Development of Concrete Mixtures Based Entirely on Construction and Demolition Waste and Assessment of Parameters Influencing the Compressive Strength

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Abstract. Demolition and reconstruction of degrading structures alongside with the repetitive repair, maintenance, and renovation applications create significant amounts of construction and demolition waste (CDW), which needs proper tackling. The main emphasis of this study has therefore been placed on the development of concrete mixtures with components (*i.e.*, aggregates and binder) coming entirely from CDW. As the binding phase, powdered CDW-based masonry units, concrete and glass were used collectively as precursors to obtain geopolymer binders, which were then incorporated with CDW-based fine and coarse concrete aggregates. Together with the entirely CDW-based concretes, designs were also proposed for companion mixtures with mainstream precursors (*e.g.*, fly ash and slag) occupying some part of the CDW-based precursor combination. Sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and calcium hydroxide ($Ca[OH]_2$) were used at various concentrations and combinations as the alkaline activators. Several factors that have impact on the compressive strength results of concrete mixtures, such as mainstream precursor replacement rate, alkaline molar concentrations, aggregate-to-binder ratios and curing conditions, were considered and these were also backed by the microstructural analyses. Our results showed that through proper optimization of the design factors, it is possible to manufacture concrete mixtures entirely out of CDW with compressive strength results able to reach up to 40 MPa under ambient curing. Current research is believed to be very likely to promote more innovative and up-to-date techniques to upcycle CDW, which are mostly downcycled through basic practices of road base/sub-base filling, encouraging further research and increasing the awareness in CDW issue.

Keywords: Construction and demolition waste · Geopolymer concrete · Recycled concrete aggregate · Compressive strength

1 Introduction

Urbanization activities such as construction, maintenance, repair, renovation, and demolition are continuously increasing due to growing population. As a result of these activities, tremendous amounts of construction and demolition waste (CDW) are generated all around the world. Correspondingly, CDW occupies the largest portion of all solid waste stream [1] with 10 billion tons of annual generation worldwide [2]. The European Action Plan's designation of the construction and demolition industry, as one of the five priority sectors within the framework of the circular economy model, makes it quite clear that CDW must be recycled in the most effective way by avoiding being dumped in clean landfills [3]. Although the research on CDW management and reprocessing are fairly active in Europe, recent sources indicate that up to 95% of waste concrete, which accounts for the largest portion of CDW, is downcycled as sub-base fillers [4]. However, to achieve a better position of CDW in the value chain and help close the loop in the construction sector for the purposes of true sustainability, the most efficient recycling/upcycling scenarios need to be identified instead of downcycling/disposing activities.

The abovementioned urbanization activities also require the production of high amounts of Portland cement (PC), which is the main binding component of conventional concrete. Despite being an indispensable material for the construction industry for centuries thanks to its outstanding strength and durability characteristics, PC is a troublesome material particularly for the environment. To put it in numbers, it has been reported that 1 ton of PC production requires energy in the range of 3.2–6.3 GJ and releases approximately 1 ton of CO_2 to the atmosphere [5, 6]. Research in recent years have therefore concentrated on the development of alternative and more eco-friendly binders than PC, taking the issue of global warming and long-term sustainability into consideration. Geopolymers synthesized by activating aluminosilicate-based materials with alkali hydroxides/silicates are one of such examples that come to the fore recently [7]. Although geopolymers have been developed mostly with industrial by-products/wastes (*e.g.*, fly ash, ground blast furnace slag, silica fume) to date, the limited availability of these materials and their high demands by the PC/concrete industry made it necessary to seek alternative sources for geopolymers. CDW stands out as a suitable resource for geopolymer manufacture due to their aluminosilicate-rich nature and widespread availability. In recent years, studies on the development of geopolymers with CDW have gained momentum, and CDW-based geopolymers reaching compressive strength level of 80 MPa have been successfully developed [8, 9]. Thus, it can be stated that upcycling CDW into novel, eco-friendly and high-performance building materials that can be an alternative to PC via geopolymerization is possible and promising especially for ensuring eco-friendliness and sustainability.

Taking the issues related to CDW generation and PC manufacture, this research work concentrated on the development of green geopolymer concretes with entirely CDW-based materials and the examination of the parameters affecting the compressive strength. CDW-based components such as hollow brick (HB), red clay brick (RCB), roof tile (RT), concrete (C) and glass (G) were used in the mixed for as the binder phase of geopolymer concretes, while waste concrete was used as different-size recycled concrete aggregate (RCA). Industrial by-products such as ground granulated blast furnace

slag (GGBFS) and Class-F fly ash (FA) were also substituted partially in some mixtures to examine their interaction with CDW-based materials. Sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and calcium hydroxide ($Ca[OH]_2$) were used in various concentrations as alkali activators. Geopolymer concretes were designed to assess the effects of various parameters such as various combinations of CDW-based precursors, alkali activator concentrations, GGBFS and FA substitutions, and binder/RCA ratios. The mixtures were subjected to ambient and water curing for 7 and 28 days before being tested for compressive strength measurement. Scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) and mercury intrusion porosimetry (MIP) analyses were also performed on the selected mixtures for an in-depth microstructural characterization.

2   Experimental Program

2.1   Materials

In this study, CDW-based materials such as hollow brick (HB), red clay brick (RCB), roof tile (RT), concrete (C) and glass (G) were used collectively as the precursor phase in the geopolymer concrete production. These materials, which were of unknown origin, were collected from a demolished residential building and then subjected to a two-step crushing-grinding process separately to obtain adequate fineness for geopolymerization. Images of the CDW-based materials were presented in Fig. 1.
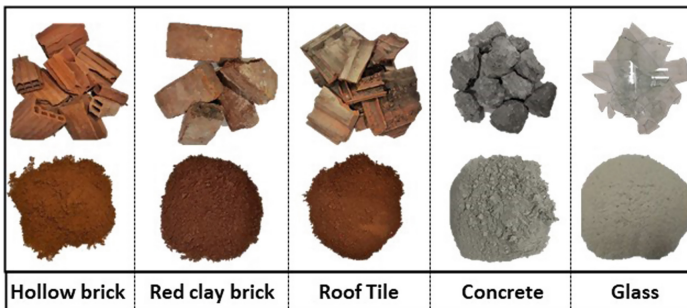

Fig. 1. Images of the CDW-based materials

The chemical compositions of the CDW-based precursors were found by X-ray fluorescence (XRF) analysis and the results were given in Table 1. According to the XRF analysis, clayey components (*i.e.,* HB, RCB, RT) had a similar chemical composition in terms of SiO_2 (39.7–42.6%), Al_2O_3 (13.8–17.3%) and CaO (7.69–11.6%) content. While C was found to have the highest CaO content with 31.3%, G was found to have the highest SiO_2 content with 66.5% and the lowest Al_2O_3 content with 0.93% among other CDW-based precursors. Particle size distribution plots of CDW-based precursors subjected to separate crushing and ball mill grinding for an hour were presented in Fig. 2. The particle size distribution of the CDW-based precursors was determined by using

dry laser granulometry method (Malvern Mastersizer Scirocco 2000 assembled with a hopper instrument). While the clayey CDW-based components exhibited the smallest particle size distribution results, G was found to be the coarsest among all CDW-based precursors.

Table 1. Chemical composition of the precursors (units are in %)

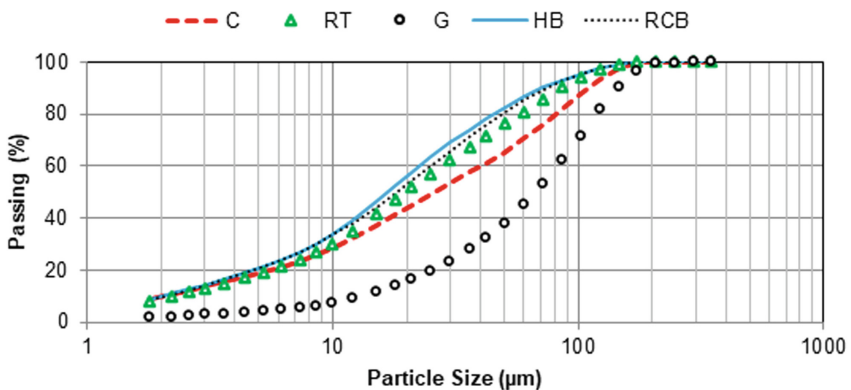| Materials	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	CaO	MgO	SO$_3$	TiO$_2$	K$_2$O	Na$_2$O	LOI[a]
HB	39.7	13.8	11.8	11.6	6.45	3.40	1.65	1.55	1.45	7.80
RCB	41.7	17.3	11.3	7.69	6.49	1.41	1.57	2.66	1.15	7.96
RT	42.6	15.0	11.6	10.7	6.26	0.71	1.82	1.60	1.60	7.49
C	31.6	4.76	3.50	31.3	5.12	0.92	0.24	0.71	0.45	20.9
G	66.5	0.93	0.25	10.0	3.93	0.24	0.06	0.20	13.6	4.15
FA	60.1	21.4	7.41	0.99	1.82	0.22	0.94	2.91	0.99	2.61
GGBFS	32.1	11.2	0.62	36.1	5.64	1.21	1.07	0.83	0.31	9.09

[a] Loss on ignition

Fig. 2. Particle size distributions of the CDW-based precursors

As the aggregate phase of the geopolymer concretes, RCA obtained by crushing the CDW-based concrete and sieving it in various sizes were used. The gradation curve of the RCA was presented in Fig. 3. Fine and coarse RCA were blended (50%, by weight each) to obtain mixed RCA.

Sodium hydroxide (NaOH), sodium silicate (Na$_2$SiO$_3$) and calcium hydroxide (Ca[OH]$_2$) were used as the alkaline activators in the production of geopolymer concretes. Class-F fly ash (FA) and ground granulated blast furnace slag (GGBFS) were also used in some mixtures to observe their effects on the mechanical performance when combined with the CDW-based precursors.
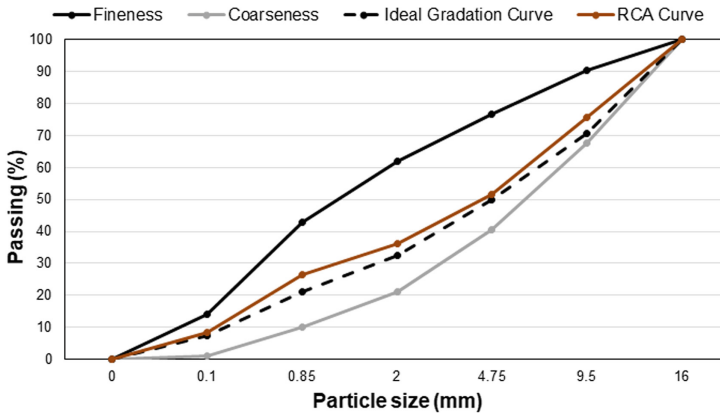
Fig. 3. Particle size distribution of the CDW-based RCA

2.2 Mixture Design

As a result of preliminary studies, 9 mixture designs were made considering the precursor combinations, alkaline solution concentrations and aggregate/binder ratios. Proportions of the mixtures were given in Table 2. In the first three mixtures (GC1, GC2 and GC3), the combination of CDW-based materials in the precursor phase were investigated. In the next three mixtures (GC4, GC5 and GC6), effect of different alkaline activator combinations was examined. In GC7 and GC8 coded mixtures, the effect of fly ash and slag addition at a rate of 20% was investigated, respectively. In the last mixture (GC9), the aggregate/binder ratio was increased to 2 and the effect of increased amount of aggregates was examined. All mixtures were produced according to the following steps: (i) NaOH solution was prepared with the mixing of NaOH pellets and water and left in a room to cool down for 1 day, (ii) Precursors and RCA were mixed for 60 s at 100 rpm and NaOH solution was slowly added to the mixture in 60 s, (iii) during mixing, Na_2SiO_3 solution was added to the mixture in 60 s and finally $Ca(OH)_2$ was added to the mixture in 60 s and mixing was kept for 180 s at 150 rpm.

2.3 Curing and Testing

For each mixture, three cubic specimens with $100 \times 100 \times 100$ mm dimensions were produced for each testing age (*i.e.,* 7- and 28-day) of compressive strength. After casting, the samples were kept in their mould with their surfaces covered for 24 h under ambient conditions set at average temperature of 23 ± 2 °C and a relative humidity of $50 \pm 5\%$, and then moved into plastic bags having controlled environment set at average temperature of 23 ± 2 °C and relative humidity of $95 \pm 5\%$ until the testing date. Additionally, three different specimens for each mixture also left to water curing until the testing age. At the end of 7 and 28 days, the specimens were subjected to compressive strength test. Compressive strength tests were performed at a loading rate of 3.0 kN/s by using a 100-ton capacity testing device. The compressive strength result was calculated by averaging the results acquired from three separate specimens tested. In addition, scanning electron

Table 2. Mixture proportions

	Materials	GC1	GC2	GC3	GC4	GC5	GC6	GC7	GC8	GC9
Precursors[a]	HB	20	23.3	26.7	26.7	26.7	26.7	21.3	21.3	21.3
	RCB	20	23.3	26.7	26.7	26.7	26.7	21.3	21.3	21.3
	RT	20	23.3	26.7	26.7	26.7	26.7	21.3	21.3	21.3
	G	20	15	10	10	10	10	8	8	8
	C	20	15	10	10	10	10	8	8	8
	FA	–	–	–	–	–	–	20	–	–
	GGBFS	–	–	–	–	–	–	–	20	20
	RCA[b]	100	100	100	100	100	100	100	100	200
Alkaline solution[b]	Water	35	35	35	35	35	35	35	35	35
	NaOH	11.2	11.2	11.2	11.2	11.2	16.8	11.2	11.2	11.2
	Na_2SiO_3	22.4	22.4	22.4	22.4	11.2	–	22.4	22.4	22.4
	$Ca(OH)_2$	–	–	–	5	5	–	5	5	5

[a] Units are in %, [b] By the total weight of the precursor (%)

microscopy (SEM), Energy-dispersive X-ray spectroscopy (EDX) and mercury intrusion porosimetry (MIP) analyses were performed on the samples obtained from the selected mixtures.

3 Results and Discussion

3.1 Compressive Strength

Compressive strength results of the CDW-based geopolymer concrete after 7 and 28 days of curing under ambient and water curing conditions were given in Fig. 4. 7- and 28-day compressive strengths of ambient-cured GC1 mixture were 9.2 and 24.7 MPa, respectively. The compressive strengths of GC2 mixture, which was produced by increasing the total ratio of clayey CDW-based precursors from 60 to 70% compared to the GC1 mixture, increased to 11.7 and 26.9 MPa after 7 and 28 days of ambient curing, respectively. For the same ambient curing ages, the compressive strengths of GC3 mixture, which included clayey precursors by 80%, were found to be 12.5 and 28.3 MPa, respectively. Considering the results of GC1, GC2 and GC3 coded mixtures, the contributions of increased amounts of clayey precursors on compressive strength may be attributed to higher aluminosilicate content and finer particle size distribution of clayey precursors. During geopolymerization, the aluminosilicate component in the precursor material is dissolved by the alkali solution and releases SiO_4 and AlO_4 tetrahedral structures to the system, and subsequently, these components are linked and re-precipitated, resulting in the formation of a 3D-cross-linked amorphous geopolymeric gel [8]. Therefore, the high aluminosilicate content and rapid dissolution rate are considered very favourable in determining the performance of final products [10]. On the other hand, the finer grain

size of the precursors provides a larger surface area to be in contact with the alkaline solution during the reaction and boosts the geopolymerization efficiency, resulting in an improvement in the mechanical performance of the final product [11].
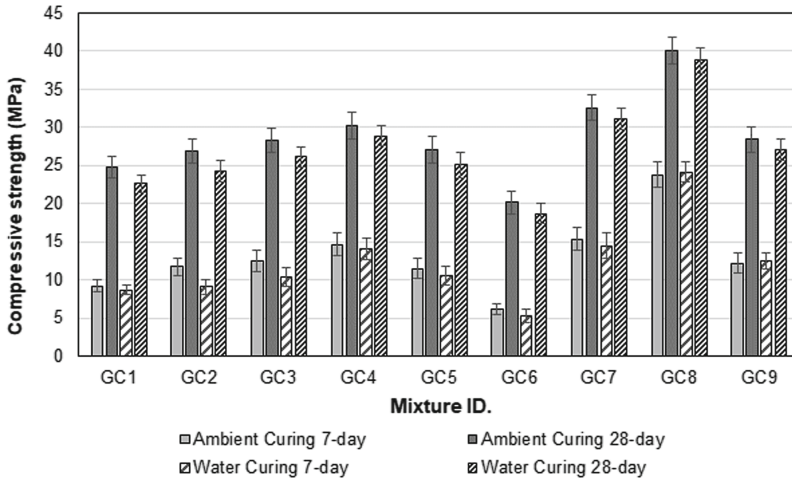

Fig. 4. Compressive strength results of the mixtures

In the next three mixtures where the effect of alkali activator combinations was investigated, the 7-day compressive strength results of the ambient-cured GC4, GC5 and GC6 were found to be 14.6, 11.5 and 6.1 MPa, while the 28-day compressive strength results were 30.2, 27.1 and 20.2 MPa, respectively. It was observed that the addition of 5% $Ca(OH)_2$ increased the compressive strength by 16.8%, which can be explained by the fact that the addition of $Ca(OH)_2$ both enhances the degree of geopolymerization by increasing the alkalinity of the system and promotes the formation of CASH gel, which can contribute to compressive strength as an extra geopolymeric gel, as a result of the release of Ca^{+2} ions to the system [12]. On the other hand, for GC5 mixture with the $NaOH:Na_2SiO_3$ ratio of 1, a decrease in the compressive strength by 21.2% after 7 days and by 10.3% after 28 days were observed compared to GC4 mixture with the $NaOH:Na_2SiO_3$ ratio of 2. The drop in compressive strength with the reduced Na_2SiO_3 ratio can be attributed decrease in the amount of soluble silicates released to the system, decreasing the degree of geopolymerization and therefore the compressive strength of the final product [13]. This was noticeable especially in the case of GC6 mixture, where the compressive strength decreased dramatically. GC6 mixture, in which only NaOH was used as the alkali activator and the NaOH ratio was increased to 16.8% to ensure sufficient alkalinity, showed the lowest strength achievement among all mixtures. NaOH is insufficient on its own for CDW-based materials to participate in geopolymerization at full capacity under ambient curing, especially when these materials are not calcined since NaOH is unable to supply Si and Ca ions to the system for effective geopolymerization, unlike Na_2SiO_3 and $Ca(OH)_2$.

In GC7 and GC8 mixtures where the partial substitution (20%, by weight) of FA and GGBFS was made with the CDW-based precursors, GC7 mixture ambient-cured

for 7 and 28 days reached 15.3 and 32.6 MPa of compressive strength, while the same results for GC8 mixture were 23.8 and 40.1 MPa, respectively. It was observed that the GC7 and GC8 mixtures achieved 7.9% and 32.8% higher 28-day compressive strength results than 100% CDW-based mixture (GC4), respectively. Such a high increase in compressive strength with the addition of GGBFS can be due to that GGBFS acts as an extra calcium source and forms CSH/CASH gel structures that contribute to the final strength by releasing Ca^{2+}, Si^{4+} and Al^{3+} ions into the matrix [14].

In the case of GC9 where the RCA/precursor ratio was increased from 100% to 200%, a drop in compressive strength by 29.2% was observed after 28 days of ambient curing compared to its counterpart mixture (GC8). In general, this decrease can be attributed to the lower strength of RCA compared to clean aggregates as well as the deterioration of the workability of the mixture when utilized at high rates due to its high water absorption capacity, which eventually lowers the compressive strength.

Another noteworthy point to mention was that drops in compressive strength in the range of 3.24–16.8% were observed in all mixtures cured in water except 20% GGBFS-substituted GC8 and GC9 mixtures. This behaviour of GC8 and GC9 mixtures contrary to the overall trend can be explained by the fact that GGBFS hydrates at an early age by showing partial cementitious properties thanks to water curing. On the other hand, the observed compressive strength drops in the rest of mixtures can be attributed to the decrease in geopolymerization efficiency as a result of a decrease in alkalinity in the medium due to water penetration into the samples through the capillary pores.

3.2 SEM/EDX Analysis

SEM/EDX analysis of the selected GC8 mixture, which exhibited the highest compressive strength result in the study, was presented in Fig. 5. The SEM images revealed that various types of NASH and CASH type gels were homogeneously and compactly dispersed in the matrix, the defects such as voids and microcracks were also observed in some regions. In the regional EDX analysis, the presence of Ca and Si elements in similar percentages confirms the formation of hybrid geopolymeric gel products [15]. Furthermore, the image acquired from the interfacial transition zone (ITZ) showed a relatively compact and dense microstructure along with small amounts of voids/cracks between the geopolymer paste and RCA. Although heterogeneity was seen throughout the aggregate, ITZ region seemed to have a strong interlocking with the matrix. In addition, the EDX analysis conducted on the marked point in the ITZ region showed that while Si and Al elements were dominant, Ca was quite low compared to the general EDX result of the matrix. This can be due to the accumulation of NASH type gel at the point analysed.
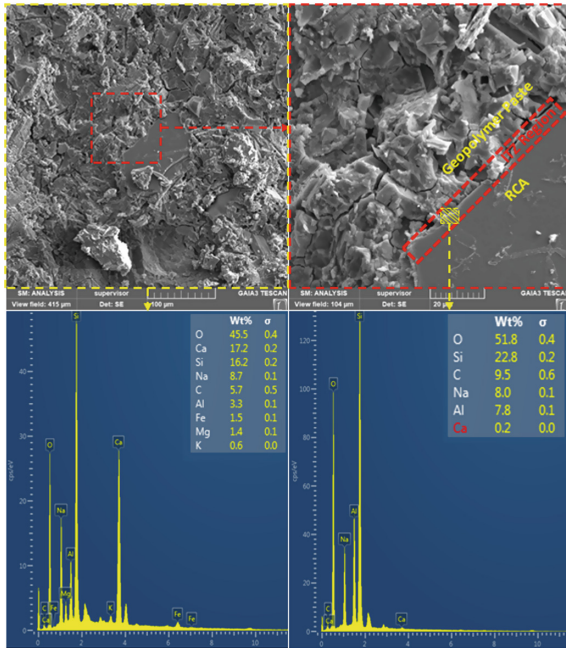
Fig. 5. SEM/EDX analysis of the selected GC8 mixture

3.3 MIP Analysis

MIP analysis results of the selected GC4, GC6 and GC8 mixtures were presented in Fig. 6. Among these three mixtures, the GC4 mixture had the largest cumulative volume intrusion value, which indicates the total porosity of the mixtures, whereas the GC8 mixture had the lowest. The total porosity results were found to be quite parallel with the compressive strength results of the mixtures. This observed correlation between compressive strength and total porosity values has also been documented in the literature [16]. Strength characteristics of the specimens are largely dependent on the pores greater than 50 nm, whereas pores smaller than 50 nm generally affect the creep and shrinkage properties [17]. As shown by the compressive strength results, having less pores greater than 50 nm may be regarded as one of the influencing criteria for achieving a more compact and denser microstructure. Likewise, Fig. 6 clearly shows that GC8 mixture, which exhibited the highest compressive strength results, showed the lowest total porosity and less number of pores with diameters larger than 50 nm among other mixtures.
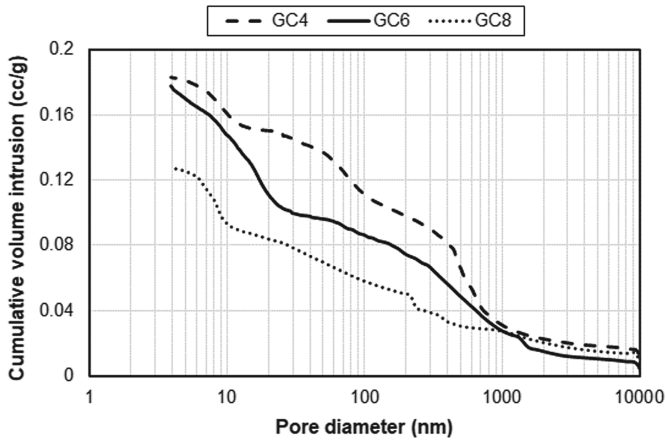
Fig. 6. MIP test results of the selected geopolymer concrete mixtures

4   Conclusions

Development of entirely CDW-based geopolymer concretes and assessment of various parameters (*i.e.*, precursor combinations, alkaline solution concentrations, FA and GGBFS substitution, and binder/RCA ratio) influencing the compressive strength were aimed in this study. Based on the experimental findings, the obtained results can be summarized as follows:

- Clayey CDW-based precursors (*i.e.,* HB, RCB and RT) exhibited better geopolymerization performance than C and glass G due to their higher aluminosilicate content and finer particle size.
- Concurrent presence of Na_2SiO_3, which provides soluble silicates into the matrix and $Ca(OH_2)$, which triggers the formation of extra CASH gels by releasing Ca^{+2} ions into the matrix, with NaOH seems more effective for geopolymerization than the single presence of NaOH in the mixtures.
- Addition of FA and GGBFS was beneficial in terms of compressive strength thanks to yielding formation of extra CASH gel structures.
- Due to its low quality and high water absorption capacity, the increase in the RCA ratio had a negative effect on the compressive strength.
- The decrease in alkalinity in the matrix due to water penetration during water curing had a negative effect on the compressive strength in general.
- SEM/EDX analysis of the geopolymer matrix revealed the simultaneous presence of NASH and CASH gel structures and very compact and dense microstructure. MIP analysis shown clear correlation between compressive strength and total porosity.
- Considering all the parameters affecting the compressive strength, green geopolymer concretes based on CDW-based materials and 20% GGBFS substitution reached 40.1 MPa of compressive strength after 28 days of ambient curing. This result clearly demonstrated that, as being more eco-friendly, CDW-based geopolymer concretes can be utilized for structural purposes given the promising compressive strength results.

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