

## Review article

# Influences of binder composition and carbonation curing condition on the compressive strength of alkali-activated cementitious materials: A review

Jinho Bang<sup>a</sup>, Jaesuk Choi<sup>a</sup>, Won-Taek Hong<sup>b</sup>, Jongwon Jung<sup>a</sup>, G.M. Kim<sup>c,d,\*</sup>,  
Beomjoo Yang<sup>a,\*\*</sup>

<sup>a</sup> School of Civil Engineering, Chungbuk National University, 1 Chungdae-ro, Seowon-gu, Cheongju, Chungbuk 28644, Republic of Korea

<sup>b</sup> Department of Civil and Environmental Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam, Gyeonggi 13120, Republic of Korea

<sup>c</sup> Mineral Processing & Metallurgy Research Center, Resources Utilization Division, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea

<sup>d</sup> Department of Resources Recycling, University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea

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## ABSTRACT

As international endeavors to diminish carbon emissions persistently escalate, the principles of net-zero emissions or carbon neutrality have gained prominence, prompting the implementation of diverse strategies globally to alleviate carbon emissions. Cement manufacturing represents a significant emission source globally, and has established formidable objectives to curtail emissions by over 60% by 2050. This review article scrutinizes the ramifications of the amalgamated composition of cement and alkali-activated construction substances, in addition to carbonation curing conditions, on compressive resilience. Initially, the resistance attributes of multi-component materials premised on alkali-activated binding agents were examined. Subsequently, the primary variables influencing the performance of cementitious materials, encompassing Portland cement, were determined. Lastly, the compressive resilience traits of these substances were assessed under an array of carbonation curing circumstances.

## 1. Introduction

The ever-growing concerns about climate change and the environmental impacts of human activities have led to a global impetus towards the reduction of greenhouse gas (GHG) emissions. As countries and industries strive to achieve carbon neutrality and adhere to the net-zero emissions concept, efforts to identify and mitigate sources of carbon emissions are increasingly significant. Among various industries, cement production is recognized as one of the primary sources of GHG emissions, accounting for approximately 7% of global carbon dioxide emissions [1,2]. Consequently, the cement industry has set ambitious targets to reduce emissions by over 60% by 2050 [3].

Alkali-activated materials (AAMs) have garnered considerable attention in recent years as potential alternatives to traditional Portland cement, due to their lower carbon footprint and comparable mechanical properties [4]. These materials are created by activating aluminosilicate (AS) precursors, such as fly ash (FA), slag, or metakaolin (MK), with

alkali metal compounds, resulting in the formation of a binding matrix with desirable properties for construction applications [5]. As AAMs do not require the energy-intensive calcination process associated with Portland cement production, they offer a promising route towards achieving the emissions reduction goals in the cement industry [6].

However, despite the promising features of AAMs, the understanding of the factors influencing their performance, particularly in terms of compressive strength, remains limited. Moreover, given the diversity of potential precursors and activators, as well as the variability in mixture compositions and curing conditions, the optimization of these materials for specific applications presents a significant challenge [7]. In this review article, a thorough analysis of the available literature on the strength characteristics of multi-component materials based on alkali-activated binders will be provided, with a focus on identifying the key parameters that influence compressive strength.

Another essential aspect of this review involves the examination of the major variables affecting the material performance of cementitious

\* Corresponding author at: Mineral Processing & Metallurgy Research Center, Resources Utilization Division, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea.

\*\* Corresponding author.

E-mail addresses: [k.gm@kigam.re.kr](mailto:k.gm@kigam.re.kr) (G.M. Kim), [byang@chungbuk.ac.kr](mailto:byang@chungbuk.ac.kr) (B. Yang).

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materials, including Portland cement. Although the use of AAMs is an emerging trend, Portland cement remains the dominant binder in the construction industry. Thus, understanding the factors that contribute to its compressive strength, as well as identifying opportunities for improving its environmental performance, is crucial. This section of the review will delve into the literature on the composition and performance of cementitious materials, exploring the role of supplementary cementitious materials (SCMs), such as FA, slag, and silica fume (SF), in enhancing the mechanical properties and reducing the carbon footprint of these materials [8].

The objective of this paper was to conduct a comprehensive review of the impact of carbonation curing on the compressive strength of alkali-activated cementitious materials. For a deeper and more continuous understanding, it was fundamentally imperative to first address the binder composition of alkali-activated cementitious materials. Consequently, the discussions on the binder composition and its consequential effects under carbonation curing could be synthesized into a single article. As pressure for sustainable development mounts, carbonation curing technology is emerging as a potential game changer for the precast and modular construction industry. By effectively sequestering and utilizing large amounts of CO<sub>2</sub>, carbonation curing holds immense potential for reducing global CO<sub>2</sub> emissions. In addition to environmental benefits, this method also improves the performance and efficiency of construction materials, indicating its promise as a catalyst for a major industry shift towards more sustainable, eco-conscious, and cost-effective construction practices. For better understanding, the following sentence has been added to the revised manuscript.

In light of these objectives, this review article aims to critically examine the current literature on the impact of the mixture composition of cement and alkali-activated construction materials, as well as carbonation curing conditions, on compressive strength. The focus will be on three main aspects: the strength characteristics of multi-component materials based on alkali-activated binders, the major variables affecting the material performance of cementitious materials, including Portland cement, and the compressive strength characteristics of these materials under varying carbonation curing conditions. By providing a comprehensive overview of the relevant research, this review intends to identify knowledge gaps, highlight potential avenues for future research, and contribute to the ongoing efforts to mitigate carbon emissions in the cement industry.

## 2. Influences of binder composition of alkali-activated cementitious materials

A cement-free alkali activator is a chemical compound that initiates the process of geopolymerization in the absence of traditional cementitious materials like Portland cement [9]. These activators are typically composed of alkaline solutions, such as sodium or potassium silicates, and are used to enhance the properties of alternative binder systems, like geopolymers or AAMs [10]. The use of cement-free alkali activators contributes to more sustainable and environmentally friendly construction materials, as they can reduce the carbon footprint associated with cement production. Typically, the cement-free alkali-activated systems have utilized AS as a supplementary or additional component within the matrix, or by incorporating additional calcium aluminate (CA) into the matrix. Some key binder materials utilized in these systems include ground granulated blast-furnace slag (GBFS), MK, red mud (RM), FA, SF, and rice husk ash (RHA) [11,12].

GBFS is an irregularly-shaped, vitreous byproduct of iron production, it can replace 25–70% of cement content in concrete mixtures [13, 14]. It offers advantages such as reduced permeability, enhanced strength, decreased hydration heat, and reduced alkali-silica reactions when hydrated. MK is a natural clay material with kaolinite (K) as its primary component, it enhances the strength of cementitious matrices. Global annual production is around 25.7 million tons, with China, Korea, Iran, the UK, Germany, Brazil, and the US producing over 75%

(19 million tons). RM is a byproduct of alumina production from bauxite, it has a high Al<sub>2</sub>O<sub>3</sub> content, strong alkalinity (pH > 10), and is difficult to dispose of due to its toxicity [15]. When used at a replacement rate of 5–20%, it can enhance compressive strength and delay setting time. FA is a byproduct of coal combustion and power generation processes, it consists of amorphous and crystalline SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and CaO. It reacts with lime (Ca(OH)<sub>2</sub>) in the presence of water, forming hydration products similar to cement. It offers benefits such as enhanced strength, durability, and resistance to acidic substances.

SF is a byproduct of silicon and ferrosilicon refining processes, it is an amorphous, spherical material with high reactivity. It contributes to strength enhancement, pore size reduction, and rapid improvement in calcium silicate hydrate (CaH<sub>2</sub>O<sub>4</sub>Si) [15]. Finally, RHA is a byproduct of burning rice husks, it mainly consists of amorphous Si with some crystalline phases. It exhibits characteristics such as low permeability, enhanced workability, and improved early and long-term strength. Herein, we reviewed research on substituting various geopolymers with slag, FA, K, MK, RM, SF, and OPC. The collected literature has been analyzed to study the characteristics of various materials and is summarized in Tables 1 and 2. According to the reviewed literature, about 30% of the studies investigated the impact of slag substitution, followed by OPC, FA, MK, SF, RM, and K.

Table 3 provides a comprehensive overview of the compressive strength (28 d) of cement-free alkali-activated materials, taking into account various influential parameters. These parameters encompass the type of binder material used, the specific classification of the material, the resulting compressive strength, the molarity of the activator employed, the conditions under which the material was cured, and the detailed features or key experimental variables that were considered during the study. This extensive compilation aims to offer valuable insights into the performance of alkali-activated materials under different circumstances and can serve as a useful reference for future research and development in the field.

Numerous researchers have conducted studies on cement-free alkali-activated systems based on SCM, investigating the effects of binder type, NaOH concentration, water, and curing temperature on their performance. The compressive strength of these materials primarily depends on the characteristics of the binder, as shown in the table above. It has been observed that increasing the slag content leads to an increase in compressive strength for sodium silicate (NS), sodium hydroxide (NH), and sodium hydroxide-sodium silicate solutions (NHNS) series [16]. This increase is thought to be due to the availability of free Ca<sup>2+</sup> ions, which can react with alumina and silica to form C-A-S-H gel. The compressive strength trends of materials with varying NaOH-based activator molar concentrations have been investigated. Generally, it was found that increasing the molar concentration resulted in geopolymer composites exhibiting higher compressive strength compared to conventional concrete in most cases [17].

Table 3 presented the compressive strength results for SCMs. In contrast, there are studies illustrating the trends in compressive strength when employing various types of binders. The findings from these studies are depicted in Figs. 1–3. Fig. 1 demonstrates that compressive strength is improved when slag is substituted in FA based concrete. This

**Table 1**  
Properties of natural and industrial sources for alkali-activated cementitious systems [4].

Materials	Natural or byproduct	Shape	Main composition
Slag	byproduct	Angular	CaO
MK	natural	Amorphous	SiO <sub>2</sub>
RM	byproduct	Amorphous and crystalline	Fe <sub>2</sub> O <sub>3</sub>
FA	byproduct	Amorphous and crystalline	SiO <sub>2</sub>
SF	byproduct	Amorphous and spherical	SiO <sub>2</sub>

**Table 2**  
Elemental composition of binder materials (%) [11].

	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	MgO	Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	TiO <sub>2</sub>
Slag	31–38	38–44	9–13	7–12	-	-	-
MK							
RM	2–20	2–8	10–30		20–60	2–10	0–28
FA							
SF	90 -	> 1	> 1	> 1	> 1	> 1	-

enhancement in strength appears to be due to the formation of calcium-aluminum-silicate-hydrate gel, resulting from an increase in calcium content, with the upward trend in compressive strength observed up to a 50% slag replacement rate. Studies on the substitution of FA in slag-based composites reveal both positive and negative effects. Generally,

**Table 3**  
Compressive strength of cement-free alkali-activated materials according to various parameters.

Binder Materials	Type	Compressive strength (MPa)	Activator molarity (NaOH; M)	Curing condition	Features	Effect of features	
Slag (30%) and FA (70%)	Concrete[18]	9.92	3	AT	L/B	0.28	
		10.44				0.30	
		9.49				0.32	
		8.58				0.35	
		6.59				0.45	
		9.04					
		33.8					
		40.92					
		42.58					
		34.1					
MK	Mortar[19]	39.76	12	AT	S/B	0.3	
		40.68					
		43.12					
		41.13					
		40.83					
		43.89					
		42.97					
		36.93					
		41.88					
		40.92					
		36.06					
		44.75					
		42.76					
		43.84					
		FA				Paste[20]	39.19
65.92	1.0						
44.14	1.5						
59.89	2.0						
57.79	2.5						
31.34	3.0						
65.36	1.0						
76.56							
63.4							
Mortar[21]	Mortar[21]		64.24	8	OD 90 °C for 24 h	Nano silica 0%	
			44.38				
			37.96				
			47.05				
			39.97				
			45.77				
			44.79				
			43				
			42.51				
			43.84				
Concrete[22, 23]	Concrete[22, 23]	39.19	16	OD 60 °C for 24 h	AAS/FA 0.4		
		65.92					
		44.14					
		59.89					
		57.79					
		31.34					
		65.36					
		76.56					
		63.4					
		64.24					
Concrete[22, 23]	Concrete[22, 23]	44.38	12	OD 60 °C for 48 h	Nano silica 0%		
		37.96					
		47.05					
		39.97					
		45.77					
		44.79					
		43					
		42.51					
		43.84					
		43.84					
Concrete[22, 23]	Concrete[22, 23]	39.19	12	OD 60 °C for 48 h	Nano silica 0%		
		65.92					
		44.14					
		59.89					
		57.79					
		31.34					
		65.36					
		76.56					
		63.4					
		64.24					
Concrete[22, 23]	Concrete[22, 23]	44.38	8	AT	Nano silica 6%		
		37.96					
		47.05					
		39.97					
		45.77					
		44.79					
		43					
		42.51					
		43.84					
		43.84					

\* . AT: Ambient temperature; L/B: Liquid/binder ratio; S/B: Sand/binder ratio OD: Oven dry; AAS: Alkaline activator solution

an increase is observed when using a 6% Na<sub>2</sub>O activator solution and polycarboxylate-based superplasticizers at substitution rates between 30% and 50% [24]. Ultimately, the influence of FA substitution on compressive strength varies depending on the FA replacement rate, activator modulus, and Na<sub>2</sub>O concentration.

When slag is substituted in FA-based geopolymers, both initial and final setting times are shortened, likely due to the acceleration of hydration reactions from the high CaO content in slag. Replacing slag with FA in geopolymer composites adversely impacts flowability and workability [25]. The flexural strength of FA-based geopolymer composites generally increases with slag substitution, a trend also observed in concrete. While overall physical properties appear to improve, further research is needed to fully understand these materials.

Fig. 2 illustrates the 28 d compressive strength trend for materials

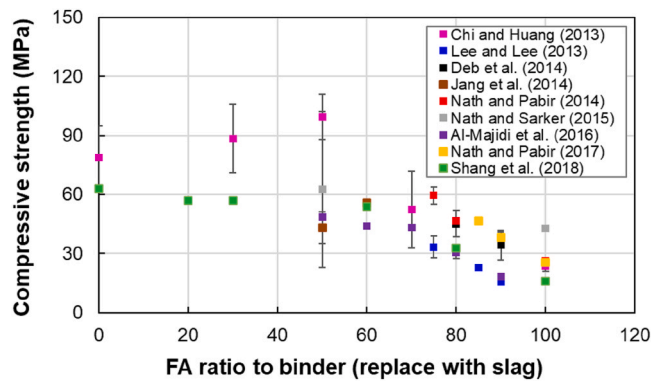


Fig. 1. Trend of 28 d compressive strength for materials with FA replaced by slag [26–33].

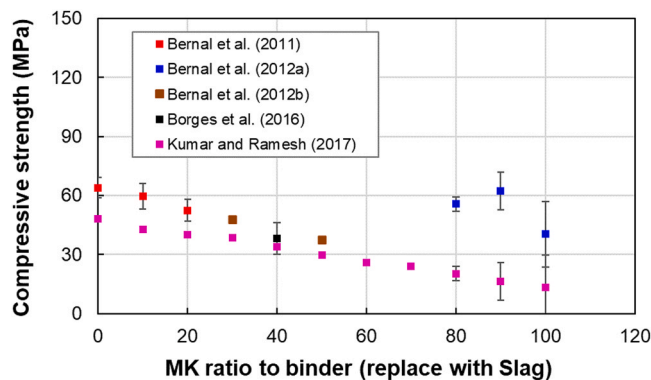


Fig. 2. Change in 28 d compressive strength for materials with MK replaced by slag [35–39].

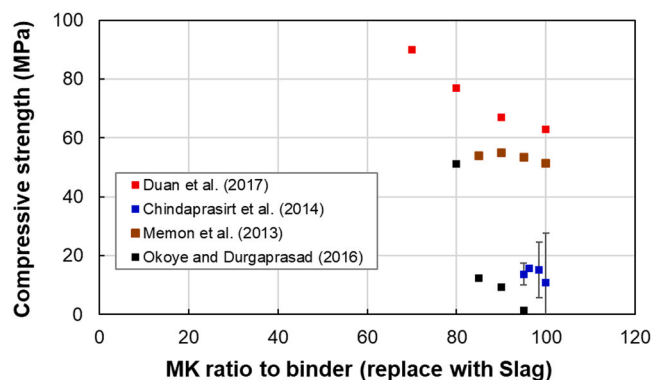


Fig. 3. Variation in 28 d compressive strength for materials with FA replaced by SF [44–47].

where slag replaces MK. The impact of slag addition on MK-based pastes is significantly influenced by the curing method used. In general, compressive strength increases when slag is added compared to specimens containing only MK; however, this depends on the chemical composition ratio, material concentration, and activators [34]. Despite many studies on substituting MK with slag, no additional benefits have been reported, except in one study. Differences have been observed depending on the curing conditions and substitution rates.

The researchers highlighted the importance of understanding the microstructure of alkali-activated binders for achieving optimal performance. Another study examined the effect of NaOH solution on the properties of metakaolin-based geopolymer mortar, demonstrating that

curing temperature significantly influences the material’s properties. These findings indicate that the advantages of replacing MK with slag may depend on various factors, necessitating further research to fully comprehend their impacts on the resulting materials.

Fig. 3 illustrates the 28 d compressive strength variation of materials in which FA was replaced with SF. It has been reported that the addition of SF to FA-based geopolymer concrete does not significantly improve the strength, with only a minor increase of up to 15.5% observed. Numerous studies have reported that replacing existing materials with SF enhances the compressive strength of FA, slag, and MK based geopolymer composites. The positive effect of SF on the compressive strength of FA-based geopolymers can be attributed to its packing effect as a fine aggregate filler, resulting in a denser microstructure [40,41]. Moreover, considering the high reactivity of SF, its reaction with calcium hydroxide within the mixture likely generated calcium silicate hydrate gel, leading to higher compressive strength. Nonetheless, in mixtures with high Si/Al ratios, the relationship between compressive strength and SF addition was not always valid. This is presumably due to the formation of non-reactive silicate oligomers caused by an excess of Si. On the other hand, incorporating SF into geopolymer mortar made with treated palm oil waste led to a reduction in compressive strength. In MK-based geopolymer pastes, the addition of SF shortened the setting time, which accelerated as the binder/solution and Si/Al ratios increased [42,43]. Studies on the effects of SF addition on fluidity and workability have been conducted for MK and FA-based geopolymer composites. Adding SF to MK-based geopolymer pastes improved fluidity and workability. In contrast, SF incorporated into FA-based geopolymer composites negatively impacted workability. The decrease in performance due to SF incorporation in FA-based mixtures is believed to result from excessive water absorption within the material, caused by SF’s higher surface area compared to FA.

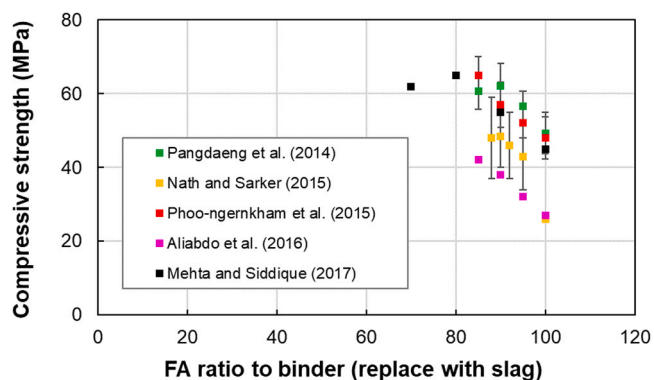
Herein, the compressive strength characteristics of multi-component cementitious materials composed of Portland cement and various binder materials were additionally investigated. The abundant limestone content in Portland cement provides a source of CaO, which enhances the hydraulic properties of pozzolanic materials, making hydration possible [48]. As hydration progresses, the internal reactions within the material lead to improvements in strength, chemical resistance, thermal resistance, impermeability, and workability [49]. The aim of this study was to identify key variables by examining various related literature to confirm the advantageous characteristics of materials utilizing Portland cement. Portland cement-based multi-component systems offer numerous benefits due to the synergistic effects of their constituents. These materials can exhibit enhanced performance in terms of strength, durability, and sustainability compared to their single-component counterparts. Some examples of supplementary materials often combined with Portland cement include slag, FA, and SF, which can improve the material’s properties while reducing environmental impact.

In order to optimize the performance of multi-component cementitious materials based on Portland cement, it is essential to understand the roles of various constituents, as well as the effects of their proportions and interactions. Future research should focus on investigating the influence of different combinations of SCMs, curing conditions, and other factors on the properties of these systems. By gaining a comprehensive understanding of the factors affecting the performance of Portland cement-based multi-component materials, it will be possible to develop more efficient and sustainable solutions for the construction industry Table 4.

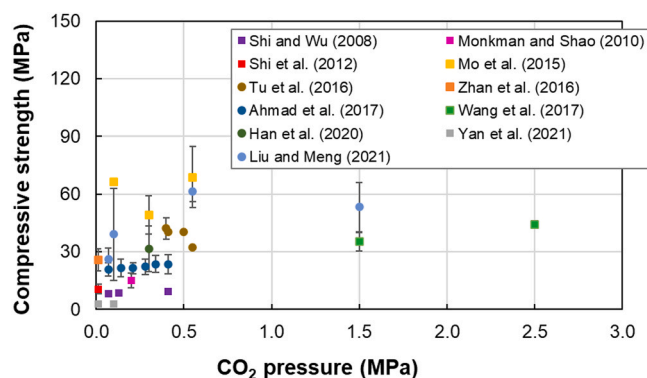
In the hydration of multi-component cementitious materials containing OPC, the activators used can be broadly divided into ordinary water and alkali activators. To understand the differences, the results have been schematically illustrated in Figs. 4 and 5. In the case of cementitious materials using alkali activators, the compressive strength of geopolymer with FA replaced by OPC showed a slight improvement. This enhancement can be attributed to the abundant calcium oxide content in OPC, which aids in the formation of aluminosilicate gels

**Table 4**  
Compressive stress of alkali-activated cementitious materials.

Binder Materials			Type	Compressive strength (MPa)	Curing condition	Features	Effect of binders	
OPC	Slag	FA						
100	0		Concrete[50]	35.32	AT for 24 h + Underwater at 25 °C for 28d		-	
40	60			29.21			↓	
33	60			32.22			Lime 7% ↑	
40	60			28.11			Water 15 kg ↑	
33	60			32.12			Water 15 kg and Lime 7% ↑	
40	60			25.31			Water 31 kg ↑	
33	60			30.03		Water 31 kg and Lime 7% ↑	↓	
90		0	Mortar[51]	59.09	Underwater for 28d		-	
80		10				51.92		↑
70		20				49.04		↓
100		30		44.26			↓	
95	0	0	Concrete[52]	24.65	AT for 24 h + Underwater for 28d		-	
95	2	3				25.93		↑
95	2.5	2.5				27.05		↑
85	3	2				28.12		↑
85	5	10				28.96		↑
85	7.5	7.5				29.14		↑
70	10	5				30.56		↑
70	10	20				31.07		↑
70	15	15				32.22		↑
70	20	10				33.45		↑



**Fig. 4.** Changes in 28 d compressive strength of cementitious materials with FA replaced by OPC using alkali activators [31,55–58].



**Fig. 5.** Impact of CO<sub>2</sub> pressurization on the compressive strength of alkali-activated cementitious materials [64,66,69,76–83].

through the additional generation of silicate oxides during the hydration process [53].

Numerous studies have investigated the interdependencies among various parameters (e.g., NaOH concentration, curing conditions, or binder content) for the improvement of compressive strength due to the addition of OPC. In the case of OPC-FA geopolymer mortar strength, it was found that factors such as moist curing, the use of specific molar

concentrations of activators, and a higher OPC content positively influenced the increase in strength [54]. Many studies confirmed the positive impact of replacing pozzolanic materials with OPC on compressive strength; however, the differences varied across experimental results, as illustrated in the Fig. 4.

### 3. Influences of carbonation curing conditions

In general, the carbonation process occurs naturally or artificially in the gas-liquid-solid triphase domain and significantly influences the increase of CO<sub>2</sub> in ordinary OPC based composite materials. Ca(OH)<sub>2</sub> is a primary hydration product sensitive to CO<sub>2</sub>, which, during subsequent carbonation stages, can form dense layers of CaCO<sub>3</sub> on the surface, either randomly or as a coating, due to nucleation sites' adhesion and molecular structure growth [59]. The Ca/Si ratio is a crucial factor in the strength and durability properties of cementitious composite materials, with the compressive strength of C-S-H paste increasing as the Ca/Si ratio decreases due to improvements in pore structure. Furthermore, the formation of CaCO<sub>3</sub> depends on the curing conditions, particularly the CO<sub>2</sub> concentration, and the Ca/Si ratio of C-S-H [59].

While this natural carbonation process can sometimes contribute to the enhancement of concrete strength, it is still considered a deterioration mechanism. This is because the highly alkaline conditions (pH values 12–14) within the concrete create a spontaneous passive oxide layer on the surface of reinforcing steel. Unlike natural weathering carbonation, many researchers reported that stable polymorphs of calcite crystal form in most CO<sub>2</sub> curing processes. This occurs because not all cement particles react during the reaction process, allowing for the continued hydration of residual portions when exposed to humid conditions after carbonation.

In this section, we have analyzed the compressive strength performance of alkali-activated cementitious materials based on various carbonation curing conditions in diverse environments. Specific variables for carbonation curing include chamber temperature, internal pressure, CO<sub>2</sub> concentration, and curing duration. Table 5 presents the effects of carbonation curing conditions on the compressive strength of cementitious materials containing alkali-activated components. Additionally, Table 6 illustrates the compressive strength of materials derived from various carbonation curing conditions applied to ordinary OPC-based construction materials. We aimed to understand the interdependencies of influential parameters among these factors. Artificial carbonation has the advantage of supporting elevated CO<sub>2</sub> partial



**Table 5**  
Compressive strength of alkali-activated cementitious materials according to various curing variables.

Binder Materials	Type	Comp. Strength (MPa)	Curing conditions					Features	Effect of binders	
			Time (d)	Temp. (°C)	Con-cent. (%)	Pres-sure	Hum-idity (%)			
OPC	Concrete[60]	14.6	28	AT	50	Atmos-pheric	87	C 2 h and H 28d	-	
		16.8							H only for 28d	↑
Slag		22						C 2 h and H 28d	↑	
		21.6							H only for 28d	↑
Slag 25/ OPC 75		17.9						C 2 h and H 28d	↑	
		17.4							H only for 28d	↑
Slag 50/ OPC 50		12.7						C 2 h and H 28d	↓	
		13.3							H only for 28d	↓
Slag 30 / OPC 70	Concrete[61]	51.9	1	30	99	Non carbon curing	65	SP 2.6%	-	
		132.6							7	↑
		165.1	28						↑	
		48.9	1			3 bar			↓	
Slag 50/ OPC 50		129.3	7			for			↑	
		148.1	28			16 h			↑	
		24.3	1			Non carbon curing		SP 2.8%	-	
		101.6	7						↑	
		132.9	28						↑	
		34.1	1			3 bar			↑	
		112.5	7			for			↑	
		139.3	28			16 h			↑	
Slag 70/ OPC 30		21.1	1			Non carbon curing		SP 2.9%	-	
		94.7	7						↑	
		130.6	28						↑	
		21.5	1			3 bar			↑	
		95.9	7			for			↑	
		131.9	28			16 h			↑	
OPC	Mortar[62]	48.9	28	23	0	Atmos-pheric	60	Utilized stainless steel argon-oxygen decarburization	-	
		41.7							40	↓
		45.6							↓	
		50.5		23	5				↑	
		44.5		40					↓	
		46.1		50					↓	
Slag 30/ OPC 70		19.0		23	0				-	
		33.4		40					↑	
		35.7		50					↑	
		41.4		23	5				↑	
		49.9		40					↑	
		55.4		50					↑	
Slag 60/ OPC 40		7.8		23	0				-	
		18.5		40					↑	
		20.5		50					↑	
		31.5		23	5				↑	
		44.1		40					↑	
		49.4		50					↑	
MgO 10 / PFA 0	Concrete[63]	17.4	20	AT	7	Atmos-pheric	5	w/c 0.7	-	
		10.6							1	↓
		16.9			3				↓	
		23.5			7				↑	
		24					20		↑	
		12.8			7			5	-	
MgO 10 / PFA 5		4			1		10		↓	
		8.1			3				↓	
		13.8			7				↑	
		15						20	↑	
OPC 40 / FA 30 / Slag 30	Aerated concrete[64]	2.31	3	60 ± 2	-	0.01 MPa	95	Curing time 4 h	w/c 0.3	-
		3.05							7	↑
		2.45				0.1 MPa		Curing time 8 h	↑	
		3.02	7						↑	
OPC	Paste[65]	42.34	1.4	25	99.8	5 bar	50			-
		92.69								28
		103.47								↑
		108.73	180							↑
		111.48	360							↑
		31.93	1.4							-
OPC + FA 20		72.88	28							↑
		96.05	90							↑
		104.81	180							↑
		112.79	360							↑
OPC + FA 50		42.23	1.4							-
		93.22	28							↑
		103.26	90							↑
		108.93	180							↑
		112.79	360							↑

\* . C: Carbonated; H: Hydrated

pressures, as it is carried out in a fluidized, sealed environment at relatively higher pressures than atmospheric pressure [30]. As a result, this method has been widely conducted in laboratory-scale experimental studies; however, it also presents a drawback in that it may not accurately represent real-world conditions.

In this work, we have consolidated and graphically depicted the notable trends found in the data presented in Tables 5 and 6. Figs. 5 and 6 display the experimental outcomes gathered from various studies examining the impact of CO<sub>2</sub> pressure on the compressive strength of treated materials. Based on the analysis, the gas pressure within a completely enclosed chamber is kept constant, ranging from 0.01 to 3 MPa during the curing process [66]. It was found that when cured at 0.4 MPa for 4 h in a moist environment, a higher amount of gas infiltrated and interacted with clinker minerals, resulting in increased compressive strength compared to 0.06 MPa, while only minor differences were noted in dry settings [73]. Moreover, a study demonstrated that nearly all cement pastes with a brief curing duration of 3 h at a high pressure of 0.55 MPa achieved higher strength values than those cured for 24 h at 0.1 MPa.

Another investigation reported a logarithmic correlation between the compressive strength of concrete blocks with recycled aggregates and gas pressure. The impact of gas pressure was more significant when limestone powder was incorporated in the mix design, due to the dilution effect and the creation of additional nucleation sites. However, excessive pressure can cause pore blockage and inadequate gas diffusion because of the development of a protective layer (extensive CaCO<sub>3</sub>), and the production of a considerable amount of heat can elevate the risk of microcracking [74]. In a similar vein, as the strength increased, CO<sub>2</sub> absorption rates generally rose with the increase in partial pressure, irrespective of the various internal reaction mechanisms. This occurrence is linked to the presence of more amorphous CaCO<sub>3</sub> at elevated pressures [75]. It was verified that a pressure of 0.4 MPa led to roughly 100% more mass increase at a steady rate over 10 h compared to lower pressures.

Figs. 7 and 8 present the analysis of studies examining the effects of CO<sub>2</sub> concentration on compressive strength and CO<sub>2</sub> absorption of materials. The substantial impact of CO<sub>2</sub> concentration on compressive strength has been confirmed in multiple studies, leading to efforts to identify the optimal value [88]. One study found a quantitative relationship between the water loss during curing and the gas absorption capacity of the specimens. Another investigation noted that raising the pressure from 0.5 to 2.5 MPa increased gas absorption from 13.3% to 18.3% over 2 h, with similar results reported elsewhere [59]. This suggests that CO<sub>2</sub> pressure strongly encourages gas absorption in cement-based composites, making it a key variable for future research.

Various studies have highlighted the critical role of CO<sub>2</sub> concentration in the carbonation degree of cementitious composites cured in a chamber. One research reported that dry-mix pressed pastes exposed to 20% CO<sub>2</sub> achieved the highest compressive strength increase, approximately four times higher than the 0.04% baseline. Another study confirmed strength increases of 3.4% and 13.7% after 15% and 25% CO<sub>2</sub> curing for 24 h, followed by two weeks of water curing [53]. A comparison of cement mortar strength cured in CO<sub>2</sub> and untreated specimens revealed that 20% CO<sub>2</sub> led to higher strength after 28 d, regardless of the manufacturing method.

As CO<sub>2</sub> concentration increased, the gas absorption rate generally rose. In most instances, absorption values were under 5%, depending on the mineralogical properties and composite mixing ratios of the raw materials [100,101]. For example, at CO<sub>2</sub> concentrations ranging from 0.04% to 20%, CO<sub>2</sub> absorption rates grew from 0.61% to 3.03%, and the degree of hydration expanded from 0.79% to 2.89%. Researchers attributed the decrease in absorption rate during the test period, under wet curing conditions and high CO<sub>2</sub> concentrations, to a reduction in

pore volume caused by continuous hydration. Additional studies reported over 15% CO<sub>2</sub> absorption rates by incorporating nano-TiO<sub>2</sub> carbonated at 20% CO<sub>2</sub> concentration and argon-oxygen decarburization slag at 15% CO<sub>2</sub> concentration, respectively.

Figs. 9 and 10 encapsulate the influence of curing temperature during carbonation on compressive strength and CO<sub>2</sub> absorption rates. The effect of temperature is evident in the different carbonate crystal forms as well. It has been discovered that vaterite, a metastable form and precursor of calcite and aragonite, is more likely to form at lower temperatures, while aragonite, an orthorhombic crystal structure with a space group, tends to form at higher temperatures [102]. Research has shown that a relatively high curing temperature carbonation method could significantly improve the initial strength (1 h) of dry-mix cement pastes. Notably, a considerable enhancement in compressive strength, from 16.9 to 36.2 MPa (~114.2%), was observed when the temperature increased from 5 °C to 50 °C. On the other hand, it was noted that raising the curing temperature from 20 °C to 80 °C resulted in only minor changes in the compressive strength of specimens, and significant strength reductions were reported after 4 h of curing at 85 °C due to the more damaging thermally induced shrinkage and cracking processes.

Moreover, temperature plays a crucial role in the carbonation of cementitious composites, affecting not only moisture evaporation but also accelerating ion movement within pore moisture, which in turn enhances CO<sub>2</sub> diffusion. Studies have shown that as the temperature increases from 20 °C to 50 °C, CO<sub>2</sub> permeability rises by approximately 13–62%, and with a further increase to 80 °C, it improves by an additional 3–55%. However, according to a model presented by researchers, at a total pressure of 101.3 kPa, the CO<sub>2</sub> solubility at 90 °C is only 14% compared to 20% at 20 °C. As a result, considering the exothermic reaction of carbonation, room temperature (20–30 °C) has been identified as an optimal curing temperature for CO<sub>2</sub> curing. In general, the pattern of CO<sub>2</sub> absorption rate changes depending on curing temperature (up to 100 °C) was found to be substantially similar to that of compressive strength. The liquid phase is a vital medium for the carbonation reaction, and almost all moisture within the specimen evaporates in a short time at temperatures above the boiling point. Indeed, when the temperature surpasses 100 °C, the sample's CO<sub>2</sub> absorption plateaus or gradually declines.

Figs. 10 and 11 illustrate the effects of carbonation curing duration on the compressive strength and CO<sub>2</sub> absorption of materials. The initial carbonation process is diffusion-controlled (Fick's second law of diffusion), making the carbonation duration a critical curing factor. Both hydration product phases and mineral phases of cementitious composites have been shown to be connected to time optimization, and the figures above reveal the impact of curing time on compressive strength and CO<sub>2</sub> absorption rates. Researchers have studied the combined effect of Ca(OH)<sub>2</sub> solution immersion and CO<sub>2</sub> curing to prevent corrosion damage caused by carbonation [105]. However, they found that the strength initially increased and then decreased as the curing time progressed, regardless of saturated solution soaking Fig. 12.

A comparable trend can be observed in the increasing CO<sub>2</sub> absorption rate values. It can be seen that the mass increase of CO<sub>2</sub>-cured specimens continued at a decreasing rate throughout the entire 10 h curing period. This decrease can be attributed to the fact that the reaction rate between CO<sub>2</sub> and the calcium compounds becomes slower as more carbonation occurs, and the CO<sub>2</sub> has to diffuse deeper into the material. Furthermore, it has been found that higher CO<sub>2</sub> pressure further reduced this rate, which could be due to the densification of the material, resulting in lower permeability and reduced diffusion of CO<sub>2</sub>. Cementitious composites, a category of construction materials that includes concrete, exhibit different curing behaviors depending on the ambient environment in which they are cured. When these materials are cured in a dry ambient environment, they may experience faster initial

**Table 6**  
Compressive strength of OPC-based materials according to various curing variables.

Binder Materials	Type	Comp. Strength (MPa)	Curing conditions					Features	
			Time (d)	Temp. (°C)	Con-cent. (%)	Pres-sure	Hum-idity (%)		
OPC	Concrete [66]	3.58	3	7.11	5	Atmos-pheric	60	Cement: sand: gravel: water = 1: 3: 2.5: 0.35	
		4.56	4	10.17					
		5.37	16	16.31					
		8.69	20	24.55					
		4.96	3	9.25	20				
		5.85	4	15.75					
		8.39	16	26.77					
		9.61	20	29.42					
		6.12	3	17.57	50				
		7.99	4	22.45					
		9.77	16	31.24					
		10.07	20	32.67					
		8.39	3	25.59	99.5				
		8.57	4	26.92					
10.26	16	32.76							
10.96	20	36.73							
OPC A	Mortar[67]	10.07	0	22	99.5	0.2 MPa for 3 h	99	w/c 0.35	Air curing 5 h
		11.72	7						
		18.43	28						
OPC B		21.08	90				60		CO <sub>2</sub> curing 3 h
		10.7	0						
		11.37	7						
OPC C		12.51	28						
		14.49	90						
		15.12	0						
OPC D		17.33	7						
		19.62	28						
		20.92	90						
Belite-rich cement	Mortar[68]	10.18	0			Atmos-pheric	60	Normal curing	
		12.47	7						
		16.66	28						
		18.08	90					Carbonation curing	
		31.58	7	20	-				
		55.96	14						
		60.39	28						
		35.73	7						
		63.99	14						
		75.35	28						
		29.36	7	5					
		52.08	14						
		56.79	28						
OPC	Concrete [69]	39.34	7					OPC: Crushed aggregate: water = 1:3:0.32	
		64.82	14						
		97.51	28						
		12.8	1	23	99.5	0.1 bar	60		
		24.1	2						
		26.2	4						
		28.3	12						
		29.7	24						
		34.5	72						
		17.7	1						
24	2								
24.6	4								
26.8	12								
28.6	24								
33.1	72								
OPC	Mortar[70]	67.14	3	20	10	Atmos-pheric	60	OPC: Recycled aggregate: water = 1:3:0.55	
		54.64							
		35.71							
		28.57							
		20.36							
		72.86	7						
		72.79							
		63.57							
		54.64							
		42.5							
89.64	28								
84.64									
85									
74.64									
52.14									

(continued on next page)



Table 6 (continued)

Binder Materials	Type	Comp. Strength (MPa)	Curing conditions					Features				
			Time (d)	Temp. (°C)	Con-cent. (%)	Pres-sure	Hum-idity (%)					
Belite-rich cement		41.48	3					w/c 0.3				
		27.91						w/c 0.4				
		25.2						w/c 0.5				
		10.62	w/c 0.6									
		11.3	w/c 0.7									
		58.56	7					w/c 0.3				
		56.2						w/c 0.4				
		58.24						w/c 0.5				
		48.74	w/c 0.6									
		39.59	w/c 0.7									
		101.44	28					w/c 0.3				
		125.89						w/c 0.4				
		94.67						w/c 0.5				
		68.89						w/c 0.6				
46.15	w/c 0.7											
19.03	48	23		20	Atmos-pheric	50	Nano-TiO <sub>2</sub> 0%					
20.62			Nano-TiO <sub>2</sub> 0.5%									
21.94			Nano-TiO <sub>2</sub> 1%									
22.13			Nano-TiO <sub>2</sub> 2%									
25			Nano-TiO <sub>2</sub> 0%									
26.81			Nano-TiO <sub>2</sub> 0.5%									
26.5			Nano-TiO <sub>2</sub> 1%									
25.6			Nano-TiO <sub>2</sub> 2%									
8.85			3				20	20	Atmos-pheric	70	Carbonation 2 h	Designed void content 25.9%
11.15											Carbonation 6 h	
13.99	Carbonation 24 h											
10.23	Carbonation 2 h	Designed void content 22.3%										
13.13	Carbonation 6 h											
17	Carbonation 24 h											
5.8	Carbonation 2 h	Designed void content 18.7%										
8.7	Carbonation 6 h											
12.26	Carbonation 24 h											
9.54	Carbonation 2 h											
16.49	Carbonation 6 h											
17.92	Carbonation 24 h											
12.07	Carbonation 2 h											
15.21	Carbonation 6 h											
20.25	Carbonation 24 h											
7.7	Carbonation 2 h											
14.32	Carbonation 6 h											
16.41	Carbonation 24 h											
12.04	Carbonation 2 h											
21.22	Carbonation 6 h											
24.92	Carbonation 24 h											
12.01	Carbonation 2 h											
20.59	Carbonation 6 h											
27.4	Carbonation 24 h											
9.06	Carbonation 2 h											
16.73	Carbonation 6 h											
21.66	Carbonation 24 h											

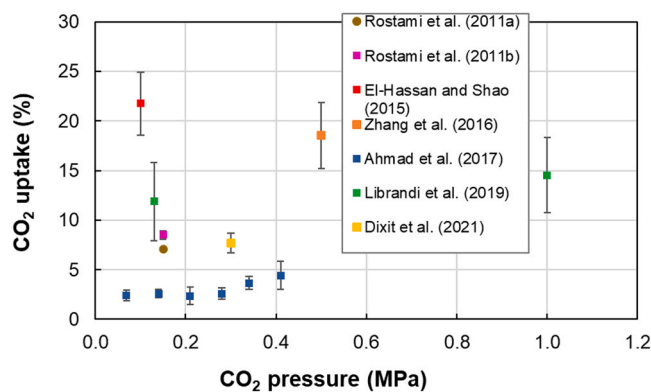


Fig. 6. Influence of CO<sub>2</sub> pressurization on the CO<sub>2</sub> absorption rate of alkali-activated cementitious materials [61,65,80,84–87].

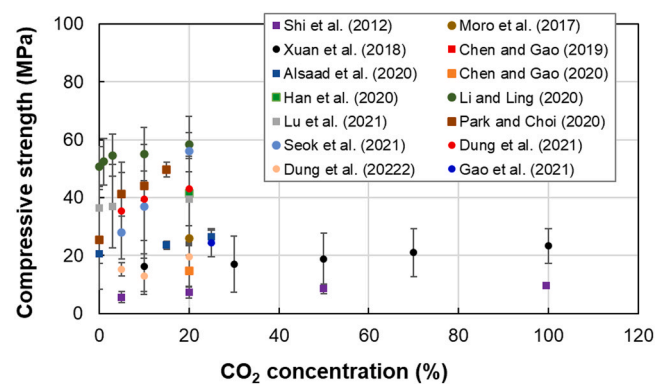


Fig. 7. Effect of CO<sub>2</sub> concentration on the compressive strength of alkali-activated cementitious materials [62,63,66,71,72,82,89–95].

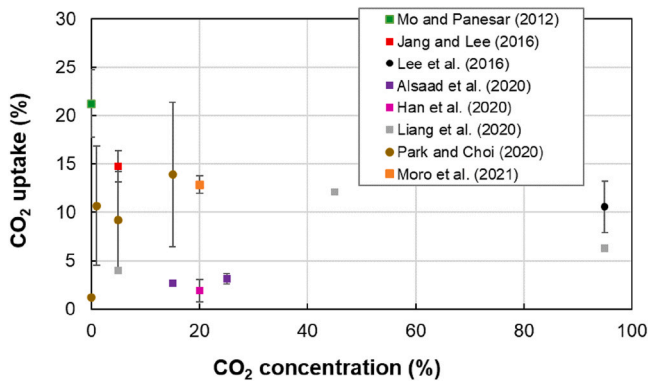


Fig. 8. Impact of CO<sub>2</sub> concentration on the CO<sub>2</sub> absorption rate of alkali-activated cementitious materials [62,68,71,82,96–99].

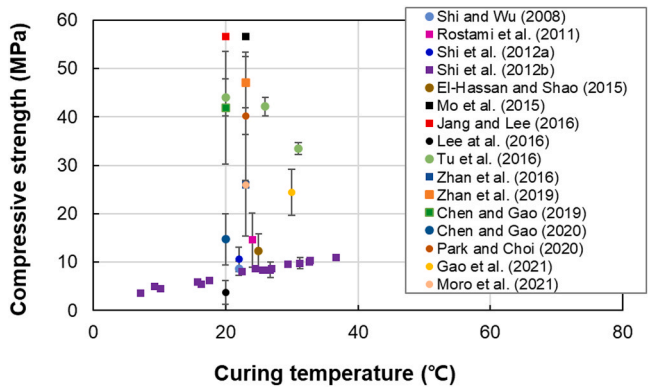


Fig. 9. Influence of curing temperature on the compressive strength of alkali-activated cementitious materials [68,69,71,72,76,78,79,84,86,90,95,96,103,104].

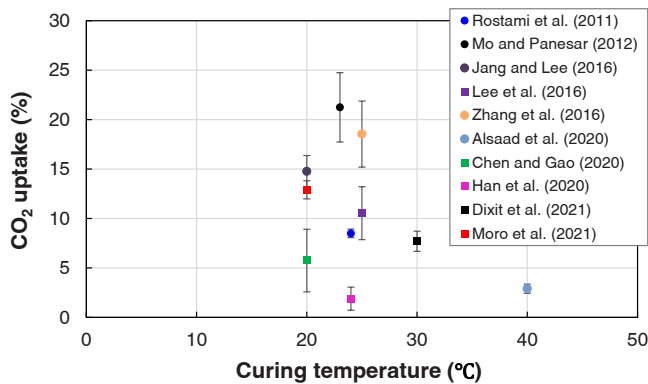


Fig. 10. Effect of curing temperature on the CO<sub>2</sub> absorption rate of alkali-activated cementitious materials [61,65,68,71,72,82,84,96,97,99].

curing. This accelerated curing is due to the rapid evaporation of water, which speeds up the hydration reactions, leading to the formation of hardened cementitious matrix more quickly. However, when concrete is cured under moist conditions, the CO<sub>2</sub> absorption rate remained stable after reaching its peak (less than 5%) during the initial carbonation (0.25 h). This observation suggests that the presence of moisture in the curing environment can significantly impact the carbonation process.

#### 4. Conclusions

In conclusion, as global efforts towards the attenuation of carbon

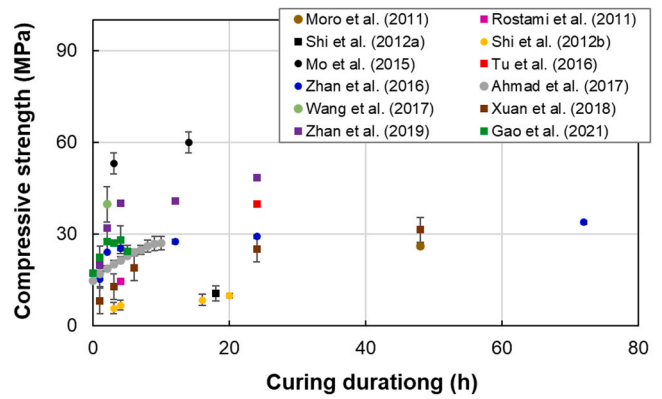


Fig. 11. Impact of curing time on the compressive strength of alkali-activated cementitious materials [10,69,71,79,80,84,89,95,103,104].

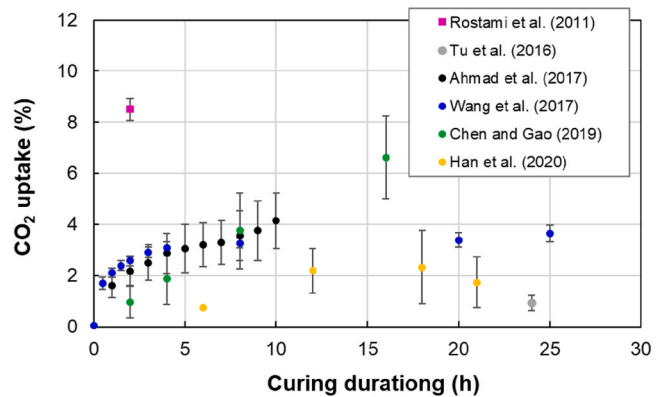


Fig. 12. Influence of curing time on the CO<sub>2</sub> absorption rate of alkali-activated cementitious materials [79–82,84,90].

emissions perpetually intensify and the doctrines of net-zero emissions and carbon neutrality emerge as increasingly salient paradigms, the adoption of a multifaceted array of strategies across the international landscape to mitigate carbon emissions is imperative. With cement production occupying a prominent position as a substantial contributor to greenhouse gas emissions worldwide, the industry has committed to the daunting challenge of attenuating emissions. This comprehensive review article meticulously investigates the implications of the intricate interplay between the constituent composition of cement and alkali-activated construction materials, as well as the influence of varying carbonation curing conditions, on the manifestation of compressive fortitude.

The analysis commences with a thorough examination of the strength properties inherent in multi-component materials predicated on the utilization of alkali-activated binding agents, followed by the identification and elucidation of the salient factors affecting the performance of cementitious materials, inclusive of Portland cement. Ultimately, the review culminates in a rigorous assessment of the compressive strength characteristics exhibited by these materials under an extensive spectrum of carbonation curing conditions, thereby contributing valuable insights to the ongoing discourse on the optimization of construction materials for sustainable development and the realization of a carbon-neutral future.

#### Declaration of Competing Interest

Please check the following as appropriate:

- o All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.
- o This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
- o The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript:

#### Data availability

Data will be made available on request.

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