Alkali-activated materials made of construction demolition waste as precursors: A review

Abstract

In recent years, researchers have expressed growing concern regarding the environmental impact of traditional binders such as lime and cement. This has led to an increased focus on finding alternative materials that not only meet the demands of modern construction but also align with international initiatives for eco-friendly building practices. In response to this need, alkali-activated materials have emerged as a promising substitute for conventional binders. However, the current production processes for alkali-activated materials involve substantial energy consumption and carbon emissions, presenting a global challenge in the quest for sustainable construction practices. This paper aims to present a novel proposition: utilizing construction and demolition waste as a potential precursor for manufacturing alkali-activated materials. Drawing upon a comprehensive survey and analysis of pertinent literature from diverse sources, this paper synthesizes a wealth of knowledge. The extensive review encompasses a thorough analysis of existing research findings, allowing for a nuanced exploration of the utilization of construction and demolition waste as a viable precursor in the manufacturing process of alkali-activated materials. Construction and demolition waste typically contains significant amounts of silica and alumina, making it an attractive and sustainable alternative for alkali-activated materials production. Moreover, this approach offers the additional benefit of mitigating the environmental repercussions associated with waste disposal. By providing an extensive overview of existing literature on the use of construction and demolition waste as a precursor for alkali-activated materials production, this paper also identifies crucial areas that warrant further research in this field.

Keywords: Waste solids recycling, Construction and demolition wastes, Precursor, Waste management, Environmental impact

Nomenclature

GHG	Greenhouse gas
CDW	Construction and demolition wastes
AAM	Alkali-activated material
WCP	Waste concrete powder
WGP	Waste glass powder
WCrP	Waste ceramic powder
WBP	Waste brick powder
RCA	Recycled concrete aggregates
GWP	Global warming potential
LCA	Life Cycle Assessment

1 Introduction

The construction industry is a significant contributor to global greenhouse gas (GHG) emissions, making it a key sector of concern. Estimates indicate that the cement industry alone is responsible for approximately 5% (Benhelal et al., 2021) to 8% (Kajaste and Hurme, 2016) of global CO_2 emissions. These anthropogenic emissions contribute to the accumulation of GHGs in the atmosphere, ultimately leading to climate warming. Additionally, a substantial proportion of waste generated during construction and demolition activities can be attributed to the construction industry (Gomes et al., 2021). Construction and Demolition Waste (CDW) typically encompasses various materials such as concrete rubble, plastic, glass, wood, metal, and other types of building waste. Concrete waste accounts for the major portion of CDW (Xiao et al., 2018). Many developing countries have made significant progress in recycling CDW, particularly through the recycling of concrete aggregates (Ruiz et al., 2020). To effectively address the increasing volume of CDW resulting from the expansion of urban infrastructure, it is crucial to incorporate all components of CDW into the recycling cycle. This approach not only reduces the amount of waste ending up in landfills but also helps conserve natural resources. By embracing comprehensive recycling practices, the construction industry can play a pivotal role in minimizing its environmental impact and promoting sustainability.

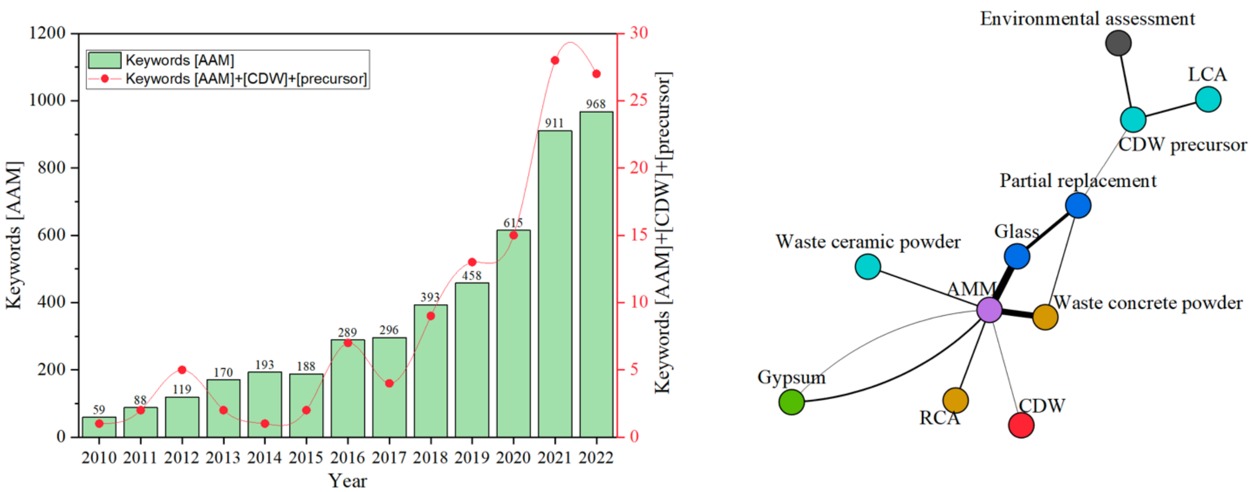
In recent years, there has been a significant increase in interest in geopolymers and Alkali-activated materials (AAMs) as the latest generation of binders. AAMs are cementitious materials that form when an intense alkaline solution activates a vitreous or amorphous aluminosilicate (Moghadam et al., 2019), resulting in a substance with high binding quality (Pacheco-Torgal et al., 2014). In general, materials with a high concentration of silicon dioxide and aluminium oxide are suitable precursors for the preparation of AAM binders. Researchers use various wastes for the production of AAMs, including fly ash (Sun et al., 2022), blast furnace slag (Khater and Abd el Gawaad, 2016) and basic oxygen furnace slag (Lu et al., 2018), natural minerals such as volcanic ash and albite (Pelosi et al., 2023), and industrial waste (Fernandez-Jimenez et al., 2017). Furthermore, the utilization of CDW is gaining momentum, particularly in large cities, due to programs for the renovation of old construction infrastructure. The selective demolition approach using the "top-down" method systematically extracts objects suitable for secondary processing and reuse (Poon et al., 2001). This method not only helps to reduce waste but also promotes a circular economy by enabling the recovery of valuable resources. Thus, dismantling concrete structures leads to the formation of high-quality concrete rubble without including other CDW, which is transported to aggregates processing plants for further processing. At the same time, waste concrete powder (WCP) is generated alongside the concrete rubble, which accounts for approximately 30% of the concrete used, depending on the production method (Ma and Wang, 2013). In addition, this method allows for the separation of generated waste ceramic and waste brick material for further processing. CDW separation, which has already been implemented in the construction and dismantling of engineering structures, enables more efficient use of waste in AAMs since each type of CDW has its own physicochemical properties.

Research on alternative precursors for producing AAM in order to reduce GHG is gaining in popularity. The process of grinding is crucial in transforming CDW into a precursor, as it reduces the size of CDW particles, making them more soluble and reactive. According to Huo et al (2021) to achieve optimal reactivity in an alkaline environment, it is recommended that the CDW precursors have a size smaller than 125 μm. Hwang et al (2019) proposed that CDW powders should have a particle size finer than 75 μm. In addition to particle size reduction, milling can activate the particles mechanically, leading to increased surface reactivity. The use of waste concrete powder (WCP), waste ceramic powder (WCrP), waste brick powder (WBP), recycled concrete aggregates (RCA), as well as waste glass powder (WGP) as precursors to AAM, promotes the development of sustainable construction and the full integration of CDW into a circular economy. Despite increasing interest in using CDW as a precursor, there is still a lack of systematic and comprehensive studies into the practical application. By examining various case studies and analyzing existing research, this review aims to not only uncover the promising prospects of CDW-based AAMs but also to identify challenges and barriers that might hinder their widespread adoption. By addressing these knowledge gaps, this review aims to pave the way for the practical utilization of CDW-based AAMs in diverse industries, thus contributing to sustainable construction practices and waste reduction.

2. Literature search strategy

The use of CDW has gained considerable attention in recent years due to its potential to reduce waste and improve sustainability in the construction industry. To provide a comprehensive summary of the current state of knowledge on the use of CDW as a precursor in

AAM production, a systematic review was carried out. This is a thorough and reliable method used to identify literature relevant to the research question. According to open data from the Web of Science, between 2010 and 2022, there were 116 articles published on the topic of using CDW as a precursor for AAMs (Fig.1a). There is a growing trend in scientific literature, with a noticeable steady increase in publications on the topic of AAM. In 2022, the number of publications on this topic reached 968 sources. However, in the same year, the number of publications on the use of CDW as a precursor in AAM amounted to 27 sources. To further categorize and analyze the selected literature sources, they were grouped based on the type of precursor, the use of CDW as a part of the precursor, as well as the assessment of environmental and economic profitability. The network analysis in Fig.1(b) illustrates the relationships between the different selected literature sources. By examining the network, patterns related to the number of publications (thickness of the line), the clustering of similar topics, and the identification of influential literature sources can be observed. It is evident that a greater number of publications on the topic of AAM are related to glass waste and waste concrete, with few publications dedicated to life cycle assessment and environmental assessment of using CDW as a precursor for AAM. Additionally, a small number of publications use a mixture of various CDW as a precursor, apparently opting for specific materials rather than their combination. This review aims to provide a detailed overview of the recent advances and challenges associated with the use of CDW as a precursor in AAM production, based on the literature findings.



(a) Number of publications related to CDW as precursor for AAMs: from 2010 to 2022

(b) Network of using CDW as a precursor for AMM in selected literature

Figure 1. Publication trends and network analysis

3. CDW generation and management practice

CDW is a significant waste stream that varies in quantity per inhabitant from country to country. This variation is due to differences in the economic and cultural characteristics of each country, as well as differences in the definitions used to characterize CDW and the methods used to record data. CDW can be divided into four main sources depending on the stage of the life cycle of the engineering structure, namely: excavation soil, construction work, repair work, and demolition work. The distribution scheme is presented in Figure 2. Infrastructure development requires the fundamental steps of soil excavation. These steps involve manipulating inclined terrain to create flat land, removing soil to establish foundations for buildings and structures, filling lowlands to provide vertical distance from water sources, and building embankments to prevent floods (Katsumi, 2015). In urban areas, where finding new land is challenging, underground space is often utilized, making excavation a crucial component of infrastructure construction. Consequently, large quantities of surplus excavated soil are generated. Luangcharoenrat et al (2019) provided statistical information on the percentage of waste from construction compared with the total CDW for certain countries. For example, in England, the proportion of CDW is 32% of the total amount of waste, while in Hong Kong and the Netherlands it is 28%, and in Australia and the United States it is up to 30%. During repair works, a large amount of waste is also generated, mainly associated with replacing worn parts, and finishing work. During the dismantling of engineering structures, the largest amount of old concrete, bricks, and old cement paste is formed, as well as metal, plastic, and glass waste. A closed-loop recycling system has been widely accepted in Germany to recycle up to approximately 91% of the CDW (Tam et al., 2018). By adopting a three-stage crushing process that includes mechanical scrubbing, heated scrubbing, and chemical and physical treatment, Japan has been able to achieve an impressive 98% recycling rate for CDW (Huang et al., 2018). In the USA, a series of successive crushing and screening methods have been adopted to maximize the utilization of CDW in construction. In China, CDW is usually randomly dumped or disposed in landfills and the rate of recycling is only about 5% (Huang et al., 2018).

There are two classifications for ceramic waste, depending on their source of raw materials. The first category consists of fired ceramic waste produced by structural ceramic factories that exclusively use red pastes for manufacturing products like bricks, blocks, and roof tiles (Ray et al., 2021). The second category comprises fired ceramic waste that originates from stoneware ceramics, including floor and wall tiles, as well as sanitary wares. In 2021, world tile production reached 18.3 million m^2, with Asia producing over 74% of the world's ceramic building materials (ACIMAC/MECS, 2021). According to some estimates, the production of ceramic tiles results in the formation of WCrP during the final polishing process, at a rate of 19 kg/m^2 of the finished product (Cheng et al., 2016). In addition, a significant amount of WCrP is generated during the construction, operation, and demolition of engineering structures due to the fragile nature of ceramic tiles. This creates a large amount of WCrP, which necessitates the need to find ways to recycle it. WCrP is often used in the production of concrete, but the recycling rate is very low. When ceramic waste is disposed of in landfills, it has the potential to harm the quality of the groundwater and soil fertility, particularly due to the presence of toxic metals such as cadmium, copper, and barium. These metals are often introduced into ceramic material during glazing and staining processes (Silva et al., 2016).

High-quality RCA is usually used as an alternative filling material for road subgrades (Zhang et al., 2020a; Poon and Chan, 2006), as a cover layer for landfill (Ng et al., 2022), and as a replacement for natural aggregates in concrete mixes. Attached mortar (cement paste) is the main reason for the lower quality of RCA compared to natural aggregates (Thomas et al., 2020). Recycled aggregate concrete usually has lower strength and durability because it is not resistant to static and dynamic loads (Thomas et al., 2013). Several aggregate cleaning methods such as heating and rubbing (Bhasya & Bharatkumar, 2018) and mechanical grinding (Yanagibashi et al. 2004) have been developed to improve the quality of RCA by removing the adhering cement paste. At these stages of processing, WCP is formed, which mainly consists of old cement paste and crushed aggregates separated from the surface of the aggregate. The inclusion of WCP in the CDW recycling cycle has been gaining momentum in the last decade. Instead of being buried in landfills, this material is being studied for potential use in compact form that can be used in non-structural constructions, such as pavement blocks (Kaliyavaradhan et al., 2020). Currently, the use of WCP as compacts or partial replacement for cement in concrete mixes (Xiao et al., 2018) is not widely practiced and is limited to only a few pilot projects. Recycling of WCP is limited in many countries and most WCPs end up in landfills due to their inferior properties (Kaliyavaradhan et al., 2020; Kim and Choi, 2012). WCPs are harmful to the environment, and their disposal leads to the contamination of soil and groundwater.

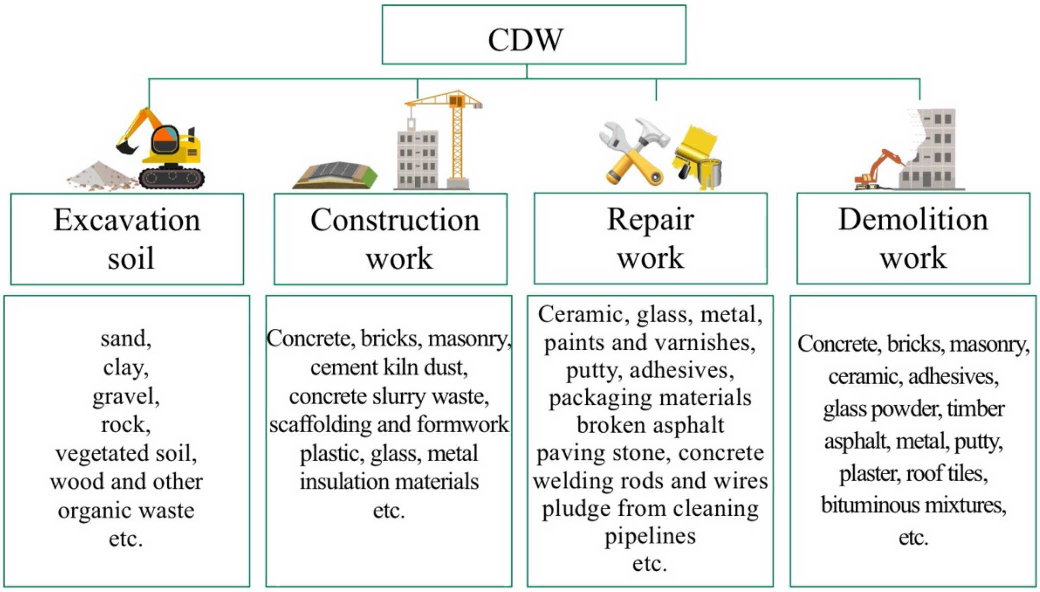


Figure 2. CDW grouping (adapted from Reis et al., 2021)

4 Characteristics of CDW

4.1 Physical properties

Important in the application of CDW as a precursor of alkali-activated materials is the particle size resulting from their mechanical grinding. The median particle sizes (d50) of CDW fine powders are typically less than 60 µm (Table 1). Small particles tend to react positively in an alkaline environment, providing acceptable AAMs mechanical properties without pretreatment (Bassani et al., 2019b). The specific gravity of the CDW depends on its granulometric, chemical and phase compositions, and ranges from 2.38 to 2.90. For clay-originated CDW (WCrP and WBP), the specific gravity averages 2.43–2.63, while for cement-originated CDW (WCP and RCA) it is 2.56–2.71. The specific gravity of the WGP and CDW powder range from 2.43 to 2.63 and from 2.46 to 2.69, respectively. Water absorption is also significantly dependent on the nature of the CDW. Higher water absorption values are observed in RCA and WCP fines and reach around 16% (Table 1), whereas glass and ceramic powder waste are characterized by the lowest values of water absorption (0.7–4.0). These differences are due to more porous and less dense particles of cement-originated CDW than the WGP, WBP and WCrP particles. The high levels of water absorption of CDW-based precursors decrease the water-to-binder ratio (W/B) and workability of fresh AAM mixtures (Wong et al., 2020). CDW are characterized by raised pH, higher values (9–12) of which are observed in cement-originated CDW due to the calcium carbonate content.

Table 1 Summary of the physical properties of CDW as reported in literature (Mahmoodi et al. (2021a); Fernandez-Jimenez et al. (2017); Komnitsas (2016); Tan et al. (2022b); Ilcan et al. (2023); Ozcelikci et al. (2023); Giannopoulou et al. (2023); Henao et al. (2023); Villaquirán-

Caicedo et al. (2021); Liang (2022b); Ren et al. (2020); Hwang et al. (2019b); Xuan et al. (2019); Mohammadinia et al. (2015); Arulrajah et al. (2013a,b); Arulrajah et al. (2012); Jiménez et al. (2012); Agrela et al. (2012); Vieira (2020); Disfani et al. (2011); Arisha et al. (2018); Binici (2007); Samadi et al. (2020); Gencel et al. (2022)).

Characteristic	Type of CDW					
	WGP	WCrP	WBP	WCP	RCA	CDW mix powder
Specific gravity	2.43–2.63	2.38–2.89	2.58–2.90	2.58–2.71	2.56 –2.70	2.46–2.69
Median particle sizes (μm) used to manufacture AAMs	9.2–58.7	10.3–48.3	7.0–35.3	2.3–11.6	10.0–48.0	10.8–20.0
Water absorption, %	1.0–1.8	0.7–4.0	6.9–10.6	10.0–15.8	9.7–13.6	8.8–10.2
pH	9.6–10.1	N.R.	8.8–10.9	9.9–11.5	9.1–11.8	7.7–8.2

Notes: N.R. = Not reported.

4.2 Chemical composition

Table 2 shows the chemical composition of various CDW used for alkali-activated materials as a precursor. In the process of geopolymerization, the molar ratio or atomic ratio of oxides (SiO_2, CaO, Na_2O and Al_2O_3) can be utilized as a controlling parameter to determine the composition of the precursor and activator. Typically, a higher concentration of Si plays a significant role in generating substantial quantities of alkaline aluminosilicate gels, while the amount of Al in the precursor governs the formation of the network and chemical structure (Alhawat et al., 2022). The interdependence of the Si and Al roles in AAMs synthesis leads to the utilization of the Si/Al ratio as a measure of the relationship between activators and CDW precursors. The desired Si/Al ratio represents the molar quantities of SiO_2 and Al_2O_3 in the system, which can vary significantly depending on the reactive characteristics and compositions of the activators and CDW precursors. Vasquez et al (2016) stated that the optimal Si/Al ratio for all AAM systems based on CDW is 10. All components and the CDW blend have a high content of silica, calcium oxide and alumina. WGP contains a higher content of sodium oxide and titanium oxide. Separated CDW powders contain over 60% silica and alumina, whereas the CDW mixture according to Abudurehman et al. (2021) contains about 40%. WBP contains a greater amount of iron trioxide compared to other powders, which is primarily derived from the presence of hematite during the manufacturing of sintered clay brick waste. Due to the presence of a significant amorphous phase and a vitreous phase in WBP, its particle size is enhanced, resulting in improved pozzolanic activity (Tang et al., 2020). WGP contains a high amount of Na_2O which should be taken into account when developing a mix design.

Typical aluminosilicate precursors for the production of geopolymers include fly ash, blast furnace slag, incinerator bottom ash, ladle slag, metallurgical slag, ceramic waste, high magnesium nickel slag, mine tailings, construction and demolition wastes, kaolin, and metakaolin, the choice of which depends largely on their availability (Liew et al., 2012; Walmiki Samadhia and Muan, 2015). The ternary diagram of CDW precursor materials is shown in Fig. 3. It can be seen from the CaO-SiO_2-Al_2O_3 ratio that RCA, WBP, WCrPm and WGP contain a high level of silica, while the mixture of CDW contains more CaO. The SiO_2 ratio is a critical parameter in AAMs because it directly influences the chemical reactivity and the resulting properties of the material. SiO_2 is typically the main source of the reactive oxide in AAMs and its ratio has a significant effect on the degree of geopolymerization that occurs during the activation process. Thus, it can be concluded that the use of separated CDWs is preferable to their mixture in terms of the ability to control the activity of reactions.

WGP has the potential to serve as a viable precursor material in the production of AAMs. WGP poses a significant environmental and economic challenge due to its widespread use in various industries, making recycling difficult due to logistical issues that render its reuse expensive and impractical. Consequently, finding effective ways to minimize waste in landfills is crucial. A possible solution to this challenge is the use of AAMs production to repurpose WGP as a source of silica in the system, as suggested by Mendes et al. (2021).

Table 2 Chemical composition of various CDW used for alkali-activated materials as a precursor.

Type of CDW	Chemical component (wt%)														References
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	P_2O_5	SO_3	TiO_2	MnO	ZnO	LOI[a]	Others	
WGP	72.27	1.49	0.62	0.26	11.15	0.51	13.37	–	–	0.08	–	–	–	–	Robayo-Salazar et al. (2017)
	58.37	3.94	0.15	0.49	6.13	4.66	8.75	–	–	2.73	–	2.57	1.85	10.35	Fernandez-Jimenez et al. (2017)
	66.5	0.9	0.3	3.9	10.0	0.2	13.6	–	0.2	0.1	–	–	4.3	–	Ilcan et al. (2023)
	72.5	0.93	0.25	0.43	10.5	0.20	12.6	–	0.24	–	–	–	2.15	–	Ozcelikci et al. (2023)
	73.4	1.27	0.18	0.18	10.9	0.08	12.8	–	0.10	0.07	–	–	0.29	0.03	Ulugöl et al. (2021)
	70.54	9.80	5.39	4.46	8.78	1.37	–	–		0.77	0.06	–	0.23	–	Komnitsas (2016)
WCrP	42.6	15.0	11.6	6.3	10.7	1.6	1.6	0.3	0.7	1.8		–	7.5	0.3	Ilcan et al. (2023)
	49.3	20.0	8.16	3.29	5.16	3.67	1.23	–	0.79	–	–	–	6.64	–	Ozcelikci et al. (2023)
	62.40	14.68	8.58	3.68	1.48	3.76	0.98	–	–	–	–	–	–	–	Giannopoulou et al. (2023)
	70.6	19.3	–	0.8	2.0	2.4	–	–	–	–	–	–	0.6	–	Henao et al. (2023)
WBP	65.92	20.08	9.10	0.86	0.73	0.97	0.44	–	–	1.09		–	–	–	Robayo-Salazar et al. (2017)
	60.31	15.61	7.72	3.05	5.60	4.48	0.56	–	–	0.88	0.11	–	0.41	–	Mahmoodi et al. (2021a)
	69.87	20.98	3.61	0.39	0.40	2.42	0.59	–	0.33	0.77	0.36	–	0.98	0.28	Likes et al. (2022)
	57.79	14.95	6.00	4.75	8.79	2.80	1.03	0.23		0.85	0.05	–	1.89	–	Komnitsas (2016)
	41.7	17.3	11.3	6.5	7.7	2.7	1.2	0.3	1.4	1.6	–	–	8.0	0.3	Ilcan et al. (2023)
WCP	56.21	10.68	10.39	3.35	15.37	0.36	2.08	–	–	0.24	–	–	–	–	Robayo-Salazar et al. (2017)
	51.00	10.13	5.36	1.38	26.31	1.78	1.23	–	1.94	0.68	0.10	–	9.9	0.09	Likes et al. (2022)
	23.81	4.16	1.96	8.41	30.33	0.67	0.60	–		0.20	0.08	–	29.60	–	Mahmoodi et al. (2021a)
	46.58	9.50	10.02	4.95	17.92	5.55	1.33	–	0.46	–	–	–	–	–	Sasui et al. (2023)
	13.9	4.8	1.2	4.7	40.4	0.6	0.4	–	–	0.2	–	–	33.1	–	Liang (2022b)
RCA	65.37	5.33	2.16	1.91	13.93	0.61	1.19	0.11	–	0.22	0.05	–	9.12	–	Limbachiya et al. (2007)
	31.6	4.8	3.5	5.1	31.3	0.7	0.5	0.1	0.9	0.2	–	–	21.1	0.2	Ilcan et al. (2023)
	37.4	10.7	3.82	1.29	21.2	2.22	1.96	–	0.54	–	–	–	19.7	–	Ozcelikci et al. (2023)
	64.81	7.77	1.59	1.54	19.14	2.94	1.76	–	–	0.45	–	–	–	–	Ren et al. (2020)
	68.41	2.44	1.10	2.01	15.01	–	0.45	–	1.06	–	–	–	6.88	–	Abdel-Gawwad et al. (2018)
	32.89	6.42	–	1.60	54.43	1.29	0.58	–	–	–	–	–	–	2.79	Abudurehman et al. (2021)
CDW mix powder	60.84	14.70	5.46	1.78	8.34	1.52	1.02	–	–	0.61	–	–	4.63	–	Villaquirán-Caicedo et al. (2021)
	46.10	13.20	8.52	7.62	16.40	2.33	–	0.23	4.02	0.84	0.22	0.07	–	0.41	Bassani et al. (2019a)
	57.7	9.1	4.2	1.7	22.3	2.0	0.6	0.2	1.5	0.6	–	–	–	–	Tan et al. (2022a)
	53.0	7.2	3.6	1.5	29.3	1.6	0.6	–	2.2	–	–	–	–	–	Tan et al. (2022b)

Notes: LOI = Loss on ignition.

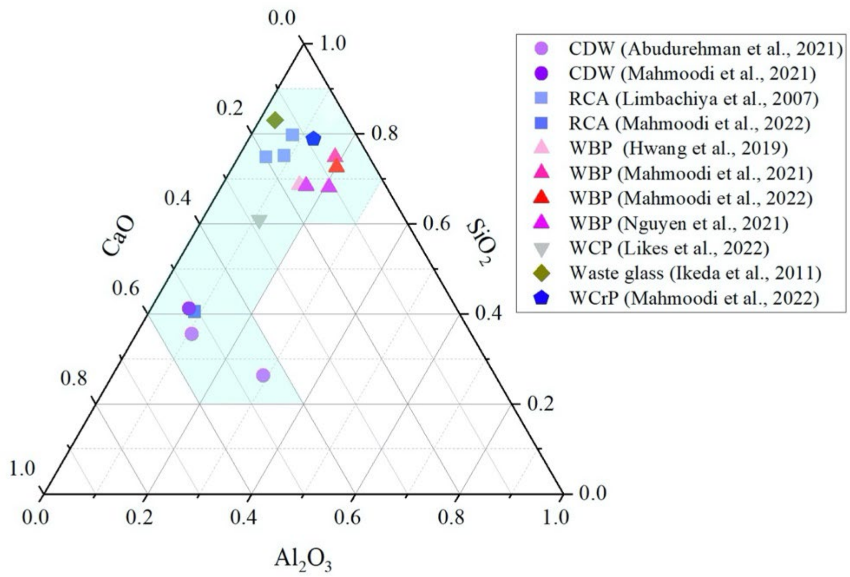


Figure 3 Ternary diagram of CDW precursor materials

4.3 Phase composition

Table 3 presents data on the phase composition of various CDW used as precursors for AAMs. A feature common to all CDW-based precursors is the presence of quartz (SiO_2). Cement-originated CDW mainly consist of calcite ($CaCO_3$) and dolomite ($Ca,Mg(CO_3)_2$). Besides quartz, calcite and dolomite, several aluminosilicate phases can be observed in WCP and RCA: muscovite ($KAl_2[AlSi_3O_{10}(OH)_2]$), albite ($NaAlSi_3O_8$), anorthite ($CaAl_2Si_2O_8$). In addition, several crystalline phases (such as portlandite ($Ca(OH)_2$), kilchoanite ($Ca_6(SiO_4)(Si_3O_{10})$), ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$), pirssonite $Na_2Ca(CO_3)_2\cdot 2(H_2O)$ have been detected in WCP and RCA fines. Clay-originated CDW contains quartz, muscovite, albite, anorthite, diopside and hematite as major crystalline phases. Mullite (3Al2O3 2SiO2) is one of the most frequently detected minerals in fired clay materials. Its content depends on the chemical and mineralogical composition of clays and the firing temperature (Duval et al., 2008). Among all products of thermal transformations, the most significant role belongs to the amorphous aluminosilicate component, which is formed from clay minerals as a result of the destruction of their crystal structure and is characterized by the highest reactivity under alkaline conditions (Komnitsas and Zaharaki, 2007). WGP precursors have a siliceous amorphous phase, which indicates their potential for alkaline activation. The crystalline phases included in CDW are characterized by a variety of chemical activity with respect to alkalis. The alkaline dissolution potential of aluminosilicate minerals was studied in detail by Xu and Van Deventer (2020) and Ouffa et al. (2020). In particular, it was found that the dissolution extents of muscovite in NaOH and KOH are significantly greater than quartz and albite (Ouffa et al., 2020). However, precursor pretreatment such as calcination could be a promising way to increase the solubility of low reactivity phases of CDW and thus promote their alkaline activation to produce high performance materials.

Table 3. Phase composition of various CDW used for AAMs as a precursor.

Type of CDW	Phase composition (wt%)																							References
	Q	Ms	Ab	An	Ca	Po	Lz	Th	Cl	Pr	Mu	Dl	Wl	Cr	Di	Lr	Hm	Or	Ph	Kl	Et	Sp	Am	
																							+	Robayo-Salazar et al. (2017)
																							+	Ozcelikci et al. (2023)
WGP																							+	Ulugöl et al. (2021)
																							+	Xuan et al. (2019)
	+																						+	Manikandan and Vasugi (2022)
	+													+	+	+								Ozcelikci et al. (2023)
	+		+								+						+	+				+	+	Giannopoulou et al. (2023)
WCrP																							+	Ulugöl et al. (2021)
																							+	Yıldırım et al. (2021)
	+				+													+						Komnitsas et al. (2015)
	+	+	+	+													+							Robayo-Salazar et al. (2017)
	+	+		+						+	+													Mahmoodi et al. (2021a)
WBP	+													+	+									Ozcelikci et al. (2023)
	+		+	+							+				+		+							Giannopoulou et al. (2023)
	+		+								+													Ulugöl et al. (2021)
	+		+	+	+	+																		Robayo-Salazar et al. (2017)
	+	+	+	+	+					+	+													Mahmoodi et al. (2021a)
WCP	+			+	+	+															+		+	Sasui et al. (2023)
	+				+							+								+				Liang (2022b)
	+				+							+												Liu et al. (2023)
	+				+																			Ozcelikci et al. (2023)
	+				+							+												Liu et al. (2022)
RCA	+				+																			Komnitsas et al. (2015)
	+				+							+												Abdel-Gawwad et al. (2019)
	+				+							+												Abdel-Gawwad et al. (2020)
	+		+		+														+					Villaquirán-Caicedo et al. (2021)
	+	+	+		+		+	+	+			+	+											Bassani et al. (2019a)
CDW mix powder	+		+	+	+																			Robayo-Salazar et al. (2020b)
	+		+	+																			+	Tan et al. (2022a)
	+		+		+																		+	Tan et al. (2022b)

Notes: Q = Quartz; Ab = Albite; Ca = Calcite; Dl = Dolomite; Ms = Muscovite; An = Anorthite; Hm = Hematite; Po = Portlandite; Pr = Pirssonite; Mu = Mullite; Lz = Lizardite; Th = Thaumasite; Cl = Clinochlore; Wl = Wavellite; Cr = Cristobalite; Di = Diopside; Lr = Lazurite; Or = Orthoclase; Ph = Phillipsite; Et = Ettringite; Kl = Kilchoanite; Sp = Spinel; Am = Amorphous phase.

5 Utilization of CDW as a precursor in AAMs

5.1 Reactivity of CDW in alkaline media

The sensitivity of alkali-activated binders to the chemical composition of the precursor, which is contingent upon the source material of CDW, has been acknowledged (Dacic et al., 2023). The utilization of remarkably amorphous precursors with sufficient reactive glassy content stands as a crucial determinant in the production of stable alkali-activated binders. Moreover, the precursor should exhibit a relatively low water demand and facilitate easy release. In the literature, a mixture of CDW and ground granulated blast furnace slag (GGBFS) is often encountered as a precursor in AAM (Ali et al., 2023; Dacic et al., 2023; Liang et al., 2022; Khan et al., 2021). However, recent studies have indicated that a high content of GGBFS (50% of the total binder) can hinder the actual reaction or performance of CDW in the mixture due to the higher reactivity of GGBFS in an alkaline media (Khan et al., 2021). Furthermore, Zhang et al., 2020b have shown that replacing GGBFS with WGP cannot improve the compressive strength of alkali-activated solution-cured under ambient conditions due to the lower reactivity of WGP compared to GGBFS. When using low-reactivity materials, it is important to consider their dual nature, meaning that only the amorphous portion of these materials can undergo reactions while the crystalline part serves as a microfiller (Fort et al., 2020). This composite nature of the resulting AAMs can give rise to unique characteristics that are not observed in AAM, derived from high-reactivity precursors.

Analysis of the literature on the use of CDW as precursors shows that the greatest interest has been shown in WBP (Table 4). This is due to both the availability of the material and its claimed strength of 25-93 MPa, as well as the possibility of replacing ground blast furnace slag with WBP up to 80% by weight (Bumanis & Vaiciukyniene, 2021; Hwang et al., 2019), which has led to further research on these materials. However, there have been issues with using WBP in the production of AAM due to the low content of amorphous SiO_2 and Al_2O_3 in WBP, as reports indicate that the amorphous content for SiO_2 and Al_2O_3 ranges from 7.7-13.9% and 9.6-12.9%, respectively, while the remaining oxides are enclosed in crystalline phases (Keppert et al., 2018; Palomo & Fernandez-Jimenez, 2020). According to recent studies by Pommer et al (2021), CDW materials need to be ground before being used in AAMs. In terms of the particle size of CDW, it should be noted that coarser particles are less involved in the geopolymerization process and cause higher porosity of the resulting activated material (Pommer et al., 2021). Higher porosity leads to reduced thermal conductivity and accelerated transport of water and water vapor in materials containing larger CDW precursors. Mixtures of different CDWs are being actively studied as precursors for AAMs. On the one hand, this optimizes the process of delivering raw CDW material, which does not require separation into different waste sources. On the other hand, the heterogeneity of CDW can lead to differences in the physical and mechanical properties of the final product. Robayo-Salaza et al. (2020) combined various CDW, such as concrete, ceramic, masonry, and mortar, to create AAM. They found that the resulting CDW binder achieved a compressive strength of up to 43.9 MPa and was classified as a general use and low heat of hydration cement according to ASTM C1157. Robayo-Salaza et al. (2020) suggest that this innovative recycling concept provides a sustainable alternative for using CDW in situations where it is not possible to separate different types of waste.

Table 4. Recent research on the application of CDW as precursors

Type of CDW as a precursor	Dosage ratio	Application	Remark	Reference
Mixture of CDW	CDW precursor=4.5; OPC=0.5 AA solution=3.3; Coarse and fine recycled aggregate=12.1	Binder	The concrete produced with this mixture reported a compressive strength of 33.9 MPa at 28 days	Robayo-Salaza et al, 2020
WCP	WCP/ NaOH ratio=3/1	Mortar	It was concluded that WCP can be recycled as the precursor to synthesize geopolymer binder.	Huo et al., 2021
Mixture of CDW	Na_2O/binder ratio and water/binder ratio were set as 0.08 and 0.4 by weight, respectively.	Paste	The optimum grinding time for CWD is 2 hours. The compressive strength after a 28-day curing period is up to 39.2 MPa.	Tan et al., 2022a
WBP	Mix proportion of alkali activating solution in mass ratio: NaOH=1; KOH=1.4; SiO_2=3.	Mortar	The thermal conductivity of the developed material is lower than that of materials with a similar density range. This material has a brick-like appearance and can serve as a substitute for making bricks from CDW for non-structural purposes.	Wan et al., 2018
WBP	Mixture of the WBP powder, fly ash and ground-granulated blast-furnace slag	Paste	The workability, reaction kinetics, micro-properties, energy and environmental cost of AAC binder would be improved with the reuse of waste red brick powder	Liang et al., 2022a
WBP	The reference mix comprised 100% WBP as a starting material and WCS as the fine aggregate. The water-to-binder and binder-to-sand ratios were fixed at 0.4 and 1:2.75, respectively.	Paste	The measured compressive strength of the alkali-activated brick and ceramic mortar ranged from 24 to 93 MPa.	Hwang et al., 2019a; 2019b
WBP	The binder content (456 g), aggregate content (1254 g) and water to binder (w/b) ratio (0.46)	Mortar	Compressive strength is 36 MPa.	Tuyan et al., 2018
Tile WCrP	ceramic waste/aggregates=1/4.3 The water-to-binder ratio is 0.45	Mortar	Compressive strength is 43 MPa.	Reig et al., 2017
WCrP	WCrP to ground blast furnace slag ratio = 1/1	Mortar	WCrP precursors and activators in alkali-activated mortar can result in cost savings of 14%. The compressive strength after a 28-day curing period is 34 MPa.	Ramagiri & Kar, 2021
WCrP	SiO_2/Na_2O = 1, WCrP to Aggregates and Activator ratio is 1/2.7/4.9	Mortar	The coarser particles are less involved in geopolymerization process and causing the higher porosity of the	Pommer et al., 2021

resulting activated material.

5.2 Processing routes

Fig. 4 illustrates the step-by-step sequence of the mix design algorithm with CDW as a precursor. As already mentioned, the phase composition of the CDW mixture is very variable and depends on the raw construction material and the management (separation) of waste at the construction site. First, CDW material is collected at the construction site and depending on waste management practices in each specific country, it can be collected separately by waste category or as a mixture of CDW. Once collected, it is taken to the AAM production site, where it needs to be dried at a temperature of around 80ºC to remove any moisture (Liang et al., 2022a). Next, the dried CDW goes through a two-step crushing and milling process to convert it into a powder form. The first step involves using a jaw crusher with a 1mm spacing to crush the material, and then it is subjected to an hour-long ball milling process (Ozcelikci et al., 2023). Further, the existing molecular weight of the CDW powder elementals has to be obtained based on the XRF analysis, and the existing molar ratios of SiO_2/Al_2O_3 and also the Na_2O/SiO_2 ratios have to be calculated using the wt.% of CDW precursor in the AAM system (Mahmoodi et al., 2021a). Robayo-Salazar et al (2020a) drew attention to the aluminosilicate composition of the geopolymeric precursor, which had a molar ratio of 7.2 for SiO_2/Al_2O_3. Reig et al (2013) determined that the optimum SiO_2/Na_2O molar ratio is 1.6 and the water to binder (w/b) ratio is 0.45, at which the best mechanical properties of AAM are observed. A close optimal w/b=0.46 was also observed by Tuyan et al. (2018), and Rakhimova and Rakhimov (2015) reported an optimal molar ratio SiO_2/Na_2O of 1.5. In case the workability of the mixture is unsatisfactory, it is necessary to reconsider the optimal CDW powder particle size, as the particle size affects the reactivity and water absorption of the mixture. It may also be necessary to reconsider the liquid/solid ratio to achieve better workability of the mixture. In addition, it is necessary to reconsider the molar ratios of the phase composition of the mixture, as the chemical composition of the CDW may be variable. Additionally, the NaOH molarity should be adjusted. The maximum amount of NaOH used in AMM studies usually does not exceed 12 wt.%, while the optimal molarities of NaOH concentration is 9M (Ouda & Gharieb, 2020; Gorhan & Kurklu, 2014).

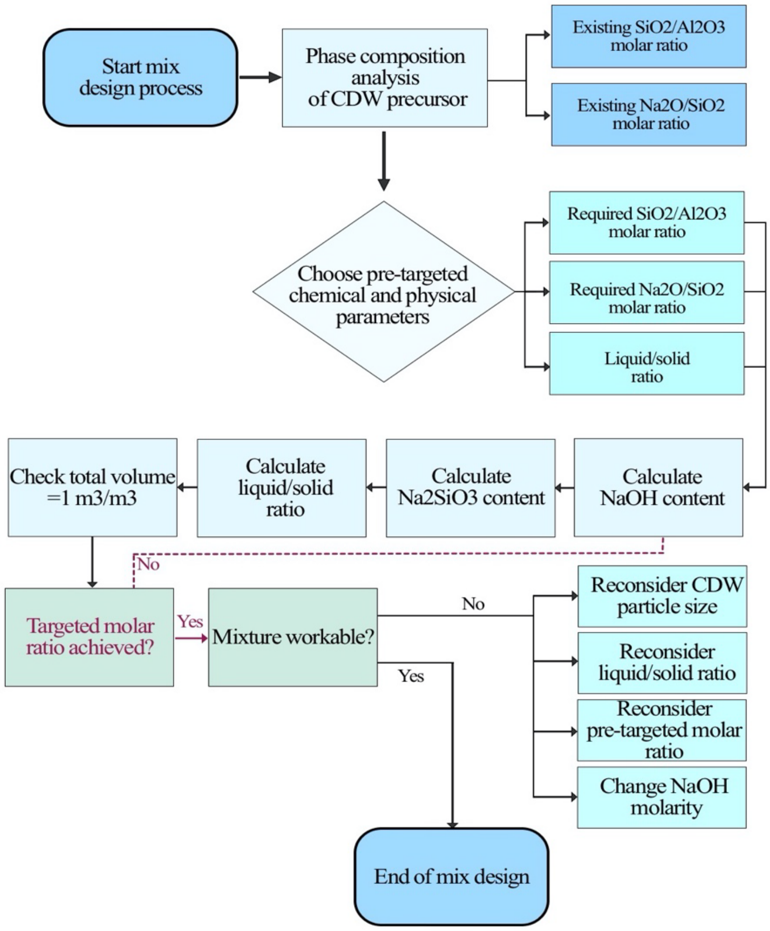


Figure 4. The mix design algorithm (adopted from Mahmoodi et al., 2021a)

5.3 Factors affecting properties of alkali-activated CDW

Multiple factors greatly influence the synthesis of AAB, such as the origin of precursor materials, their constituents, quantity, and particle size, as well as the alkaline activators' type and composition, the amount of free water, and the duration and type of curing (Ibrahim and Maslehuddin, 2021). The fresh properties of geopolymers, such as workability, stability, and flowability, generally lag behind those of normal concrete due to the highly viscous nature of the silicate mixture components. The workability of geopolymers based on CDW relies on the aluminosilicate source, while the impact of alkaline liquid concentration and the silicate-to-hydroxide ratio appears to be more significant (Mahmoodi et al., 2020). Keppert et al. (2018) employed WCrP as a precursor and concluded that the flow curves exhibited thixotropic characteristics in precursor-activator dispersions, demonstrating pseudoplastic (shear-thinning) behavior. The yield stress of pastes decreased with the increasing dosage of alkali activator, indicating a transition to a more fluid state. This aligns with expectations as higher silicate solution content enhances the solubility of precursor particles. According to Mostafa and

Allahverdi (2016), the initial fresh properties and subsequent hardened characteristics of AAM are significantly affected by the composition of the source materials. Assessing the workability of AAM fresh pastes involves a crucial parameter known as the setting time. Liang et al. (2022a) used WBP as a replacement for fly ash as a precursor and observed that pastes containing WBP had a shorter setting time compared to the control paste. WGP was used as a replacement for fly ash (Samarakoon et al., 2020) or slag (Huseien et al., 2020) as a precursor in AAMs, resulting in increased set times. The increase was due to the physical properties of WGP, which made more water available in the fresh AAM. Nano WGP also extended the set times when used as a replacement in AAMs. There was a significant correlation between the dissolution rate of soluble species from precursors, the reaction rate of geopolymerization, and the setting times. When using CDW as precursors, it was found that a higher concentration of alkalis promotes faster dissociation of the precursors and earlier setting of the geopolymer mixtures. In addition, at an increased SiO_2/Al_2O_3 ratio, the interaction between aluminate and silicate species during the precipitation phase intensifies, resulting in accelerated polycondensation and decreased setting times (Yaseri et al., 2017). It was found by Mahmoodi et al (2021b) that the higher content of Na_2O in the CDW powder may have initiated the quicker dissolution of silico-aluminates, which led to a rapid generation of heat when anhydrous precursor particles reacted with the alkaline solutions, thus causing a speedy coagulation stage.

The type and duration of curing play significant roles in determining the properties of AAM (Alhawat et al., 2022). The curing conditions have a direct impact on the polymerization mechanism, the quality of the polymeric product, and the subsequent strength development. In the past, various methods such as ambient temperature (Ramagiri et al., 2021; Robayo-Salaza et al, 2020), elevated temperature (Huo et al., 2021; Tuyan et al., 2018) and steam curing (Rakhimova and Rakhimov, 2015), as well as water ponding (Wan et al., 2018) have been employed to cure AAMs synthesized with different CDW precursors. However, it is important to note that low-Ca precursor materials are particularly sensitive and typically require heat curing within the range of 40 to 120°C in order to achieve sufficient strength (Alhawat et al., 2022).

Normally, increased molarity of the alkaline activator has a beneficial effect on the compressive strength of the CDW-based AAMs. At the same time, very high molarities of the activating solution may result in residual alkali concentration that remains unreacted, which negatively affects the mechanical strength (Komnitsas et al., 2015). CDW mixtures activated solely with low molarity NaOH solutions (from 4 M to 8 M) demonstrate low mechanical strength and durability performance (Ilcan et al., 2024). In addition, in this case there is a low resistance against water ingress and low freeze-thaw resistance. The observed negative effects can be mitigated by the inclusion of slag and microsilica, due to their high reactivity, promoting the formation of calcium-based gel structures (Ilcan et al., 2024).

The characteristics of AAMs heavily depend on the fine nature of the precursor. When the precursors have finer particles, they exhibit enhanced reactivity and stronger geopolymerization, resulting in the production of a more robust paste with a denser microstructure (Alhawat et al., 2022). This is primarily due to the increased specific surface area attained through the finer source materials, which accelerates the reaction rate by facilitating faster dissolution. As a consequence, the setting time is shortened, and strength development occurs earlier. Nevertheless, achieving improvements in mechanical and durability properties necessitates striking a balance between the higher water requirement and the fineness of the source materials. According to Tan et al (2022a), the optimal grinding time is considered to be 2 hours, based not only on the optimal particle size of CDW (D90 is 63.2 μm) but also on the rational use of electrical energy for production efficiency from a carbon emission perspective. Longer grinding duration increases the compressive strength of the AAMs synthesized with CDW mix powder and promotes the formation of a more densely packed structure due to reactive SiO_2 and Al_2O_3 in CDW particles and accelerated gel formation (Tan et al., 2022a). Pommer et al. (2021) utilized WCrP as a precursor material and discovered that the precursor exhibited the most favorable mechanical performance when particles retained on a 0.5 mm sieve were removed. This removal led to a higher geopolymerization rate. On the other hand, the inclusion of coarser particles in the WCrP precursor resulted in increased porosity, which subsequently impacted on the transport properties of AAMs. Specifically, it led to lower thermal conductivity and faster moisture transport.

AAMs made of CDW as precursors are characterized by a high tendency to efflorescence (Tan et al., 2022b). One of the main factors for this is the relatively low Al availability of CDW precursors, which leads to a high content of free alkali cations. In addition, AAMs are produced by activating low-reactivity CDW-based precursors under circumstances of high alkalinity. The addition of Al-rich materials (e.g., metakaolin) provides efflorescence mitigation in CDW based AAMs by decreasing the number of free alkalis and N-A-S-H gels formation as reported by Tan et al. (2022b).

6 Environmental and economic sustainability

6.1 Life cycle assessment

The use of CDW for the production of new construction materials undoubtedly brings benefits both in terms of resource conservation and reducing the amount of waste disposal in landfills. Scientists undertake Life Cycle Assessment (LCA) based on ISO 14040/14044 to quantitatively evaluate the benefits of such CDW recycling (Kravchenko et al., 2024; Besklubova et al., 2023). The replacement of Portland cement with industrial waste and by-products in the production of AAMs is expected to make a sustainable construction material, and this claim can be supported by conducting a thorough LCA analysis. The environmental sustainability of AAMs is mainly related to their precursors and activators (Cunningham & Miller, 2020). The calculation carried out by Liang et al (2022) showed that the inclusion of WBP reduced the energy consumption in the preparation of AAMs. For a binder based on 40 wt.% WBP, the overall energy savings were about 55% compared to a reference sample containing GGBS and fly ash. Such energy savings are significant considering the large volumes of construction materials produced. According to the authors, incorporating WBP as a solid precursor in AAM production is a viable strategy to lower energy consumption and develop eco-friendly binders, a concept that was similarly emphasized in the research of Irshidat et al (2021). Furthermore, a study conducted by Mahmoodi et al. (2022) demonstrated a significant decrease in embodied energy and CO_2 emissions when utilizing a ternary precursor consisting of WBP, WCrP, and WCP, resulting in reductions of approximately 86% and 76% respectively compared to OPC binder. Similarly, Fort et al. (2018) found that using WBP alone as a precursor in AAM resulted in a reduction of the consumed energy and GHG emissions by 63% and 81% respectively. In another study by Migunthanna et al (2021), a mixture of alkali-activated paste with superior mechanical properties exhibited a reduction in the consumed energy and GHG emissions by 85% and 78% respectively when compared to a cement paste. Ramagiri & Kar (2021) proved that WCrP as a precursor for AAMs warrants a higher dosage of sodium silicate and sodium hydroxide, thereby increasing the environmental impact. According to Robayo-Salazar et al (2022), the use of CDW in AAMs has a carbon footprint that is 44% lower than reference concretes made with 100% Portland cement. This classification indicates that these AAMs are more environmentally friendly than conventional concretes.

Tan et al (2022a) found that the process of CDW milling substantially increased the embodied CO_2 of the CDW geopolymer product, with an increase in emissions of approximately 10% for every hour of milling. The GHG emissions per unit strength were slightly reduced when using AAM made from CDW powder due to its higher strength. This suggests that a longer milling process can lead to greater environmental benefits for CDW. However, when the milling exceeds 2 hours, geopolymers exhibit an increased carbon footprint indicating that the efficiency of the milling duration gradually decreases. Therefore, the practical application of CDW in AAMs needs to consider the optimal milling time and the environmental friendliness of the raw materials. The contribution of material transportation to the Global Warming Potential (GWP) emphasis the need to reduce transportation distances in order to decrease fuel consumption. Thus, the recycling of CDW in large cities with short distances between the center and the production areas, as in the case of Hong Kong, is promising according to the sensitivity analysis of GWP to distance (Hossain, 2017).

6.2 Cost savings

The analysis of the economic feasibility of using CDW depends heavily on the infrastructure location and local waste management practices. For example, Ramagiri & Kar (2021) assessed the cost of using CDW as a precursor for AAMs in the Telangana market, in India. The results showed that using WCrP as a precursor in AAM production is more expensive than using fly ash due to the electricity costs involved in preparing WCrP through crushing, grinding, and sieving processes. On the other hand, Huseien et al. (2019) calculated the energy consumption required to prepare one tonne of WCrP, fly ash, and ground blast furnace slag, showing values of 1.1, 0.2, and 2.4 GJ/t, respectively, for Malaysia. The results indicate a reduction in the production cost of AAMs when using WCrP instead of ground blast furnace slag, which is commonly used in practice. The use of WGP to replace ground blast furnace slag was also calculated as saving up to 13% of costs in the Malaysian market (Huseien et al., 2020). In contrast, an analysis of the Chinese market showed that the use of WGP in AAMs can reduce costs by up to 37% compared to traditional cement use (Xiao et al., 2021).

7 Future directions and challenges

While the utilization of CDW powders as precursors is an optimal approach for processing construction waste, there are still areas that require significant improvement. One such area is enhancing the reactivity of CDW, which is largely dependent on particle size. However, processes like crushing and separation involved in achieving the desired particle size distribution are energy-intensive, leading to increased costs and higher GWP in AAM production. Therefore, it is crucial to carefully observe the optimal grinding time and particle size distribution of CDW powders, as well as to optimize waste separation management on construction sites. For example, Waste Concrete Powder (WCP) is generated partially during the dismantling of engineering infrastructure and at concrete aggregate recycling plants, where old cement paste is separated from the surface of Recycled Concrete Aggregates (RCA). Managing this type of CDW only requires sieving, which can significantly reduce costs in AAMs production. Despite its potential benefits, the use of WCP as a precursor in AAMs is relatively rare compared to Waste Ceramic Powder (WCrP) and Waste Brick Powder (WBP), which are often studied in the literature as replacements for traditional precursors. The limited use of WCP may be attributed to the reactivity of WCP, which depends on the carbonation period of the concrete and the content of non-reactive aggregates. Further research is needed to establish reliable comparisons among different CDWs as precursors under constant laboratory conditions to determine the optimum composition of AAMs. Currently, studies have mainly provided comparative data for the use of a single type of CDW replacing fly ash or ground blast furnace slag. Addressing these challenges and conducting comprehensive research will enable more effective and efficient utilization of CDW powders as precursors in AAM production, leading to reduced costs and improved environmental outcomes in the construction industry.

8 Conclusion

The escalating volume of CDW, particularly in densely populated urban areas, underscores the urgency of finding optimal processing solutions. In recent years, the use of CDW as a precursor in the production of AAM has gained significant traction as a promising approach to reduce GWP and decrease the cost of AAM production, while also capitalizing on resource conservation opportunities. This review focuses on the latest scientific literature, which provides compelling evidence supporting the feasibility of employing CDW as a precursor. By consolidating the findings of CDW research papers published since 2010, the following conclusions can be drawn:

- When processed to the optimal particle size, both CDW as a composite material and its individual components such as WCP, WCrP, WBP, RCA, and WGP exhibit remarkable strength as precursors for AAM.
- Alkali-activated binders' stability hinges on the chemical composition of CDW precursors, emphasizing the importance of amorphous content. Low-reactivity materials like WGP exhibit a dual nature, resulting in unique characteristics compared to high-reactivity precursors. WBP attracts interest due to availability and strength claims, but challenges arise from its low amorphous content, requiring grinding before use. Coarser CDW particles increase porosity, affecting thermal conductivity and water transport. Mixtures of different CDWs optimize raw material delivery but introduce heterogeneity.
- Curing conditions, including ambient temperature, elevated temperature, steam curing, and water ponding, play vital roles in determining AAM properties, particularly for low-Ca CDW precursors that require heat curing for sufficient strength. The fine particles of CWD enhances reactivity, accelerates geopolymerization, shortens setting times, and promotes earlier strength development of AAM. However, achieving optimal mechanical and durability properties involves balancing water requirements with the fineness of source materials.
- Preliminary estimations suggest that utilizing CDW precursors can lead to a 44% reduction in carbon footprint and a 37% decrease in costs compared to the use of traditional cement.

It is essential to conduct further comparative research to fine-tune waste management practices and establish a closed recycling loop for CDW powders within the construction industry. This comprehensive review underscores the potential of CDW as a valuable resource for sustainable AAM production. By optimizing the use of CDW and integrating it into a circular economy framework, the construction industry can significantly contribute to waste reduction, cost efficiency, and environmental conservation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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