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Review Paper

The influence of recycled aggregate on the properties of geopolymeric recycled concrete: A comprehensive review

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Abstract: This paper offers a comprehensive review of geopolymeric recycled concrete (GRC) research, particularly focusing on mechanical properties, durability, microstructure, and the interfacial transition zone (ITZ). The study emphasizes the influence of recycled aggregate (RA) content on GRC performance. Findings indicate that higher RA content leads to a gradual reduction in GRC's compressive, tensile, and flexural strengths, elastic modulus, and toughness. The elastic modulus is most affected, followed by compressive strength, while tensile strength experiences the least decline. Moreover, increased RA content is associated with elevated water absorption, decreased resistance to chloride ion permeability, sulfate corrosion, acid, frost, and carbonization in geopolymer concrete. The integration of RA creates more intricate ITZs in geopolymer concrete, resulting in reduced bonding strength and a looser, more porous microstructure. However, the use of geopolymers can mitigate these effects by enhancing bonding in ITZs. The paper also presents a statistical analysis of compressive strength test results from various studies and proposes a preliminary method for estimating the compressive strength of geopolymer concrete with different RA replacement rates.

Keywords: Geopolymer, Recycled aggregate, Mechanical properties, Durability, Interfacial transition zone, Microstructure.

1. Introduction

At present, the world is facing the problem of climate change and the greenhouse effect. The central environmental agencies have put forward the climate goals of carbon neutrality. Since the purpose of carbon neutrality was put forward in 2020 [1], China's construction and building materials industry has been moving toward green, low-carbon, energy-saving and emission reduction. However, the high energy consumption and high emission characteristics of the production process of cement, the primary cementitious material, run counter to the carbon neutrality goal. It is estimated that producing 1 ton of Portland cement requires approximately 1.5 tons of limestone, and the process of fossil fuel combustion and limestone calcination will emit nearly 1 ton of carbon dioxide [2]. As a result, the carbon dioxide emissions from the cement industry account for 6 % to 7 % of the total global carbon dioxide emissions [3]. Therefore, it is necessary to develop low-carbon cementitious materials. Geopolymer proposed by Davidovits is an inorganic polymer with three-dimensional network structure composed of $[SiO_4]^-$ and $[AlO_4]^-$ tetrahedral structural units, which is synthesized by geochemical or geological processes [4]. In engineering and research, the materials used to form geopolymers are usually industrial aluminosilicate wastes such as fly ash, rice husk ash and blast furnace slag, or natural minerals such as

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metakaolin and clay [5–8]. The geopolymer formed by the above aluminosilicate precursors through chemical activation, mechanical activation or mechanochemical activation has the properties of cementitious binders [9–13]. However, geopolymer has a relatively less carbon footprint than conventional cementitious binders [14]. Using geopolymer to prepare concrete, carbon dioxide emissions can be reduced by 70 % to 90 % compared to cement [15]. Geopolymer concrete has higher compressive strength, lower shrinkage and thermal conductivity, better acid and alkali resistance, higher temperature resistance and wear resistance than Portland cement concrete under good mix ratio and curing conditions [16–22]. Therefore, geopolymer can be used as a sustainable alternative to cement in the preparation of concrete.

On the other hand, only 40 countries in the world produce more than 3 billion tons of construction and demolition (C&D) waste every year [23], while China's annual C&D waste exceeds 2.35 billion tons [24]. Recycled aggregate (RA) is produced from C&D waste and is used to replace natural aggregate to prepare recycled concrete, which can effectively solve the problem of C&D waste treatment and reduce carbon emissions [25, 26]. Compared with mining natural aggregate, producing the same amount of RA can reduce carbon emissions by 23 % to 28 % and production costs by 34 % [27]. However, due to the existence of old mortar and old interfacial transition zones (ITZs) on the aggregate surface, the RA shows the characteristics of low strength, low density, high crushing index, high porosity and water absorption [28, 29], which significantly limits the application of RA. The combination of geopolymer and RA to prepare geopolymeric recycled concrete (GRC) is a new way to reduce carbon emission and solid waste.

For over a decade, many scholars have incorporated RA into geopolymer concrete to explore its mechanical properties and durability. However, few studies have reviewed GRC. This paper focuses on the influence of RA and its content on the mechanical properties and durability of GRC. The research status of GRC is summarized and analyzed from the aspects of mechanical properties, durability, microstructure, bonding properties of the ITZ and initial curing conditions, which provides a reference for the research and engineering application of GRC.

2. Research status of geopolymeric recycled concrete

2.1. Mechanical properties

The precursors of GRC mainly include three types: fly ash, slag, and slag-fly ash blend. The compressive, tensile, and flexural strengths and elastic modulus of these three types of GRC were extensively studied. Due to the large number of pores and cracks in the old mortar and old ITZ attached to the surface of RA, the mechanical properties of geopolymer concrete will be reduced after incorporating RA.

2.1.1. Fly ash based GRC

Shi et al. [30] prepared RA concrete (RAC) and alkali-activated fly ash based GRC with RA replacement rates of 0 %, 50 % and 100 %, respectively. The research showed that with the increase of RA content, the compressive strength of RAC and fly ash based GRC decreased, but the compressive strength of fly ash based GRC was higher than that of RAC under the corresponding RA replacement rate, indicating that fly ash based geopolymer instead of cement paste can effectively improve the compressive strength of recycled concrete. Nuaklong et al. [31] prepared high-calcium fly ash based GRC. It was found that when RA was used to replace natural aggregate by 100 %, the 7-day compressive strength of GRC was 30.6 to 38.4 MPa, which was 7 % to 24 % lower than that of concrete without RA, indicating that the incorporation of RA in geopolymer concrete will have strength reduction, but the concrete still has a high compressive strength. Shaikh [32] tested the tensile strength and elastic modulus of GRC and found that when RA replaced natural aggregate by 15 % to 50 %, the tensile strength decreased by 6.82 % to 15.91 %, and the elastic modulus decreased by 16.67 % to 41.67 %. In addition, for the study of the performance of GRC members, Shi et al. [33] prepared concrete-filled steel tube columns filled with fly ash based GRC. It was found that the bearing capacity of the column was reduced by 25 %, and the ductility index was increased by 45 % after incorporating RA. Most of the above studies take the replacement rate of RA as a variable. However, Liu et al. [34] tested the fly ash based GRC with different liquid-solid ratios and found that with the increase of liquid-solid ratio (0.4/0.45/0.5), the compressive strength of GRC specimens decreased by 6.04 % to 33.55 %, and the Young's modulus decreased by 21.94 % to 86.84 %, which may be due to the deterioration of geopolymer performance due to the increase of liquid-solid ratio.

2.1.2. Slag-based GRC

The mechanical properties of GRC mixed with blast furnace slag differ from those of fly ash based GRC. Parthiban et al. [35] found that compared with the specimens without RA, the compressive strength of the specimens with RA replacement rates of 25 %, 50 % and 75 % increased by 10 %, 15 % and 6 %, respectively, and the tensile strength increased by 9 %, 16 % and 17 %. It shows that the mechanical properties of alkali-activated slag geopolymer concrete will not deteriorate significantly after incorporating RA. Zhang et al. [36] replaced all-natural sand and gravel aggregates with recycled coarse and fine aggregates and prepared slag-based geopolymeric fully recycled concrete. The test results showed that its 28-day compressive strength was still considerably (30.2 MPa to 44.6 Mpa). In addition, Parthiban [37] studied the effect of RA on alkali-activated slag-based reinforced concrete beams. It was found that when the replacement rate of RA was less than 75 %, the bearing capacity of the beam increased with the increase of RA, and the maximum increase was 22.53 %. When the replacement rate continued to increase to 100 %, the bearing capacity decreased, and the deflection and ductility of the beam increased with the increase of RA content. The above studies show that the incorporation of RA does not significantly reduce the mechanical properties of slag-based geopolymer concrete. Incorporating RA into slag-based geopolymer concrete at a replacement rate of no more than 50 % is recommended, which can achieve the same mechanical properties as geopolymer natural aggregate concrete.

2.1.3. Slag-fly ash based GRC

The incorporation of slag can improve the mechanical properties of concrete but cause a decrease in workability. Considering the fluidity gain effect of fly ash, scholars have studied the performance of slag-fly ash based GRC. Xie et al. [38] found that in GRC, slag and fly ash showed an excellent synergistic effect; that is, the mechanical properties were mainly determined by slag, and the workability was mainly determined by fly ash. They proposed that the prepared GRC had good workability and mechanical properties under the liquid-solid ratio of 0.5 and the mass ratio of slag/fly ash of 1:1. Some other studies have shown that [39–41], when slag partially replaces fly ash, the compressive strength of GRC increases, and the concrete can form high strength under room temperature curing conditions without high-temperature curing process. Xie et al. [42] proposed that the slag-fly ash based geopolymer and RA combination can show good mechanical properties, and slag-fly ash based GRC has higher compressive strength, Poisson's ratio and toughness compared with ordinary cement concrete. In addition, with the increase of liquid-solid ratio (0.3 / 0.4 / 0.5), the compressive strength of slag-fly ash based GRC decreased by 29.26 % to 33.81 %, the elastic modulus decreased by 21 % to 43.9 %, the toughness decreased by 5.56 %, and the Poisson's ratio increased by 4.52 % to 9.95 %. With the increase of RA replacement rate (0 % to 100 %), the compressive strength of GRC decreased by 14.93 % to 42.93 %, the elastic modulus decreased by 9.45 % to 31.09 %, and the toughness decreased by 4.88 % to 14.63 %, while the Poisson's ratio changed little ($<$ 4 %) [42]. The study of Tang et al. [43] on the stress-strain relationship of slag-fly ash based GRC under uniaxial compression also showed that the peak stress, elastic modulus and toughness of the specimens decreased with the increase of RA content and increased with the increase of slag content, while the ductility showed the opposite trend. In addition, Tang et al. [44] found that under quasi-static compression, the compressive strength of geopolymer concrete decreased by 8.33 % to 32.43 % after incorporating RA, while the compressive strength increased by 1 to 2 times after incorporating slag, but it also increased the brittleness of concrete. Under dynamic load, the dynamic compressive strength of geopolymer concrete increased with the increase of strain rate, but it had little to do with the incorporation of RA. Therefore, although the RA reduces the quasi-static compressive strength of GRC, it has little effect on the compressive strength at a high strain rate.

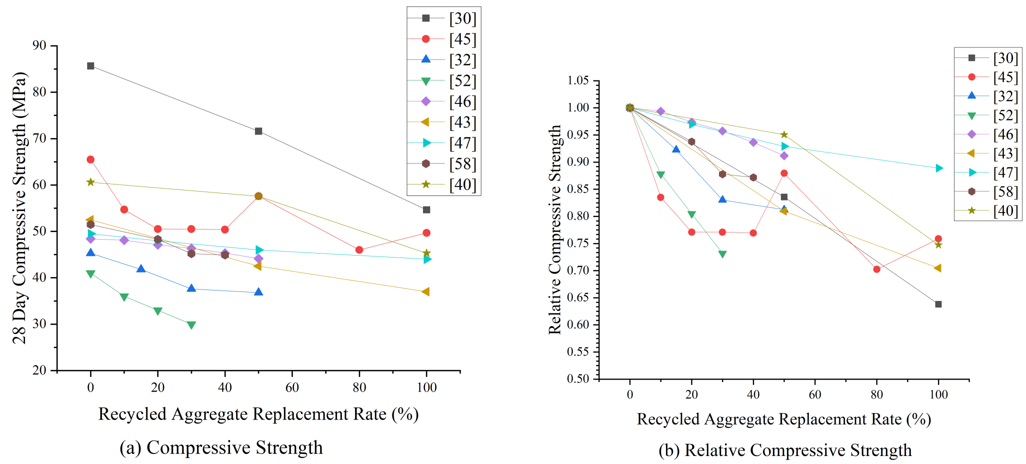


Fig. 1 – Variations in the compressive strength of GRC with the replacement rate of RA.

2.1.4. Comprehensive analysis of mechanical properties of GRC

Through the comprehensive analysis of the data in the literature [45–50], the influence of RA and its content on the mechanical properties of GRC was discussed. Fig. 1 shows the variation of the compressive strength of GRC measured in each study with the replacement rate of RA. It can be seen from Fig. 1 that with the increase of RA content, the compressive strength of GRC decreases continuously. When the replacement rate of RA is 50 %, the compressive strength decreases by 4.95 % to 19.05 %. When the replacement rate is 100 %, the compressive strength decreases by 11.11 % to 36.19 %. The reduction amplitude of compressive strength at each replacement rate level is summarized in Table 1.

Table 1 – Reduction amplitude of compressive strength of GRC corresponding to RA replacement rate.

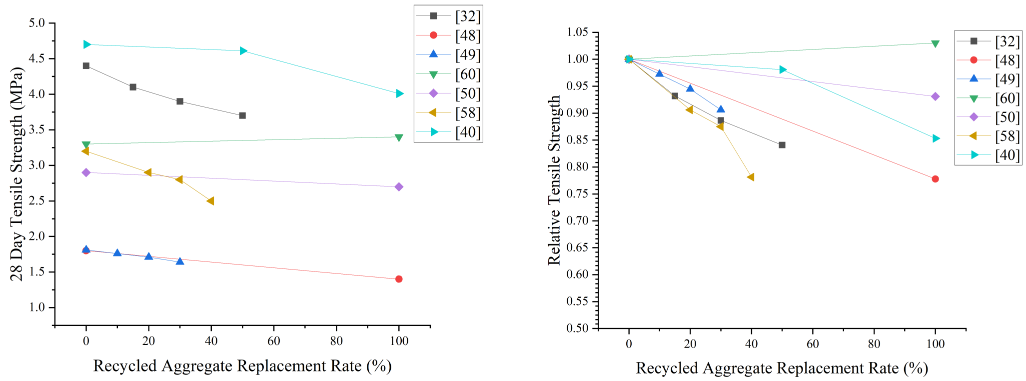
Recycled Aggregate Replacement Rate	Reduction Amplitude of Compressive Strength
10 %	0.62 % to 16.49 %
20 %	2.64 % to 22.90 %
30 %	4.26 % to 26.83 %
40 %	6.36 % to 23.05 %
50 %	4.95 % to 19.05 %
100 %	11.11 % to 36.19 %

Although the mix ratio, cementitious materials, and RA sources used in each study differ, the compressive strength of the GRC obtained is also quite different. However, each study's compressive strength curves with the RA replacement rate seem to have similar rules. As shown in Fig. 1, the compressive strength varies approximately linearly with the RA replacement rate, and each data group's slope is in a similar range. For summarizing the consistent law of the compressive strength of GRC with the replacement rate of RA, the literature data of each group of relative compressive strength was linearly fit and the longitudinal axis intercept was fixed to 1 in the fitting control. The slope values of each group are recorded as k. The slope values k and the corresponding alkali-activated precursors and data source literature are shown in Table 2.

Table 2 – Corresponding information for each slope value k.

Slope Value k	Alkali-activated Precursor	Data Sources
-0.00355	Fly ash	[30]
-0.00348	Fly ash	[45]
-0.00431	Fly ash	[32]
-0.00941	Metakaolin	[52]
-0.00160	Slag and fly ash	[46]
-0.00312	Slag and fly ash	[43]
-0.00118	Slag, fly ash and HPA	[47]
-0.00346	Slag	[58]
-0.00222	Slag and fly ash	[40]

In this paper, the slope value k obtained by linear



(a) Tensile Strength (b) Relative Tensile Strength

Fig. 2 – Variations in the tensile strength of GRC with the replacement rate of RA.

fitting is defined as "recycled aggregate influence factor", which characterizes the influence of RA on the compressive strength of concrete. The greater the absolute value of k, the more quickly the compressive strength is affected by the incorporation of RA. This paper speculates that the difference in the slope value k comes from the difference in the composition of the alkali-activated precursors of GRC prepared in each study. It can be seen from Table 2 that when the precursor is a single fly ash or slag, the k value is about -0.0035 and -0.0043. When part of the slag replaces fly ash, the absolute value of k decreases, indicating that the compressive strength of this kind of geopolymer concrete is less susceptible to the influence of the incorporation of RA. In other words, the preparation of GRC by partially replacing fly ash with slag is helpful to resist the adverse effect of RA on compressive strength. When the precursor is mixed with some kaolinite ultra-fine fly ash (HPA), the absolute value of k is the smallest, indicating that the RA has the lowest deterioration effect on the compressive strength of GRC. The k value of metakaolin-based GRC is -0.00941, indicating that the incorporation of RA efficiently reduces the compressive strength of this kind of concrete.

For reasonably predicting the compressive strength of GRC under different RA replacement rates, this paper defines γ as "compressive strength reduction coefficient":

$$\gamma = 1 + k \cdot \mu \cdot 100 \tag{1}$$

In the Eq. 1, k - RA influence factor, determined by test or engineering experience; μ - RA replacement rate, μ in [0, 100 %].

Define f_{cf} as "the predicted value of cubic compressive strength":

$$f_{cf} = \gamma \cdot f_c \tag{2}$$

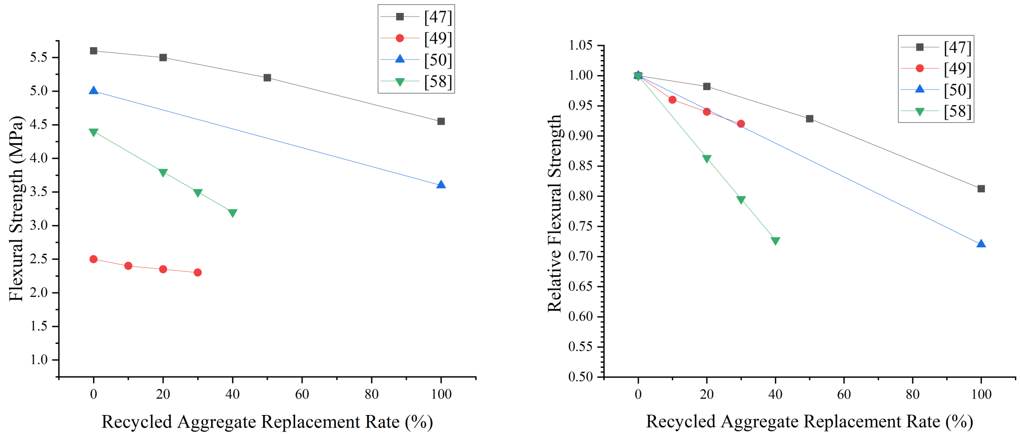
In the Eq. 2, γ-compressive strength reduction coefficient, determined by Eq. 1; f_c - the cubic compressive strength of concrete without RA.

Based on the data in Table 2, the average values of k corresponding to the precursor types are taken as the recommended k values of geopolymer concrete, which are listed in Table 3. According to Table 3, the precursor type determines the k value, and the compressive strength of geopolymer concrete under different RA replacement rates can be preliminarily estimated using Eq. 1 and Eq. 2. In addition, researchers need to expand the research of other alkali-activated precursor recycled concrete to provide a more scientific and perfect reference range of k value for future scientific research and engineering applications.

Table 3 – The reference value of k of geopolymer concrete.

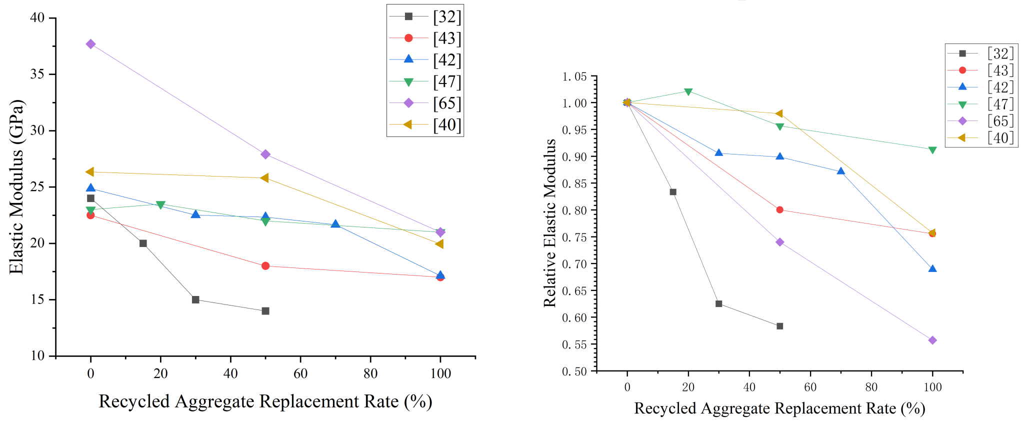
Precursor Type	Reference Range of k	Recommended Value
Slag or fly ash	-0.00431 to -0.00346	-0.0037
Slag and fly ash	-0.00312 to -0.00160	-0.0023

Fig. 2 shows the variation of the tensile strength of GRC with the replacement rate of RA. When the replacement rate of RA is 30 %, the tensile strength



(a) Flexural Strength (b) Relative Flexural Strength

Fig. 3 – Variations in the flexural strength of GRC with the replacement rate of RA.

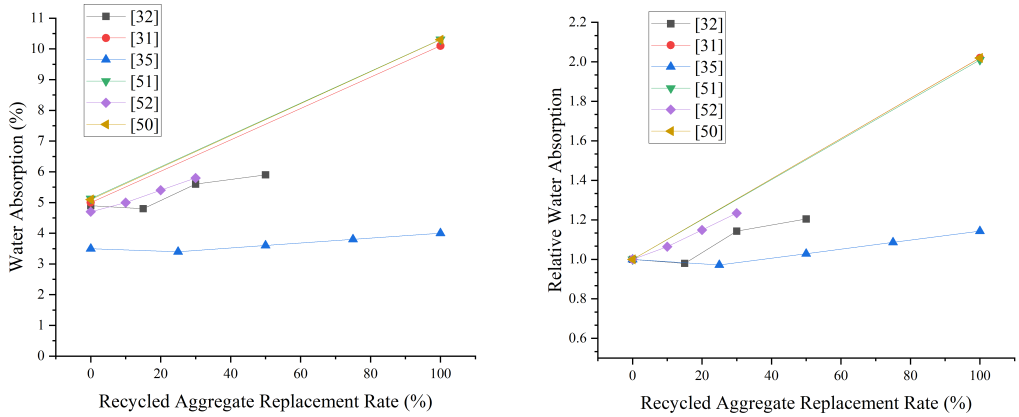


(a) Elastic Modulus (b) Relative Elastic Modulus

Fig. 4 – Variations in the elastic modulus of GRC with the replacement rate of RA.

decreases within 12.5 %. When the replacement rate is 50 %, the tensile strength decreases within 15.91 %. When the replacement rate is 100 %, the tensile strength decreases within 22.22 %. It can be found that the tensile strength reduction effect is not as obvious as the compressive strength, and even at the 100 % replacement rate, the tensile strength is slightly improved. The reason for this difference may be that the compressive strength of GRC is more susceptible to aggregate properties than the tensile strength, and the strength of RA is generally lower than that of natural aggregate. Moreover, compared with natural aggregate, RA has more edges and rougher surfaces, which may compensate for the loss of tensile strength in concrete.

Fig. 3 and Fig. 4 show the variations of flexural strength and elastic modulus of GRC with the replacement rate of RA. It can be found that the flexural strength and elastic modulus decrease with the increase of RA replacement rate, and the decrease of elastic modulus is more obvious. When the replacement rate of RA is 30 %, the flexural strength decreases by 8 % to 20.45 %, and when the replacement rate is 100 %, the flexural strength decreases by 18.75 % to 28 %. When the replacement rate of RA is 30 %, the elastic modulus is reduced by 9.45 % to 37.5 %. When the replacement rate is 50 %, the elastic modulus is reduced by 2.05 % to 41.67 %. When the replacement rate is 100 %, the elastic modulus is reduced by 8.7 % to 44.3 %. In summary, for geopolymer concrete, when the content of RA increases, the elastic modulus of concrete decreases most obviously, followed by compressive strength, and the tensile strength decreases the least.



(a) Water Absorption

(b) Relative Water Absorption

Fig. 5 – Variations in the water absorption of GRC with the replacement rate of RA.

The mechanical properties of GRC are summarized as follows:

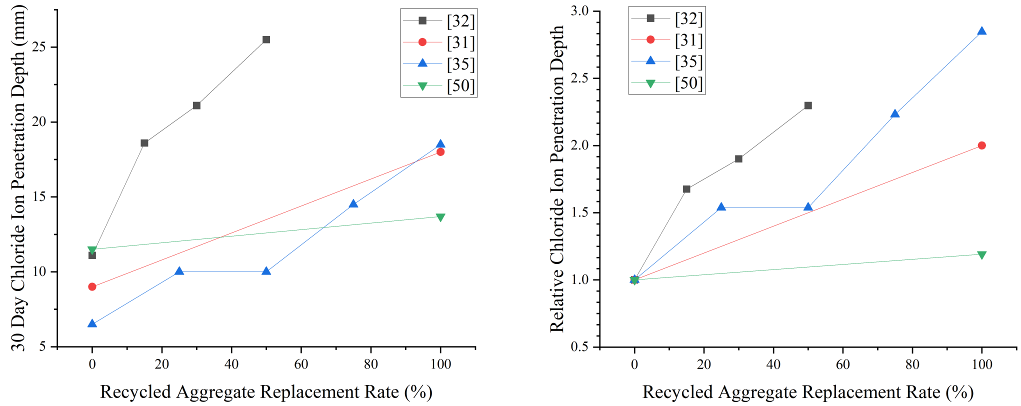
1. The replacement of cement paste by geopolymer paste can effectively improve the mechanical properties of recycled concrete and make up for the negative impact of RA to a certain extent;
2. The incorporation of RA in geopolymer concrete will lead to a certain loss of strength, but the concrete still has a high enough compressive strength, which is due to the excellent mechanical strength and compactness of the geopolymer matrix;
3. Incorporating slag into GRC can improve the mechanical properties of concrete, and the specimens can achieve high strength without high-temperature curing. With the increase of slag content, the compressive strength, peak stress, toughness, and elastic modulus of GRC gradually increase, and the ductility decreases;
4. With the increase of RA content in GRC, the compressive strength, tensile strength, flexural strength, elastic modulus, and toughness decrease gradually, and the ductility increases. After incorporating RA with different replacement rates, the elastic modulus of concrete decreases most obviously, followed by compressive strength, and the tensile strength decreases the least. In addition, RA has little effect on the dynamic compressive strength of GRC.

2.2. Durability

Durability affects the service life of concrete. The lack of durability of concrete will cause the spalling of the concrete cover and the corrosion of the internal steel bars, thus affecting the structure's safety. In recent years, the water absorption, chloride ion permeability, sulfate resistance, acid resistance, frost resistance, and carbonization performance of GRC have been studied.

2.2.1. Water absorption

The water absorption of concrete reflects the volume and distribution of its internal pores. Many studies have shown that [31, 35, 37, 51, 52], the more RAs incorporated, the higher the water absorption of GRC. As shown in Fig. 5, when the replacement rate of RA is 30 %, 50%, and 100%, the water absorption rate increases by 14.29 % to 23.4 %, 2.86 % to 20.41 %, and 14.29 % to 102 %, respectively. The increase in water absorption of GRC is mainly due to the large number of pores and cracks in RA. One is due to the mechanical damage caused by the crushing and screening process of waste concrete, and the other is derived from the old mortar of RA. These two reasons lead to increased concrete pores, providing a channel for water flow. In addition, Koushkbaghi et al. [52] studied the effect of Na_2SiO_3 / NaOH mass ratio on the water absorption of GRC and found that when the mass ratio increased from 2:1 to 3:1, the water absorption decreased by 5.5 % to 10 %. The study of Bernal et al. [53] also showed that when the content of Na_2SiO_3 in an alkali-activated solution



(a) Chloride Ion Penetration Depth (b) Relative Chloride Ion Penetration Depth

Fig. 6 – Variations in the Chloride Ion Penetration Depth of GRC with the replacement rate of RA.

increased, the water absorption and pore volume of concrete decreased by 73 % and 63 %, respectively, which was mainly due to the formation of more dense geopolymer matrix by more sodium aluminosilicate gel. Nuaklong et al. [51] found that with the increase of metakaolin content in GRC, the porosity of concrete reduced, and the water absorption decreased. It was speculated that the fine metakaolin particles filled the concrete matrix and ITZ.

2.2.2. Chloride ion permeability

Concrete exposed to the marine environment is prone to performance degradation under chemical erosion. Therefore, chloride ion permeability affects its service life. Relevant studies have found that the depth of chloride ion penetration increases after adding RA into geopolymer concrete, and RA improves the chloride ion permeability of concrete [31, 32, 35, 52]. As shown in Fig. 6, when the replacement rate of RA is 50 %, the penetration depth of chloride ion increases by 53.85 % to 129.73 %, and when the replacement rate is 100 %, the penetration depth of chloride ion increases by 19.13 % to 184.62 %. Chloride ion permeability mainly depends on the number of pores in concrete and the connectivity of pores [54]. The incorporation of RA introduces many micropores and cracks, thereby improving the chloride ion permeability. However, at higher RA content, the chloride ion penetration rate decreases due to the residual C_3A in the old mortar of RA reacting with Cl^- and filling the pores [52].

2.2.3. Sulfate resistance

When sulfate ions invade concrete, it is easy to form ettringite inside, accelerating the expansion of micro-cracks and resulting in cracking, spalling, and strength reduction of the concrete. Parthiban et al. [35] found that with the increase of RA content, the weight loss rate and strength reduction rate of GRC specimens exposed to sulfate solution increased, indicating that RA reduced the sulfate resistance of geopolymer concrete. In addition, Xie et al. [55] found that slag-fly ash based GRC showed lower mass loss and higher residual compressive strength than cement-based concrete under sulfate attack, indicating that slag-fly ash geopolymer paste instead of cement paste is beneficial to the resistance of recycled concrete to sulfate attack. The residual compressive strength of GRC with high slag content increased first and then decreased under sulfate attack. This is because the formed ettringite could fill the pores to a certain extent and improve the compactness, while too much ettringite would lead to concrete cracking and strength reduction [55].

2.2.4. Acid resistance

In an environment of acid erosion, the components of Portland cement concrete, such as calcium hydroxide and hydrated silicate, will react and decompose, decreasing strength. The geopolymer matrix's relatively low water absorption and calcium content make it have higher acid resistance [56]. Ariffin et al. [57] also found that geopolymer concrete showed stronger

Fig. 7 – SEM images of the microstructure of GRC matrix with different RA contents [30].

acid resistance because the chemical composition and phase composition of the geopolymer concrete matrix differed from those of Portland cement concrete. The incorporation of RA in geopolymer concrete will reduce its acid resistance. This is because the porosity and water absorption of concrete increase after the incorporation of RA, and the calcium hydroxide ($Ca(OH)_2$) and hydrated calcium silicate (C – S – H) in the old mortar of RA easily react with acid solution and aggravate the deterioration of concrete [31, 51]. In addition, the acid resistance of GRC is also related to the concentration of NaOH in the alkali-activated solution, that is, the acid resistance increases with the increase of NaOH concentration [31].

2.2.5. Frost resistance and carbonization performance

RA has little effect on geopolymer concrete's frost resistance and carbonization performance. Nazarpour et al. [58] showed that the average mass loss of GRC was 2.1 % under one hundred freeze-thaw cycles, and the compressive strength did not decrease significantly, indicating that GRC had good frost resistance. Huang et al. [59] compared the effect of RA on the carbonization performance of Portland cement concrete and geopolymer concrete and found that the carbonization resistance of both decreased after the incorporation of RA, but the geopolymer concrete was less affected.

Based on the above research, it can be seen that RA has an adverse effect on the durability of concrete, and a geopolymer matrix can alleviate this adverse effect to a certain extent. RA can increase the water absorption and chloride ion permeability of geopolymer concrete and deteriorate sulfate resistance, acid resistance, frost resistance, and carbonization resistance. This is mainly due to two aspects. First, a large number of pores and cracks in RA and its old mortar will directly lead to increased concrete porosity. Second, $Ca(OH)_2$ and C – S – H in old mortar react with sulfate and acid solutions, aggravating concrete deterioration. Therefore, it is recommended to remove the old mortar on the surface of RA or explore its strengthening ways to improve aggregate performance.

2.3. Microstructure

The microstructure significantly affects the mechanical properties and durability of concrete. Many researchers used the scanning electron microscope (SEM) to observe the microstructure of GRC under different RA replacement rates. It was found that with the increase of RA content, the microstructure of concrete became looser, and the pores and cracks in the ITZ increased, as shown in Fig. 7. This is mainly due to the loose porous old mortar and old ITZ on the surface of RA [30, 52].

As shown in Fig. 8, Shi et al. [30] found that, compared with cement-based recycled concrete, the microstructure of GRC is denser and more uniform, with fewer pores and cracks. This is because the hydration products in cement-based recycled concrete are mainly layered $Ca(OH)_2$ and amorphous or low crystalline phase C-S-H, while in GRC is amorphous aluminosilicate gel. Continuous alkali activation and gel formation fill pores and cracks, thus improving the microstructure of GRC [30, 41, 60]. When fly ash or metakaolin is added to GRC, these fine particles can fill the pores, play a micro-aggregate effect, and make the microstructure denser [30, 51]. The above studies reveal why the mechanical properties and durability of GRC are better than those of cement-based recycled concrete from a micro perspective [30, 34, 42, 52, 60].

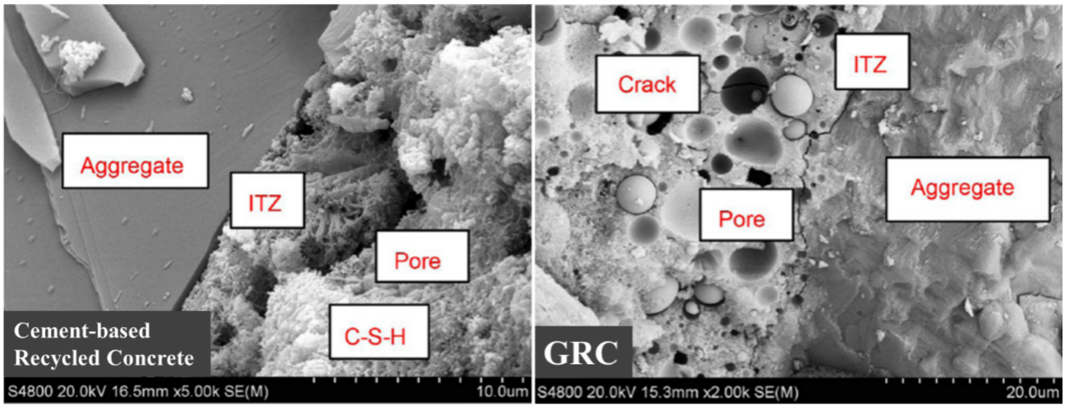


Fig. 8 – Comparison of the microstructure of cement-based recycled concrete and GRC [30].

2.4. Interfacial transition zone

Interfacial transition zone (ITZ) is one of the weak parts of concrete, which is often accompanied by the generation and development of micro-cracks and significantly affects concrete's mechanical properties and durability [61]. Compared with ordinary concrete, the ITZ of GRC is more complex. As shown in Fig. 9, there are three types of ITZs in GRC, namely, the original old ITZ of RA, the newly formed ITZ between geopolymer mortar and aggregate, and the newly formed ITZ between geopolymer mortar and old mortar [62].

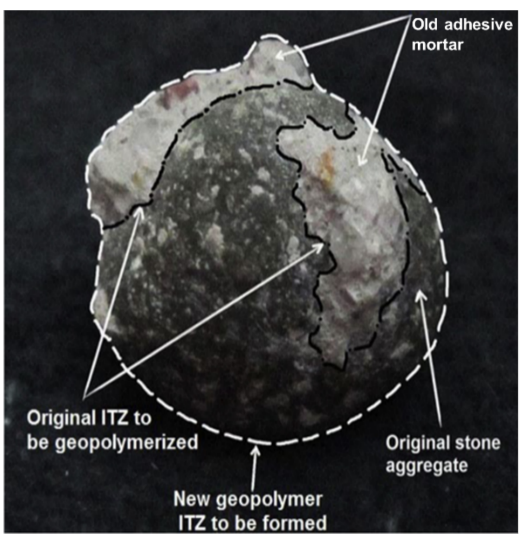


Fig. 9 – Various ITZs in GRC [62].

Because RA has one more layer of old mortar than the natural aggregate, compared with natural aggregate concrete, the ITZ of recycled concrete has more pores, looser microstructure, and lower bonding strength [30, 52, 60]. As shown in Fig. 10, Shi et al. [30] found that, with the increase in RA replacement rate, the microstructure of ITZ in GRC is similar, and more pores and reaction gels appear in ITZ. Using geopolymer instead of cement paste to prepare recycled concrete can compensate for the deterioration of ITZ performance caused by RA. Shi et al. [63] showed that the ITZ in alkali-activated slag concrete was denser than in Portland cement concrete. Luo et al. [64] also showed a denser gel-rich slurry in the ITZ of geopolymer concrete, and the bonding strength of the ITZ between geopolymer mortar and aggregate was higher than that between cement mortar and aggregate. Ren et al. [62] developed the equivalent model of ITZ in GRC and tested its bonding strength. The results showed that the bonding strength of ITZ between geopolymer mortar and RA was the highest, which was 7.14 % higher than that between geopolymer mortar and natural aggregate, 22.45 % higher than that between cement mortar and natural aggregate, and 50 % higher than that between cement mortar and RA.

The ITZ of cement-based recycled concrete often has a large number of holes and $Ca(OH)_2$ crystals. These $Ca(OH)_2$ crystals are aligned near the ITZ, resulting in the formation and development of micro-cracks along the ITZ [30, 65]. However, the hydration products in geopolymer concrete are dense hydrated sodium aluminosilicate (N-A-S-H) gel and C-S-H gel. The pores and micro-cracks in ITZ are filled with gel to a certain extent. Therefore, compared with the ITZ of cement-based recycled concrete, ITZ in GRC is denser, with fewer pores and higher bonding strength [30, 37, 42, 60, 65, 66]. Khedmati et al. [66] compared the old and new ITZ of cement-based recycled concrete and GRC, and found that the bonding properties of the ITZ

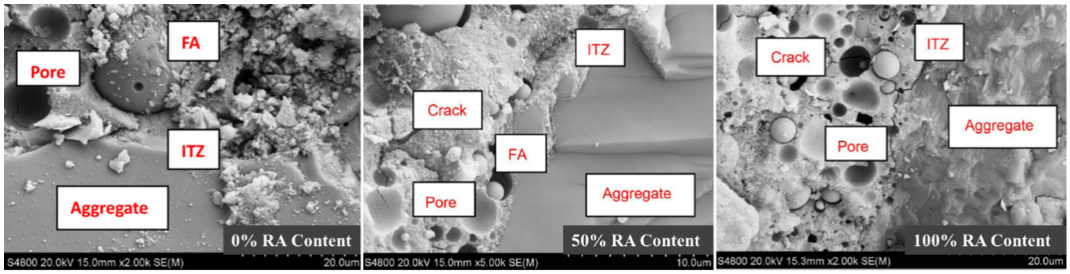


Fig. 10 – SEM photos of the microstructure of ITZ in GRC with different RA content [30].

between geopolymer mortar and old mortar, and the original old ITZ of RA in GRC were better than the corresponding parts in cement-based recycled concrete, indicating that the geopolymer pastes not only promoted the bond between new mortar and aggregate, but also strengthened the bonding performance of the old ITZ on the surface of RA. Nanayakkara et al. [60] found that the gel formed by the continuous alkali-activated reaction in GRC filled the pores and micro-cracks of ITZ well. In addition, the alkali-activated solution also affects the formation of ITZ. Koushkbaghi et al. [52] found that with the increase of Na_2SiO_3 / NaOH ratio (2 / 2.5 / 3) in alkali-activated solution, the width of ITZ in GRC decreased gradually, and the bond between geopolymer mortar and aggregate was enhanced.

In summary, the incorporation of RA in concrete will have adverse effects on ITZ, which can be summarized as: increasing the complexity of ITZ in concrete and changing from one kind of ITZ to multiple ITZ; making the microstructure loose and porous; resulting in lower bonding strength of ITZ. The geopolymer can alleviate these adverse effects and improve the bonding performance of the old and new ITZs.

2.5. Initial curing conditions

Curing conditions affect the development of concrete strength. The hydration reaction mechanism of geopolymers and cement is different, so it is necessary to explore the best curing conditions of GRC. Wang et al. [67] cured GRC specimens at different initial curing temperatures (20 to 100 °C). The test results showed that the compressive strength, elastic modulus, and toughness of GRC increased first and then decreased with the increase of curing temperature. The maximum value corresponds to the curing temperature of 80 °C, as shown in Fig. 11. The increase in strength can be attributed to the increase in temperature promoting the

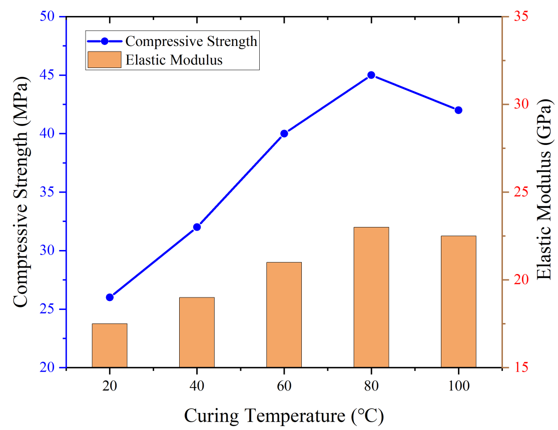


Fig. 11 – Variations of compressive strength and elastic modulus of GRC with curing [67].

activation of aluminosilicate. When slag and fly ash are activated by alkali, the activation at low temperatures mainly occurs on slag, and both slag and fly ash can be activated at higher temperatures [68, 69]. The strength decrease at high temperatures (100 °C) can be attributed to the loss of water and the deterioration of microstructure in GRC caused by excessive temperature [67]. The compressive strength of GRC increased rapidly and then tended to be stable with the increase in high-temperature curing duration. After 24 hours of high-temperature curing, the compressive strength increased slowly, and the internal reaction of concrete tended to be completed [67]. In addition, Xu et al. [40] found that compared with GRC specimens cured at room temperature, the compressive strength, tensile strength, and elastic modulus of GRC specimens cured at 75 °C for 12 h increased by 27.81 %, 15.71 % and 25.06 %, respectively. Ding et al. [70] proposed that the optimum initial curing temperature of GRC is about 60 °C. Based on the above studies, it is suggested that GRC should be cured at 60 to 80 °C for 12 to

24 h during the high-temperature curing process, and the mechanical properties of GRC cured under this condition are relatively high.

3. Conclusions and Prospects

In this paper, the mechanical properties, durability, and microstructure of geopolymeric recycled concrete (GRC) are reviewed. The main conclusions and future research prospects are as follows:

1. As the content of recycled aggregate (RA) increases, the compressive, tensile, and flexural strengths, as well as the elastic modulus and toughness of GRC, decrease gradually, with a notable decline at a 100 % replacement rate of RA. Specifically, the compressive strength decreases by 11.11 % to 36.19 %, tensile strength by 22.22 %, flexural strength by 18.75 % to 28 %, and elastic modulus by 8.7 % to 44.3 %. It is observed that in geopolymer concrete, the elastic modulus is most affected by increased RA content, followed by compressive strength, while tensile strength decreases the least.
2. A method for preliminarily estimating the 28-day compressive strength of GRC was proposed, which is suitable for the replacement of natural coarse aggregate by recycled coarse aggregate according to mass ratio. The "RA impact factor k" was defined, with recommended values for commonly used alkali-activated precursors. For single slag or fly ash precursors, the recommended k is -0.0037, and for a combination of slag and fly ash, it is -0.0023.
3. RA negatively impacts the durability of GRC. With increased RA content, concrete's water absorption rises, and its resistance to chloride ion permeability, sulfate corrosion, acid, frost, and carbonization decreases.
4. Incorporating RA in concrete adversely affects the interfacial transition zone (ITZ), making it more complex, diverse, and with weaker bonding and a looser, more porous microstructure. The geopolymer mitigates this effect and enhances the bonding of old and new ITZs.
5. Current research on GRC at the micro-level primarily focuses on microstructure and chemical composition, with limited studies on ITZ bonding properties. Given the complexity of GRC's ITZ types, further research on their bonding properties is recommended.

GRC exhibits synergistic benefits from both geopolymer and RA, offsetting RA's mechanical and interface deficiencies while reusing building solid waste. As a novel, eco-friendly concrete material, GRC, combining the advantages of geopolymer and recycled concrete, merits extensive research and application. At present, the research of GRC mainly involves recycled coarse aggregate, while there are few studies on the incorporation of recycled fine aggregate into geopolymer concrete and the use of recycled powder as alkali-activated precursor. It is necessary to further explore the performance of geopolymer concrete prepared by recycled coarse and fine aggregate and recycled powder, so as to realize the comprehensive utilization of C&D waste.

CRediT authorship contribution statement

Shaoxiong Lyu: Investigation, Formal analysis, Writing- Original Draft; **Jianzhuang Xiao:** Conceptualization, Writing- Review and Editing, Supervision; **Amardeep Singh:** Writing- Review and Editing; **Taohua Ye:** Writing- Review and Editing.

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