



## Review

## Carbonation of cement-based materials: Challenges and opportunities



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## HIGHLIGHTS

- Carbonation kinetics of alternative binder materials requires further investigation.
- Carbonation resistance of OPC is higher than that of alternative binder materials
- Cement-based materials can be used as CO<sub>2</sub> storage systems.
- Recently developed carbonate binders are reviewed.

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## ABSTRACT

This article summarizes the existing knowledge regarding the carbonation of cement-based materials and identified the areas which require further investigations. Available studies regarding the carbonation test scenarios, influences of supplementary cementitious materials (SCMs) on carbonation resistance, and effects of carbonation on the properties of cement-based materials are reviewed here. In addition to ordinary portland cement (OPC) based materials, this article has reviewed the performances of sulfoaluminate belite and alkali activated materials (AAM) while subjected to carbonations. Some very recent topics such as the potential of CO<sub>2</sub> storage in concrete and the newly developed carbonate binders are also discussed.

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## 1. Introduction

Carbonation is one of the most well-discussed research topics in cement and concrete industry. Almost all of the cement-based materials have to undergo a certain extent of carbonation reaction during their service life due to the presence of CO<sub>2</sub> in earth's atmosphere. Conventionally, carbonation reaction of concrete is considered as an unfavorable event as it demeans the durability performances of such materials. In the case of OPC-based systems, carbonation reaction reduces the alkalinity of concrete and hence, making the reinforcement susceptible to corrosion. For alkali activated materials (AAM) and sulfoaluminate belite cements, carbonation reaction possesses a greater risk as it causes the disintegration of the binding matrix (detailed discussion are in Section 6.4.2). However, only a limited number of studies have been performed to investigate the behavior of these alternative binder matrices in the CO<sub>2</sub> bearing environment.

In last decade, research interests focusing on the beneficial aspects of carbonation of cement-based materials have been observed to be growing. Briefly, there are two major beneficial features involved in the carbonation of OPC based systems including (i) rapid strength gain of the cementitious matrix when subjected to curing in the presence of CO<sub>2</sub> (this is because the presence of CO<sub>2</sub> accelerates the reaction of calcium silicates [1]), and (ii) sequestration of CO<sub>2</sub> in concrete. Concrete is the second largest commodity (in terms of total volume of the material) consumed by any society annually after water [2,3]. Hence, if successful, concrete and other cement-based materials have the potential to be one of the largest global CO<sub>2</sub> sequestration sectors [4], leading towards possible reduced CO<sub>2</sub> footprint of the cement industry. Varieties of approaches can be followed to sequester CO<sub>2</sub> in concrete. Some of these approaches include accelerated carbonation curing, atmospheric carbonation, adding CO<sub>2</sub> with concrete mixing water, etc. Moreover, several new cementitious systems have been

developed in the last decade based on the concept of storing CO<sub>2</sub> in concrete in the stable forms of carbonates.

This paper presents a comprehensive review on the following: (i) various experimental scenarios and kinetics of carbonation of cement-based materials; (ii) influence of SCMs addition on the carbonation resistance; (iii) effects of carbonation on the properties of OPC, AAM, sulfoaluminate belite cements and their microscopic phases; and (iv) recent studies focusing on the potential of storing CO<sub>2</sub> in cement-based materials and newly developed carbonate cementitious systems. At this point, it should be acknowledged that Bertos et al. [5] presented an elaborate discussion on the carbonation of cement-based materials with the focus on the utilization of solid wastes. On the other hand, Torgal et al. [6] comprehensively reviewed the carbonation behavior of concrete containing SCMs and recycled aggregate concretes (RAC). Detail discussions on these particular topics are not included in this article.

## 2. Accelerated vs. natural carbonation

The carbonation reactions of cement-based materials occur in natural environment at a very slow rate due to the low CO<sub>2</sub> concentration in the atmosphere (400 ppm or 0.04% [7]). Usually, accelerated carbonation schemes are used in the laboratory to investigate the effects of carbonation on concrete. The carbonation rates of accelerated carbonation tests are considerably higher than those of atmospheric condition [8,9]. The higher carbonation rates are obtained by using higher CO<sub>2</sub> concentration and controlled environment (i.e., temperature, RH). Nonetheless, a wide range of variation in the accelerated curing environment can be observed in literature (Table 1). From Table 1, it can be seen that a RH within the range of 50–70% is commonly used in the experiments. This is because the carbonation reaction rate of concrete is highest within this RH range [10,11].

**Table 1**  
Accelerated carbonation curing test conditions.

Binder types	RH (%)	CO <sub>2</sub> concentration/ partial pressure	Temperature (°C)	Maximum exposure duration	References
OPC	55 ± 5	4% ± 0.5%	20 ± 2		[21]
OPC	70	20%	20		[22]
OPC	–	0.15 MPa	–	28 days	[23]
OPC (concrete with recycled aggregate)	~0	0.01 MPa	23	24 h	[24]
OPC	70	20%	23	16 weeks	[25]
OPC	65 ±	50% ± 5%	20 ± 2	42 days	[26]
OPC	35, 55, 80	40%	–	3 days	[27]
OPC	–	1.5 MPa	–	2 weeks	[14]
OPC	65	3%, 10%, 100%	22	103 days	[18]
OPC + fly ash (FA)	62	10%	25	16 weeks	[28]
OPC + FA	65 ± 5	5%	20	3 months	[29]
OPC + FA	55	4%	40	28 days	[30]
OPC + FA	65 ± 5	50 % ± 5%	20 ± 2	120 days	[31]
OPC + FA/ blast furnace slag (BFS)	65 ± 5	50 % ± 5%	20 ± 2	123 days	[32]
OPC + FA/ BFS + silica fume (SF)	50	4%	20	30 weeks	[33]
OPC + BFS	60	10%	20	24 weeks	[34]
OPC + BFS	50	3%	20	9 weeks	[35]
OPC + BFS	40 ~ 90	10%	20	21 days	[10]
OPC + PFA, GGBS, MgO, talc	70–90	20%	20	7 days	[36]
Self-compacting concrete	75 ± 5	100%	19 ~ 24	240 days	[37]
High initial strength and sulfate-resistant Portland cement (HS SR PC)	60	20%	25	24 h	[38]
White cement, OPC	70 ± 2	100%	25 ± 1	150 days	[39]
GGBFS, metakaoline (MK), alkali activated slag	50 ± 5, 65 ± 5, 80 ± 5	1.0 ~ 5%, 10–20%	25 ± 2		[20,40–43]
Alkali activated slag	70	–	–	4 months	[44]
Basic oxygen furnace (BOF) slag	0–80	0–40%	25–250		[45]
MgO	55–98	5–20%	20	7 days	[46]
MgO / GGBFS	98	99.9%	23 ± 2	56 days	[47,48,49]
Rice husk ash, hemp fiber	65 ± 5	50%	20 ± 2		[50]
Ladle slag		0.15 MPa		24 h	[51]

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