete, and it seems to be a promising contribution towards the sustainability of the construction industry.

The optimum replacement level is governed by different factors such as the characteristics of the recycled aggregates, the level of workability adopted during the mixture design, the amount of fines available in the recycled aggregates etc. Hence, the suitable level of replacement varies with respect to materials characteristics as well as required level of workability and strength

To increase the industrial acceptance of geopolymer concrete, research needs to be done on the mix design procedures, durability properties, structural performance etc.

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