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Structural Performance of Geopolymer Concrete with Recycled Concrete Aggregate: A review

Bahareh Nikmehr[1], Riyadh Al-Ameri[2], Bidur Kafle[3]

[1]PhD student, School of Engineering, Deakin University, Geelong, Vic 3216, Australia
[2]Senior Lecturer, School of Engineering, Deakin University, Geelong, Vic 3216, Australia
[3]Lecturer, School of Engineering, Deakin University, Geelong, Vic 3216, Australia

Corresponding author's E-mail: b.nikmehr@research.deakin.edu.au

Abstract

Geopolymer concrete (GPC) is an emerging construction material with a promising role in the industry. Recent research confirms the suitability of GPC in structural applications due to the higher compressive strength, better fire resistance, low permeability, and alkali and acid resistance compared to ordinary Portland concrete (OPC). Moreover, geopolymer concrete allows replacing the natural aggregate with more recycled concrete aggregate (RCA) than OPC. At the same time, its mechanical properties remain acceptable for structural applications. Thus, it will help waste reduction and natural resource preservation simultaneously. However, RCA adversely impacts concrete's rheological and mechanical properties, which is crucial for an optimum concrete mix. Recently, there has been a growing knowledge development on the structural applications of Portland concrete with RCA. However, there is a need to conduct a comprehensive assessment of the potential structural applications of RCA-based GPC. Hence, in the present study, previous research on various parameters that affect the structural behaviour of RCA-based GPC will be critically assessed and reviewed. These parameters include the type and content of alumina silicate materials, alkaline activator, curing regime, and RCA content. Besides, the load capacity, failure mode, and structural behaviour of composite elements with RCA-based geopolymer concrete, such as columns, beams, thin wall panels, and steel tubular columns, have been examined. Identified knowledge gap in this study area is also provided for further research.

Keywords: Recycled concrete aggregates, structural elements, structural behaviour, geopolymer concrete.

1. INTRODUCTION

Geopolymer is an environmental-friendly substitution for ordinary Portland cement, which reduces CO_2 generation and reuses industrial by-product material. Geopolymer concrete (GPC) is obtained through the reaction between alkaline activator and aluminosilicates, found in fly ash (FA), ground granulated blast-furnace slag (GGBS) and metakaolin (MK) and is available as industrial wastes (Rahman & Al-Ameri, 2021a, 2021b).

As for reducing natural resource consumption and reusing construction and demolition waste, a proper solution is using recycled concrete aggregates for developing new concrete (Tavakoli et al., 2018). GPC provides the opportunity of using more amount of RCA. Lim and Pham (2021) replaced all the aggregates with RCA, and 46.24 MPa compressive strength was achieved, which is a proper compressive strength for structural application. There exist several studies that reviewed the application of RCA in geopolymer concrete (Nikmehr & Al-Ameri, 2022), but the review on the structural application of RCA-based geopolymer has been overlooked.

Throughout this paper, the effect of RCA on the structural behaviour of geopolymer concrete will be assessed. To this end, the compressive strength and workability of the RCA-based GPC will be reviewed, and the effect of RCA on the structural performance of elements made by RCA-based geopolymer concrete will be evaluated.

2. REVIEW OF EFFECTIVENESS OF RCA ON GPC

Although using RCA reduces overall waste and helps preserve natural resources, it may have some adverse impacts on the mechanical and rheological properties of the concrete, which should be evaluated. Furthermore, incorporating RCA in GPC on the performance of structural elements needs to be studied.

2.1. Compressive strength

RCA has a diverse effect on the compressive strength of geopolymer concrete. Compressive strength has been observed to be increased and decreased by incorporating various amounts of RCA in geopolymer concrete.

Some studies reported a drop in compressive strength by adding RCA. For example, adding 50% and 100% RCA reduces the compressive strength of FA/GGBS-based geopolymer concrete by 1.75-4.46% and 12.89-17.77%, respectively (Xie et al., 2019). On the other hand, the geopolymer concrete's compressive strength has been improved by adding RCA. For instance, adding 50% of RCA rises the compressive strength of the FA/GGBS-based geopolymer concrete from 24.27 MPa to 24.91 MPa (Liu et al., 2019). It shows that the addition of RCA affects the compressive strength of the geopolymer concrete; hence, there is a need for rigorous investigation on this topic. The reason for this contradiction is that the properties of RCA-based geopolymer concrete can be related to several parameters as follows:

- Alkali activator-related matters. For example, increasing the NaOH molarity from 8 to 12 improves compressive strength (Tho-In et al., 2017). In addition, increasing the ratio of alkali activator solution to binder materials enhances the workability and decreases the compressive strength (Le et al., 2021).

- The curing regime is another parameter that significantly affects the compressive strength of GPC. It is possible to cure GPC at ambient temperature. However, higher temperature helps accelerate the geo-polymerisation process, increasing compressive strength (Ahmed et al., 2011).

- Various treatment techniques improve the properties of RCA and the mechanical properties of concrete. Among these techniques, bio deposition, carbonation, adding nanoparticles and saturating RCA in sodium silicate or polymer emulsion reduce the porous structure of the RCA. Besides, removing old mortars can be possible by acid, mechanical methods and heating, leading to the better properties of RCA (Wang et al., 2021).

- The quality of RCA also impacts the properties of geopolymer. For example, the parent concrete with a compressive strength of higher than 50 MPa has no adverse impact on the geopolymer concrete, but incorporating RCA extracted from low to regular grade concrete decreases the compressive strength of GPC (Ohemeng et al., 2021).

- The type and amount of binding material influence the properties of the concrete. For example, increasing the amount of GGBS reduces the negative impact of using 100% RCA on the compressive strength of the geopolymer concrete (Uğurlu et al., 2021).

2.2. Workability

Adding RCA to the geopolymer concrete has a mixed effect on the slump of the geopolymer concrete. For example, using 100 % RCA reduces the slump from 117 to 106 mm in GGBS-based geopolymer concrete, as RCA has higher water absorption than natural aggregates (NA) (Parthiban & Saravana Raja Mohan, 2017). But, as illustrated in

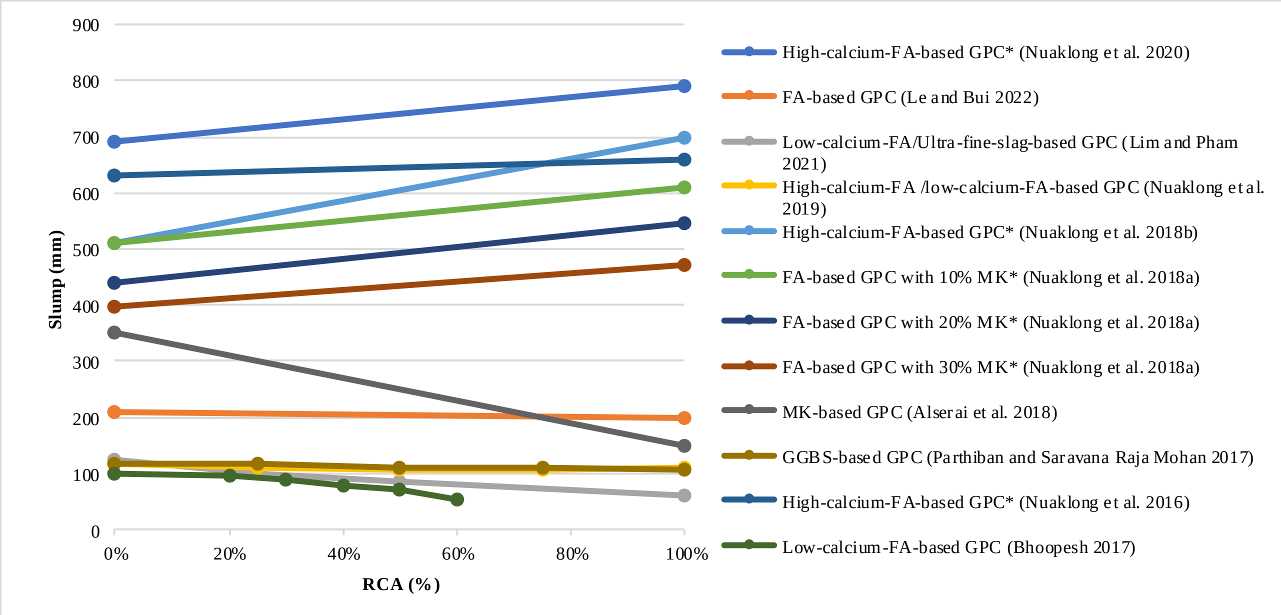

Figure 1, using RCA in saturated surface dry (SSD) form does not adversely impact the workability. For example, replacing NA with 100% RCA in SSD form in a high-calcium-FA-based GPC increases the slump by 14%, from 692 to 789. It is because further water in SSD recycled concrete aggregates increases the flowability (Nuaklong et al., 2020).

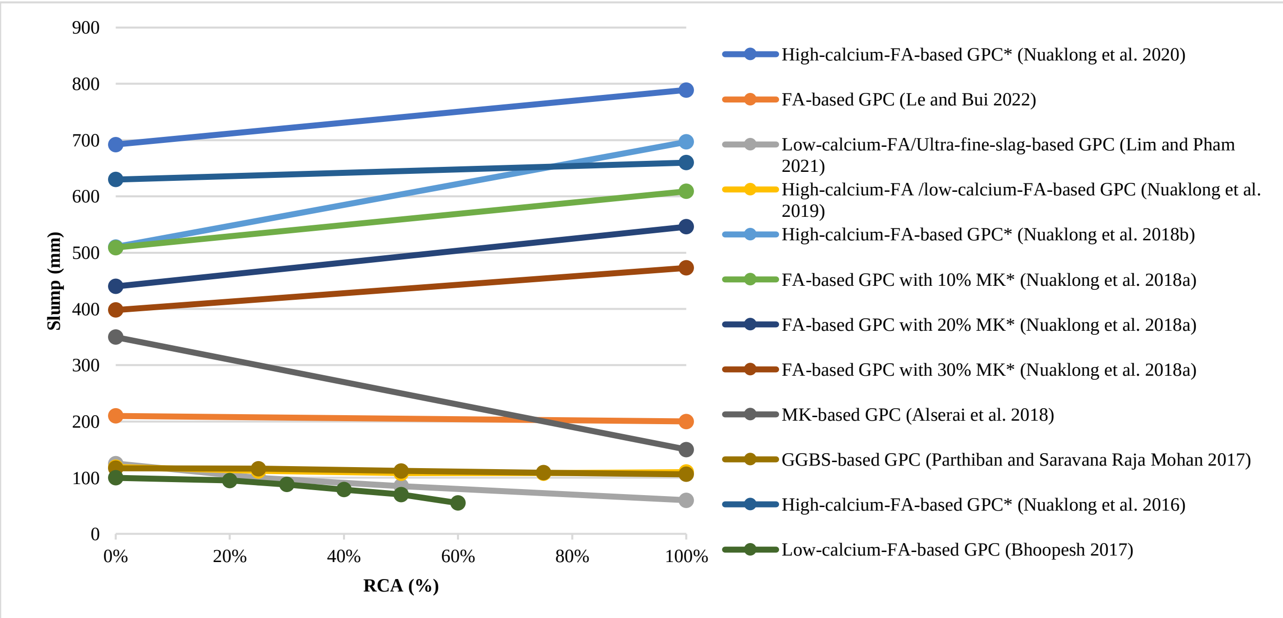

Figure 1. The link between RCA content and slump (* RCA applied in SSD form)

2.3. Structural elements

Although the research on RCA-based GPC is numerous in terms of material, minimal studies investigate the structural behaviour of RCA-based GPC, as summarised in Table 1.

Table 1. Relevant studies on the structural elements made by RCA-based geopolymer concrete

Reference	Structural element	Test	RCA content	Binder	Curing regime
(Bhoopesh, 2017)	Beam	Two-point bending	40%	FA	60 °C for 24

					hours
(Raza et al., 2021)	A column with GFRP bars	Axial loading	100% C	FA/GGBS 45:55	Ambient
(Alsaraj et al., 2019)	Wall panel	Axial eccentric uniformly distributed loading	100%	MK	Ambient
(Alalikhan et al., 2018)	Steel tubular columns	Axial loading	100% F&C	FA	Ambient
(Shi et al., 2015)	Steel tubular columns	Axial loading	0%, 50%, 100%	FA	80∘C for 24 hours
(Ayub et al., 2021)	100×200 cylinder	Pull-out test	30%	FA	70∘C for 24 hours
(Tho-In et al., 2017)	100×200 cylinder	Pull-out test	100%	Class C FA	60∘C for 48 hours

Coarse RCA (C), Glass fibre reinforced polymer (GFRP), Fine RCA (F), Fly ash (FA), Metakaolin (MK), Ground granulated blast-furnace slag (GGBS)

2.3.1 Beams

Regarding the flexural behaviour of beams made by RCA-based GPC, Bhoopesh (2017) conducted a two-point-loading test on the reinforced beams made of GPC with 40% RCA and without RCA (with NA). The study reported that increasing the load results in flexural cracks in the bending zone. Further loading results in the widening of existing cracks for both beams with NA and RCA. However, beams with RCA-based GPC demonstrated a higher number of cracks and more crack width than the beams with NA. It might be due to the drop in tensile strength of the RCA-based GPC because of the more pores and voids in RCA. The first crack load and ultimate load of RCA-based GPC beams are less than beams with NA-based GPC by 21% and 9%, respectively. The reason contributes to the porous structure of the RCA, resulting in weaker bonds among the concrete particles.

Moreover, RCA reduces energy absorption capacity and toughness index by 15.7% and 16.82%, respectively. It is also reported that RCA reduces displacement and curvature ductility by 10.4% and 9.6%, respectively. It is due to the porous structure of RCA. However, despite decreasing the compressive strength by 20% (32.8MPa), this concrete was suggested to be used as green concrete. However, to better understand the effect of RCA on the geopolymer beams, there is a need to study the impact of various percentages of RCA on the performance of GPC reinforced beams against bending moments, shear forces, and deflections (Le & Bui, 2020).

2.3.2 Columns

As for evaluating the effect of RCA on the columns, Shi et al. (2015) pointed out that increasing the amount of RCA reduces the ultimate strength of columns grouted with GPC. A study has found that the maximum strength of steel columns filled by GPC with 100% RCA was 25% less than NA-based GPC. Besides, a higher amount of RCA increases the peak strain and improves ductility. Similarly, Alalikhan et al. (2018) used RCA-based GPC grout for steel columns and compared the performance of steel columns with those filled with OPC concrete grout. The failure load of the steel column with RCA-based GPC grout was higher than OPC concrete, although the compressive strength of OPC concrete was higher than GPC. They believe that better performance of GPC is due to the stronger bonding between GPC material and the steel column. However, the effect of RCA-based GPC was not compared with NA-based GPC in this research.

Raza et al. (2021) studied the behaviour of columns with GFRP grouted with RCA-based GPC. This research aims to optimise the number of GFRP bars and their spaces. To this aim, the columns were subjected to the axial compression test to evaluate the effects of various amounts of GFRP and the spaces between them on the ductility, crack generation and ultimate load. Although they did not compare the impact of RCA incorporation with NA, this type of column was suggested as an efficient and environmentally friendly structural element.

There is not any study on the effect of incorporating RCA on the reinforced columns made of GPC. Therefore, it is suggested to conduct a compression test on both non-cylinder and cylinder columns made with GPC with various replacing levels of RCA to evaluate the structural stiffness. The requirement for this study is crucial as RCA results drop in elastic modulus, which might decrease the ultimate resistance of the columns (Le & Bui, 2020).

2.3.3 Wall panels

The structural behaviour of wall panels made of RCA-based GPC was assessed by Alsaraj et al. (2019). They analysed the effect of aspect ratio and steel reinforcement ratio on the load-carrying capacity and lateral deflection of the walls subjected to the axial eccentric uniformly distributed loading. The results revealed that increasing the steel reinforcement enhances the load-carrying ability of wall panels and decreases their lateral deflection. They also reported that reducing the aspect ratio decreases the lateral deflection and increases the load-carrying capacity of the walls. Ultimately, they pointed out that the performance of RCA is like natural aggregates in geopolymer concrete, while RCA incorporation is economical.

2.3.4 Pull-out strength

Conducting a pull-out test revealed that geopolymer concrete with RCA demonstrates weaker bond strength than its counterpart with NA (Ayub et al., 2021; Tho-In et al., 2017). For instance, replacing 30% of the aggregates with RCA reduces the bonding strength of FA-based GPC from 5.6 to 4.15 KN/mm^2 (Ayub et al., 2021).

3 CONCLUSION

Incorporating RCA in the geopolymer concrete needs some consideration, especially for the geopolymer concrete with structural application. Based on the relevant literature, GPC has the potential to use a higher amount of RCA compared to OPC. Still, it is significant to consider the downsides of using RCA in terms of mechanical and rheological properties. The reason is that structure of the recycled concrete aggregates is weaker than the natural aggregates. Therefore, it is crucial to look for methods for improving the properties of RCA and RCA-based GPC. Removing old mortars is possible by high-temperature heating, mechanical techniques, acid, and high-pressure water washing. In addition, some materials, such as sodium silicate or polymer emulsion improve RCA by filling the pores. The type of bonding material, NaOH molarity and curing regime also influence the properties of RCA-based GPC. Added to the analysis of the effect of RCA on the mechanical and rheological properties of the GPC, it is vital to consider the structural behaviour of elements made with RCA-based GPC and try to improve them, so the following tracks need further research:

- Finding better treatment techniques for improving the quality of the RCA.
- Novice techniques should be investigated to increase the rate of replacing fine and coarse aggregates with RCA for developing GPC with the structural application.
- It is required to study the effects of various levels of replacing RCA on the GPC reinforced beams in terms of energy absorption capacity, toughness index, bending moments, ductility, shear forces, and deflections.
- The effect of RCA on the reinforced columns made with GPC needs more investigation.
- A study on the creep and fatigue of RCA-based GPC by experimental and numerical methods is also suggested.

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