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REVIEW **Open Access**

A Concise on the Effect of Calcium Oxide on the Properties of Alkali-Activated Materials: A Manual for Civil Engineers

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Abstract

As known, calcium oxide (CaO) is an alkaline material, which can be used widely to increase the clay-containing soils load carrying capacity, to produce aerated concrete and calcium aluminate cement. In the last few years, introducing CaO into alkali-activated materials (AAMs) became a hot topic and attained more attention than other times. Generally, CaO can be incorporated into AAMs as an additive/a part of the main precursor and a sole activator without/with an auxiliary activator. Incorporating CaO into the matrices may improve some properties and worsen others. This mainly depends on the ratio of CaO, curing conditions, activator type and activator concentration, precursor type and testing age. This review collected, summarized and analyzed the available studies focused on the effect of CaO on the fresh (reaction kinetic, workability, setting time) and hardened (mechanical strength, durability and length change) properties of AAMs. In addition, some recommendations for future works were included. The results showed that the inclusion of CaO in AAMs decreased workability and setting time. In spite of there are contradictory results about the effect of CaO on the compressive strength of AAMs, most of them reported higher compressive strength, especially at the early ages. The incorporation of CaO up to 5% in the matrix is more effective than the incorporation of higher ratios. The inclusion of CaO in the matrix decreased water absorption, decreased total porosity, increased wetting/drying as well as acid attack resistivity. The CaO (5–10%) can be used as a sole activator for precursors. Auxiliary activators such as $Al_2(SO_4)_3$, Na_2CO_3, Na_2SiO_3, Na_2SO_4, $CaSO_4$, NaOH, $Ca(NO_3)_2$, $NaNO_3$, $Mg(NO_3)_2$, $Mg(HCOO)_2$, $Ca(HCOO)_2$, SO_3, gypsum and MgO can be used to enhance the compressive strength of CaO-activated materials, especially at the early ages.

Keywords Calcium oxide, Alkali-activated material, Fresh properties, Hardened properties

1 Introduction

As known, Portland cement (PC) is still the main binder for paste, mortar and concrete production. The current production of cement is around 4.6 billion tonnes/year, and it is anticipated to reach around 5.5 and 6 billion tonnes by the end of 2025 (Hilburg, 2020) and 2050 (Singh & Subramaniam, 2019), respectively. Unfortunately, the cement industry is one of the largest air polluting industries, since a huge amount of hazardous gases such as sulfur dioxide, particulate matter, nitrogen oxide and carbon dioxide are released during production. This industry is responsible for releasing about 8% of global carbon dioxide emissions (Tang et al., 2022). It consumes a huge amount of thermal and electrical energy (around 4427 MJ/tonne) (Singh & Subramaniam, 2019) (Abriyantoro et al., 2019), of which around 12–15% of the total energy consumed in industries is consumed by the cement industry (Madlool et al., 2011) (Hossain et al., 2017). The production of cement not only consumes a

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huge amount of energy but also consumes a huge amount of virgin raw materials, of which around 1.5 tonnes of virgin raw materials are required to produce 1 tonne of cement (Rashad, 2014). This means that the cement industry may cause a depletion of natural raw materials. In order to minimize these problems, it is required to use sustainable construction materials blended with cement such as slag (Rashad, 2018a), fly ash (FA) (Rashad, 2015a), metakaolin (MK) (Rashad, 2013a) and pumice (Rashad, 2020a). However, a significant reduction in the negative effect of cement production can be further attained by using the third generation of binder (geopolymer).

Alkali-activated materials (AAMs) or geopolymers are favourable cementitious materials in light of their low energy consumption, CO_2 emissions, superior durability and mechanical strength in comparison with PC (Alsalman et al., 2021) (Rashad, 2019a). AAM is based on an inorganic aluminosilicate polymer. It can be synthesized by activating the industrial by-product materials derived from various activities such as slag (Rashad, 2013b) and FA (Rashad, 2014) in addition to natural materials such as kaolin (after calcination) (Rashad, 2013c) and pumice (Rashad, 2020a). All these materials are rich in aluminosilicate. Since the first manufacture of AAM, the developments and improvements of its properties have been continued. The strategies of the current studies are not to search for new binders, but to look for how to improve the properties of AAMs. For this reason, different methods were proposed to enhance the properties of AAMs such as increasing precursor fineness, adding chemical admixtures, adding nanoparticles (Rashad, 2019b), adding fibers (Rashad, 2018b) (Rashad, 2019c) (Rashad, 2020b) and cementitious materials (Rashad, 2014) (Rashad, 2013b) (Rashad, 2013c) (Rashad, 2022a) (Rashad, 2023). The former method is the most widely used due to the variety and availability of these materials such as silica fume (SF), limestone powder, $Ca(OH)_2$, CaO,…etc.

Calcium oxide (CaO), commonly known as burnt lime, quicklime or pebble lime, which can be produced by heating limestone powder at a temperature higher than 825 °C (Greenstein, 2007). This heating process produces CaO and CO_2 as follows:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

CaO shows white colour (Fig. 1) and a cubic crystal structure with a slight earthy odour. It is an alkaline material. Its apparent density is below 1.4 g/cc and may reach 3.2 g/cc, whilst its bulk density is in the range of 900–1200 kg/m^3. Most of CaO products have a hardness in the range of 2–3 Mohs, whilst those produced from burned dolomite is in the range of 3–5 Mohs. Its specific heat at 20 °C, thermal conductivity, coefficient of thermal expansion, melting point and electrical resistivity is 0.182 cal/g °C, 0.0015–0.002 cal/cm^2.sec.°C, 140×10^{-7}, 2580 °C and 71×10^{8} at 15 °C, respectively (Oates, 2008) (Oates, 2000) (Boynton, 1980). The main use of CaO is in the basic oxygen steelmaking process (Oates, 2008) (Rashad, 2022b). It can neutralize the acidic oxides such as Al_2O_3, Fe_2O_3 and SiO_2 to produce a basic molten slag. It can be used to increase the clay-containing soils load carrying capacity, to produce aerated concrete blocks as well as the production of organic chemicals, calcium aluminate cement and glass (Oates, 2000) (Boynton, 1980). It can be used with $Ca(OH)_2$ for thermochemical energy storage systems (Wang et al., 2022). Recently, CaO is incorporated into AAMs as a cementitious material, solely activator or a part of activator aiming to improve their properties. In this article, the scattered available studies focused on the effect of CaO on the properties of AAMs were collected, summarized and analyzed. In addition to using CaO as an activator or a part of the activator. Fig. 2 shows the main schedule of this review.

Fig. 1 General view of CaO

2 CaO as an Additive/a Part of a Precursor

2.1 Reaction Kinetic, Workability and Setting Time

Ju et al., (2020) found higher heat release of AAS mortars activated by KOH and K_2SiO_3 solution with the incorporation of 1% and 3% CaO. After 7 h of hydration, the incorporation of 1% and 3% CaO increased the cumulative heat by 3.2% and 14.48%, respectively, whilst after 24 h of hydration, the cumulative heat was increased by 2.9% and 14.48%, respectively. After 72 h of hydration, the growth rate was 1.3% and 5.7% with the incorporation of 1% and 3% CaO, respectively. Chen and Ye, (2022) found 40.72% and 55.64% reduction in the slump flow of AAS paste mixtures activated with sodium carbonate by partially replacing slag with 2.5% and 5% CaO, respectively. Rashad and Gharieb, (2021) proved that carbonation beet residue resulting from the sugar beet industry is CaO after calcination (CCR). Thus, herein, CaO is used

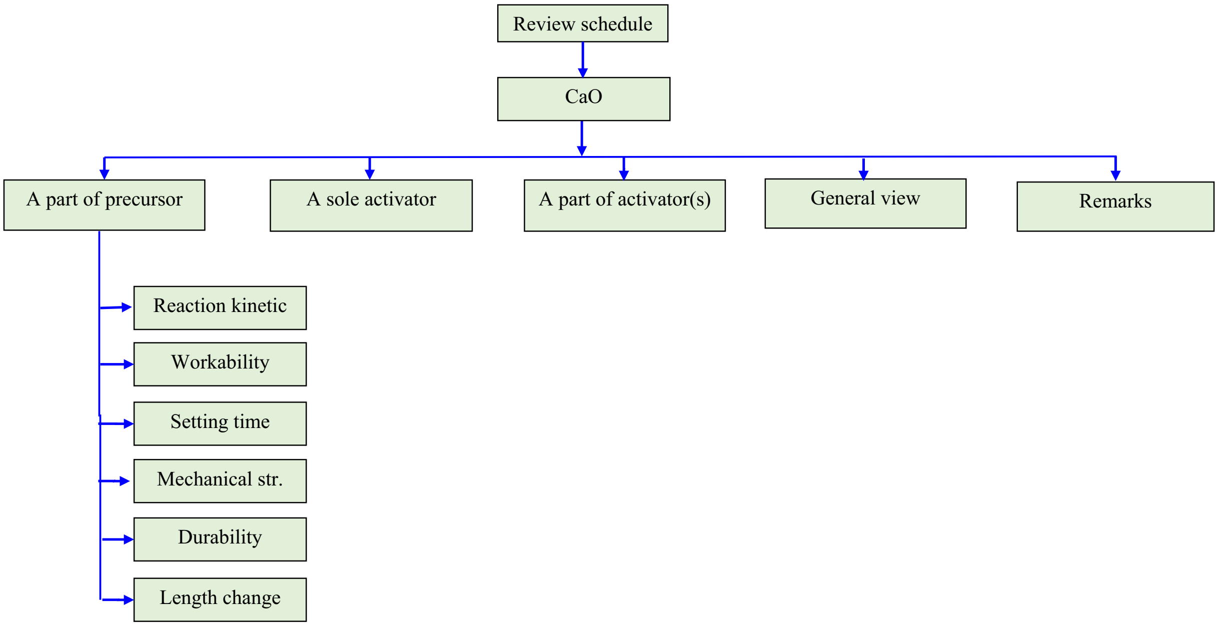

Fig. 2 Overall schedule of the review

instead of CCR. They prepared FA geopolymer paste mixtures activated with NaOH and sodium silicate solution. The FA was partially replaced with 2.5–10% CaO. The results showed 15.8%, 26.3%, 36.84% and 47.37% reduction in the flow with the incorporation 2.5%, 5%, 7.5% and 10% CaO, respectively. They also fund a huge reduction in the setting time, of which the initial setting time was reduced from 1440 min (for the control) to 17, 15, 10 and 6 min with the incorporation of 2.5%, 5%, 7.5% and 10% CaO, respectively, whilst the final setting time was reduced from 1800 min (for the control) to 17, 30, 20 and 11 min, respectively. In a similar study, Gharieb and Rashad, (2022) found 6.49%, 16.22%, 24.32% and 44.6% reduction in the flow of alkali-activated slag (AAS) paste mixtures activated with NaOH and sodium silicate solution by partially replacing slag with 2.5%, 5%, 10% and 15% CaO extracted from sugar beet industry waste after calcination, respectively. The incorporation of these ratios of CaO decreased the initial setting time by 10.29%, 19.12%, 27.94% and 35.29%, respectively, whilst the final setting time was reduced by 7.12%, 10.97%, 14.63% and 21.95%, respectively.

Chen and Ye, (2022) found a reduction in the initial and final setting times of AAS pastes activated with sodium carbonate by partially replacing slag with 2.5% and 5% CaO. The period of the initial and final setting time was shortened from > 3 days for the control to 610 and 828 min with the incorporation of 2.5% CaO, respectively, whilst the initial and final setting time reached 73 and 123 min with the incorporation of 5% CaO, respectively. Ju et al., (2020) found a shorter setting time of AAS mortars activated with KOH and K_2SiO_3 cured at different temperatures with the incorporation of 1–4% CaO. As the amount of CaO increased as the setting time became shorter. For the specimens cured at 20 °C, the incorporation of 4% CaO decreased the setting time from 20 min (for the control) to 8 min, with a reduction rate of 60%. For the specimens cured at − 10 °C, the incorporation of 4% CaO decreased the setting time from 32 min (for the control) to 12 min, with a reduced rate of 62.5% (Fig. 3). Chindaprasirt et al. (2018) found shorter initial and final setting time of FA geopolymer pastes activated with NaOH and sodium silicate solution by

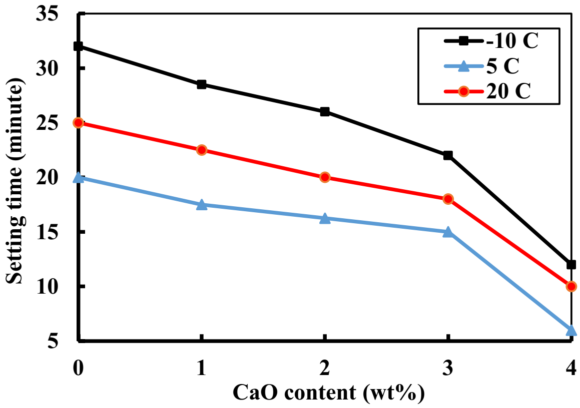

Fig. 3 Effect of different ratios CaO on setting time of AAS mortar mixtures (Ju et al., 2020)

partially replacing FA with 5–15% CaO. As the amount of CaO increased as the setting time became shorter. The incorporation of 5–15% CaO decreased the initial setting time from 30 min (for the control) to 19–5 min, with a reduced rate of 36.67–83.3%, whilst the final setting time was decreased from 58 min (for the control) to 26–8 min, with a reduced rate of 55.17–86.2%. Lee and Deventer, (2002) reported that the addition of 0.08764 mol of CaO into FA/kaolinite geopolymer pastes activated with KOH and sodium silicate solution shortened the final setting time from 67 to 49 min, with a reduced rate of 26.9%. Table 1 summarizes the effect of CaO on the reaction kinetics, workability and setting time of AAMs.

From the above discussions, it can be noted that there are too limited studies focused on the hydration heat, workability and setting time of AAMs containing CaO. However, according to the available studies, the incorporation of CaO accelerated the hydration, of which when CaO is mixed with water, $Ca(OH)_2$ can be formed, a large amount of heat can be released and the reaction between Ca^{2+} and $[SiO_4]^{4-}$ can be promoted (Ju et al., 2020). Because the incorporation of CaO in the matrix accelerated the hydration, the workability and setting time were decreased. Rashad and Gharieb, (2021) related the reduction in the workability due to the higher dissolution of aluminosilicate during geopolymerization process with the higher alkalinity of the mixture caused by CaO. This process is associated with a shortage of water in the alkaline mixture. Gharieb and Rashad, (2022) related this reduction to the increased calcium amount which accelerated the reaction. However, the reduction in the setting time could be attributed to the heat released during mixing CaO with water as well as the higher alkalinity of the matrix due to the formation of $Ca(OH)_2$ (Ju et al., 2020).

2.2 Mechanical Strength

Ju et al., (2020) partially replaced slag in AAS mortars activated with KOH and K_2SiO_3 solution with 1–3% CaO. The specimens were cured at -10, 5 and 20 °C. The results showed higher 1, 7 and 28 days compressive strength and flexural strength with the incorporation of CaO at all curing conditions. As the ratio of CaO increased as the strength increased. For the specimens cured at 20 °C, the incorporation of 3% CaO increased the 1, 7 and 28 days compressive strength by 15%, ~ 6.25% and 6.1%, respectively, whilst the flexural strength was enhanced by 19% and 5.5%, respectively. For the specimens cured at 5 °C, the incorporation of 3% CaO increased the 1, 7 and 28 days compressive strength by 18.6%, 13% and 5.2%, respectively, whilst the flexural strength was enhanced by 31.5%, 9.5% and 7.1%, respectively. For the specimens cured at − 10 °C, the incorporation of 3% CaO increased the 1, 7 and 28 days compressive strength by 40%, 14% and 5%, respectively, whilst the flexural strength was enhanced by 48%, 11% and 7%, respectively. Chen and Ye, (2022) found higher compressive strength of AAS pastes activated with sodium carbonate at the ages of 1–56 days by partially replacing slag with 2.5% and 5% CaO. The CaO has a significant effect on the early age compressive strength compared to the later ages. Gharieb and Rashad, (2022) reported that the 7, 28, 56 and 90 days compressive strength of AAS pasted activated with NaOH and sodium silicate solution cured at room temperature was enhanced by 20.53%, 17.74%, 10.17% and 8.79% with the incorporation of 2.5% CaO extracted from sugar beet industry waste after calcination, respectively, whilst the incorporation of 5% CaO increased it by 36.61%, 30.21%, 17.82% and 15.95%, respectively. The incorporation of 10% CaO increased the 7, 28, 56 and 90 days compressive strength by 19.23%, 13.28%, 3.4% and 2.24%, respectively, whilst the incorporation of 15% CaO decreased it by 45%, 40.9%, 44.1% and 42.4%, respectively. They related this reduction to excessive alkalinity and the formation of porous microstructure.

Rashad and Gharieb, (2021) found 141.67%, 8.33% and 3.51% enhancement in the 7, 28 and 90 days compressive strength of FA geopolymer pastes activated with NaOH and sodium silicate solution cured in

Table 1 Effect of CaO on the reaction kinetics, workability and setting time of AAMs

Reference	Precursor	Activator	CaO (%)	Type	Effect
Ju et al., (2020)	Slag	KOH and K_2SiO_3	1–3	Mortar	-Increased heat release
Chen and Ye, (2022)	Slag	sodium carbonate	2.5 and 5	Paste	-Decreased workability
Rashad and Gharieb, (2021)	FA	NaOH and sodium silicate	2.5–10	Paste	-Decreased workability and setting time
Gharieb and Rashad, (2022)	Slag	NaOH and sodium silicate	2.5, 5 and 10	Paste	-Decreased workability and setting time
Chen and Ye, (2022)	Slag	sodium carbonate	2.5 and 5	Paste	-Decreased setting time
Ju et al., (2020)	Slag	KOH and K_2SiO_3	1–4	Mortar	-Decreased setting time
Temuujin et al., (2009)	FA	NaOH and sodium silicate	1, 2 and 3	Paste	-Decreased setting time
Lee and Deventer, (2002)	FA/kaolinite	KOH and sodium silicate	0.08764 mol	Paste	-Decreased setting time

room temperature with the incorporation of 2.5% CaO extracted from sugar beet industry waste after calcination, respectively, whilst the incorporation of 5% CaO increased it by 173.88%, 17.14% and 7.9%, respectively. The incorporation of 7.5% CaO increased the 7, 28 and 90 days compressive strength by 199%, 22.61% and 12.3%, respectively (Fig. 4). Chindaprasirt et al., (2018) partially replaced FA in FA geopolymer pastes activated with NaOH and sodium silicate solution with 5–15% CaO. The specimens were cured at ambient temperature. The incorporation of 5%, 10% and 15% CaO decreased the 7 days compressive strength by ~ 17%, 69.8% and 76.3%, respectively, whilst the 28 days compressive strength was decreased by ~ 29.4%, 73.9% and 76.95%, respectively. Temuujin et al., (2009) partially replaced FA in FA geopolymer pastes activated with NaOH and sodium silicate solution with 1–3% CaO. The specimens were cured at either 20 °C or 70 °C for 24 h. The results showed higher 7 days compressive strength with the incorporation of CaO for the specimens cured at 20 °C, whilst the incorporation of CaO decreased it for the specimens cured at 70 °C. For the specimens cured at 20 °C, the incorporation of 1%, 2% and 3% CaO increased the 7 days compressive strength by ~ 74%, 82.6% and 95.6%, respectively. For the specimens cured at 70 °C, the incorporation of 1%, 2% and 3% CaO decreased the 7 days compressive strength by ~ 51.7%, 43.4% and 42.2%, respectively. Nguyen et al., (2017) added 2–15% CaO into FA geopolymer mortars activated with NaOH and sodium silicate solution. Natural curing (28 ± 2 °C) was used. The addition of 2–9% CaO increased the compressive strength, whilst the addition of 10% and 15% CaO decreased it. The addition of 5% increased the strength at the ages of 28 and 60 days by 45% and 15%, respectively. The order of increasing strength is 4% CaO > 3% > 5% > 2% > 6% > 7% > 8% > 9%.

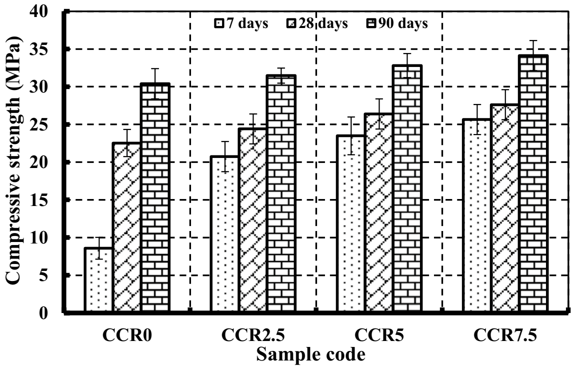

Fig. 4 Effect of different ratios of CaO extracted from sugar beet industry waste after calcination on the compressive strength of FA geopolymer pastes (Rashad & Gharieb, 2021)

Lee and Deventer, (2002) reported that the addition of 0.08764 mol of CaO into FA/kaolinite geopolymer pastes activated with KOH and sodium silicate solution cured at 40 °C for 24 h, then at 20–25 °C increased the 7 days compressive strength by ~ 63.9%. Matalkah et al., (2020) added 5–20% CaO into calcined kaolin geopolymer mortars activated with sodium silicate. The specimens were cured in sealed condition at room temperature. The results showed higher 7 days compressive strength with the incorporation of CaO. The 7 days compressive strength increased with increasing CaO up to 10%, then started to decrease with the incorporation of 15% and 20% CaO, but still higher than the control. Dişçi and Polat, (2022) prepared perlite geopolymer concretes activated with NaOH and anhydrous sodium silicate. The specimens were cured at 90 °C for 72 h, then at ambient temperature. The results showed that the incorporation of 1%, 2% and 3% CaO in nano size decreased the 3–120 days compressive strength. The incorporation of 1%, 2% and 3% nano-CaO decreased the 3 days compressive strength by 12.17%, 15.96% and 28.1%, respectively, whilst the 28 days compressive strength was decreased by 7%, 15.36% and 0.4%, respectively. The 120 days compressive strength was decreased by 27.9%, 14.11% and 17.5% with the incorporation of 1%, 2% and 3% nano-CaO, respectively. They found 10.46% enhancement in the flexural strength at the age of 90 days with the incorporation of 1% nano-CaO, whilst 2% and 3% nano-CaO decreased it by 15.54% and 14.95%, respectively. Table 2 summarizes the effect of CaO on the mechanical strength of AAMs.

From the above discussions, it can be noted that there are contradictory results about the effect of CaO on the compressive strength of AAMs (Fig. 5). The variation of the results mainly depends on the ratio of CaO, precursor type, curing conditions, activator type, activator concentration and testing age. In spite of this variation in the results, it was agreed that the CaO has a higher effect on compressive strength at the early ages than at later ages. From the results plotted in Fig. 5, it can be seen that the incorporation of 5% CaO may show the optimum ratio for compressive strength. However, in the case of increasing compressive strength with the incorporation of CaO, Ju et al., (2020) related this enhancement to the heat released during mixing CaO with water, which can promote hydration. At the same time, $Ca(OH)_2$ can be formed during the interaction between CaO and water, which can generate C–S–H. In such a way, Nguyen et al., (2017) related this enhancement to the released heat energy during the reaction between CaO and water to produce $Ca(OH)_2$. This heat can accelerate the

Table 2 Effect of CaO on the mechanical strength of AAMs

Reference	Precursor	Activator	CaO (%)	Type	Curing condition	Age (day)	Effect
Ju et al., (2020)	Slag	KOH and K_2SiO_3	1–3	Mortar	-10, 5 and 20 °C	1, 7 and 28	-Increased compressive and flexural strengths
Chen and Ye, (2022)	Slag	sodium carbonate	2.5 and 5	Paste	NA	1–56	-Increased compressive strength
[Calcined beet slag, 2022] Gharieb and Rashad, (2022)	Slag	NaOH and sodium silicate	2.5, 5 and 10	Paste	Room	7–90	-Increased compressive strength
	Slag	NaOH and sodium silicate	15	Paste	Room	7–90	-Decreased compressive strength
Rashad and Gharieb, (2021)	FA	NaOH and sodium silicate	2.5, 5 and 7.5	Paste	Room	7–90	-Increased compressive strength
Chindaprasirt et al., (2018)	FA	NaOH and sodium silicate	5, 10 and 15	Paste	Room	7 and 28	-Decreased compressive strength
Temuujin et al., (2009)	FA	NaOH and sodium silicate	1, 2 and 3	Paste	20	7	-Increased compressive strength
	FA	NaOH and sodium silicate	1, 2 and 3	Paste	70 for 24 h	7	-Decreased compressive strength
(Nguyen et al., 2017)	FA	NaOH and sodium silicate	2–9	Mortar	28 ± 2	28 and 60	-Increased compressive strength
	FA	NaOH and sodium silicate	10 and 15	Mortar	28 ± 2	28 and 60	-Decreased compressive strength
Lee and Deventer, (2002)	FA/kaolinite	KOH and sodium silicate	0.08764 mol	Paste	40 for 24 h	7	-Increased compressive strength
Matalkah et al., (2020)	Calcined kaolin	Sodium silicate	5–20%	Paste	Sealed -room	7	-Increased compressive strength
Dişçi and Polat, (2022)	Perlite	NaOH and anhydrous sodium silicate	1, 2 and 3	Concrete	90 °C for 72 h	3–120	-Decreased compressive strength -1% increased 90 days flexural strength

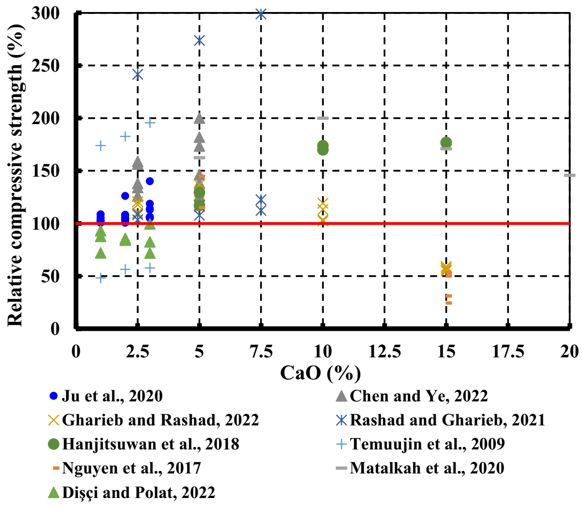

Fig. 5 Variation in compressive strength with the different ratios of CaO (Ju et al., 2020) (Chen & Ye, 2022) (Rashad & Gharieb, 2021) (Gharieb & Rashad, 2022) (Chindaprasirt et al., 2018) (Temuujin, 2009) (Nguyen et al., 2017) (Matalkah et al., 2020) (Dişçi & Polat, 2022)

geopolymerization process. The formed $Ca(OH)_2$ can increase the pH value of the geopolymer, which has a positive effect in breaking and dissolving Si and Al atoms ($CaO + H_2O \rightarrow Ca(OH)_2 + \Delta$ Hr, Hr = − 63.7 kJ/mol of CaO). It has been confirmed that the incorporation of CaO in the matrix increased its pH value (Chen & Ye, 2022). Matalkah et al., (2020) related the enhancement in the compressive strength of calcined kaolin geopolymer mortars with the incorporation of CaO to the reaction between CaO and silica in the alkaline activator or/and calcined kaolin, which formed C–A–S–H gel. The formation of this gel can reduce water in the alkaline medium resulted in higher alkalinity, which enhanced the dissolution of Al and Si. On the other hand, including higher ratios of CaO dropped the compressive strength due to $Na_2O–CaO–SiO_2–Al_2O_3–H_2O$ gel destabilizing through C–A–S–H formation. In the case of decreasing compressive strength with the incorporation of CaO, Hanjitsuwan et al. (Chindaprasirt et al., 2018) related this negative effect to the speed setting which led to poor formwork as well as the released heat during CaO hydration that caused expansion. Some studies related this reduction to heat curing, of which Temuujin et al. (Temuujin

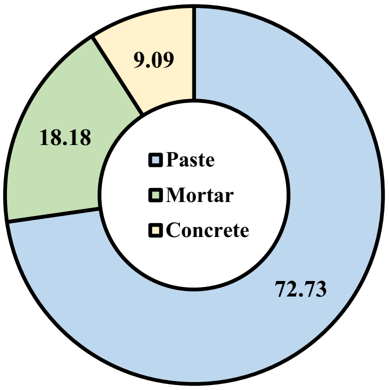

Fig. 6 Relative study number of different matrices for mechanical strength

et al., 2009) related this reduction to the higher porosity caused by evaporation of water due to heat curing even though heat curing accelerated the dissolution of the aluminosilicate and polymerization reaction. In the same trend, Dişçi and Polat, (2022) related this reduction to heat curing. The incorporation of CaO can generate C–S–H gel jointed to N–A–S–H gel. In heat curing, C–S–H has lower strength than N–A–S–H. It is important to note that, as indicated in Fig. 6, the majority of the mentioned studies (about 72.73%) focused on pastes, whilst those focused on mortars and concretes came in the second (about 18.18%) and third (about 9.09%) place, respectively.

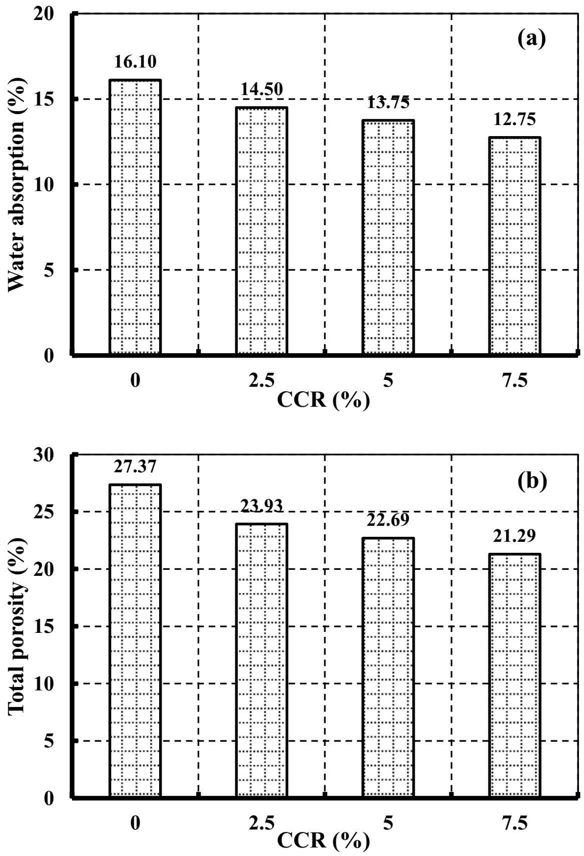

Fig. 7 Effect of different ratios of CaO extracted from sugar beet industry waste after calcination on water absorption **a** and total porosity **b** of FA geopolymer pastes (Rashad & Gharieb, 2021)

2.3 Durability and Length Change

Ju et al., (2020) found 34.5% and 41.6% reduction in the 7 days total porosity of AAS mortars activated by KOH and K_2SiO_3 solution cured at 20 °C and − 10 °C with the incorporation of 3% CaO, respectively. Rashad and Gharieb, (2021) found 9.94%, 14.6% and 20.81% reduction in the 28 days water absorption of FA geopolymer pastes activated by NaOH and sodium silicate solution cured at room temperature with the incorporation of 2.5%, 5% and 7.5% CaO extracted from sugar beet industry waste after calcination, respectively, whilst the total porosity was reduced by 12.57%, 17.1% and 22.2%, respectively (Fig. 7). Temuujin et al., (2009) reported that partially replacing FA in FA geopolymer pastes activated by NaOH and sodium silicate solution with 1%, 2% and 3% CaO increased the apparent porosity from 5.2% (for the control) to 9.2%, 8.4% and 10.4%, respectively, for the specimens cured at 20 °C. For the specimens cured at 70 °C for 24 h, the incorporation of 1% and 2% CaO decreased the apparent porosity from 16.1% (for the control) to 15.4% and 15.2%, respectively, whilst the incorporation of 3% CaO increased it to 16.4%. Chen and Ye, (2022) found higher chloride binding capacity and lower chloride diffusivity of AAS pastes activated with sodium carbonate by partially replacing slag with 2.5% and 5% CaO, The results revealed that the incorporation of 5% CaO was more effective than 2.5% CaO. Gharieb and Rashad, (2022) exposed AAS pastes containing 2.5%, 5% and 10% CaO extracted from sugar beet industry waste after calcination to two types of wetting/drying cycles. The first one, immersing the specimens in water at 20 °C for 24 h followed by drying in the lab air for 24 h. The second one, immersing the specimens in water at 20 °C for 24 h followed by drying at 55 °C for 22 h and cooling in the air lab for 2 h. For each type, 10 cycles were performed. The results showed that the specimens containing 5% CaO showed the highest compressive strength after cycles followed by those containing 2.5%, 10% and 0%, respectively. They also exposed other specimens to HCl for 90 days, the results showed that the specimens containing CaO are less affected by the deterioration of acid attack compared to the control even though they have a higher calcium ratio than the control. They also exposed other specimens to wetting in 5% Na_2SO_4 for 15 h followed by drying at 80 °C for 6 h and cooling for 2 h. The specimens were exposed to 90 and 120 cycles. After exposure to 120 cycles, the specimens containing 5% CaO showed the highest compressive strength followed by those containing 2.5%, 10% and 0%, respectively. Zheng et al., (2021) found lower autogenous shrinkage up to 252 days of AAS mortars activated by NaOH cured at 20 ± 0.3 °C with the incorporation of 3–12% CaO. After 252 days, the incorporation of 3%, 6%, 9% and 12% CaO decreased the drying shrinkage by 14.67%, 27.92%, 39.49% and 50.53%, respectively. On the other hand, Dişçi and Polat, (2022) reported that the incorporation of 1–3% nano-CaO into perlite geopolymer concrete specimens activated with NaOH and anhydrous sodium silicate increased their length change. The length change increased with increasing the nano-CaO ratio. The incorporation of 1% nano-CaO increased the expansion of the specimens, whilst the incorporation of 2% and 3% nano-CaO showed different changes as shrinkage–expansion-shrinkage during 80 days of length change. They related this negative effect of CaO to its nano size which has more fineness with a high surface area. Table 3 summarizes the effect of CaO on the durability and length change of AAMs.

From the above discussions, it can be noted that there are too limited studies focused on the durability and length change of AAMs containing CaO. However, according to the available data, the incorporation of suitable ratios of CaO in AAMs increased durability. The incorporation of 3–5% CaO seems to be the optimum ratios. The total porosity and water absorption can be decreased with the incorporation of CaO, whilst the resistivity of the specimens against wetting/drying cycles and acid attack can be increased with the incorporation of CaO. The higher durability of the matrix with the incorporation of CaO could be related to the accelerated and more hydration products caused by CaO that can reduce the micropores (Fig. 8) (Ju et al., 2020), the denser and more compact microstructure with the inclusion of CaO that can act as a barrier against the diffusion of harmful materials (Gharieb & Rashad, 2022), the ability of CaO to promote hydration process and packing effect (Rashad & Gharieb, 2021). In the literature, there is only one study that confirmed lower autogenous shrinkage of AAS mortars with the inclusion of 3–12% CaO. This reduction could be related to the increased C–S–H (II) (high stiffness) and the decreased C–S–H (I) (low stiffness) with the inclusion of CaO. The incorporation of CaO can inhibit the increase of polymerization degree of C–A–S–H, C–S–H (I) arrangement and micropores closure resulted in lower autogenous shrinkage (Zheng et al., 2021).

3 CaO as an Activator/a Part of Activator

3.1 CaO as a Sole Activator

Yum et al., (2019) activated slag pastes with 4% CaO. The specimens were cured at 23 °C with 99% RH. The obtained 3, 7 and 28 days compressive strength was 7.15, 16.25 and 27.5 MPa, respectively, whilst the 3 and 28 days porosity was 39.45% and 38.51%, respectively. The obtained flowability, initial setting time and final setting time was 16.5 mm, 540 min and 1140 min, respectively. In a similar investigation, Yum et al., (2020) found similar compressive strength for slag pastes activated with 4% CaO. The 28 days total porosity was 36.8%. Kolhe et al., (2022) used 4–16% thermal treated calcium carbide residue as a source of CaO to activated slag pastes. The specimens were cured in limewater at 23 ± 2 °C with 65% RH. The results showed a reduction in the flowability

Table 3 Effect of CaO on the durability and length change of AAMs

Reference	Precursor	Activator	CaO (%)	Type	Curing condition	Effect
Ju et al., (2020)	Slag	KOH and K_2SiO_3	3	Mortar	-10 and 20 °C	-Decreased total porosity
Rashad and Gharieb, (2021)	FA	NaOH and sodium silicate	2.5, 5 and 7.5	Paste	Room	-Decreased water absorption and total porosity
Temuujin et al., (2009)	FA	NaOH and sodium silicate	1, 2 and 3	Paste	20	-Increased apparent porosity
	FA	NaOH and sodium silicate	1 and 2	Paste	70 for 24 h	-Increased apparent porosity
	FA	NaOH and sodium silicate	3	Paste	70 for 24 h	-Decreased apparent porosity
Chen and Ye, (2022)	Slag	sodium carbonate	2.5 and 5	Paste	NA	-Decreased chloride diffusion
Gharieb and Rashad, (2022)	Slag	NaOH and sodium silicate	2.5, 5 and 10	Paste	Room	-Increased resistivity of wetting/drying cycles and acid resistance
Zheng et al., (2021)	Slag	NaOH	3–12	Mortar	20 ± 0.3	-Decreased autogenous shrinkage
Dişçi and Polat, (2022)	Perlite	NaOH and anhydrous sodium silicate	1, 2 and 3	Concrete	90 °C for 72 h	-Increased length change

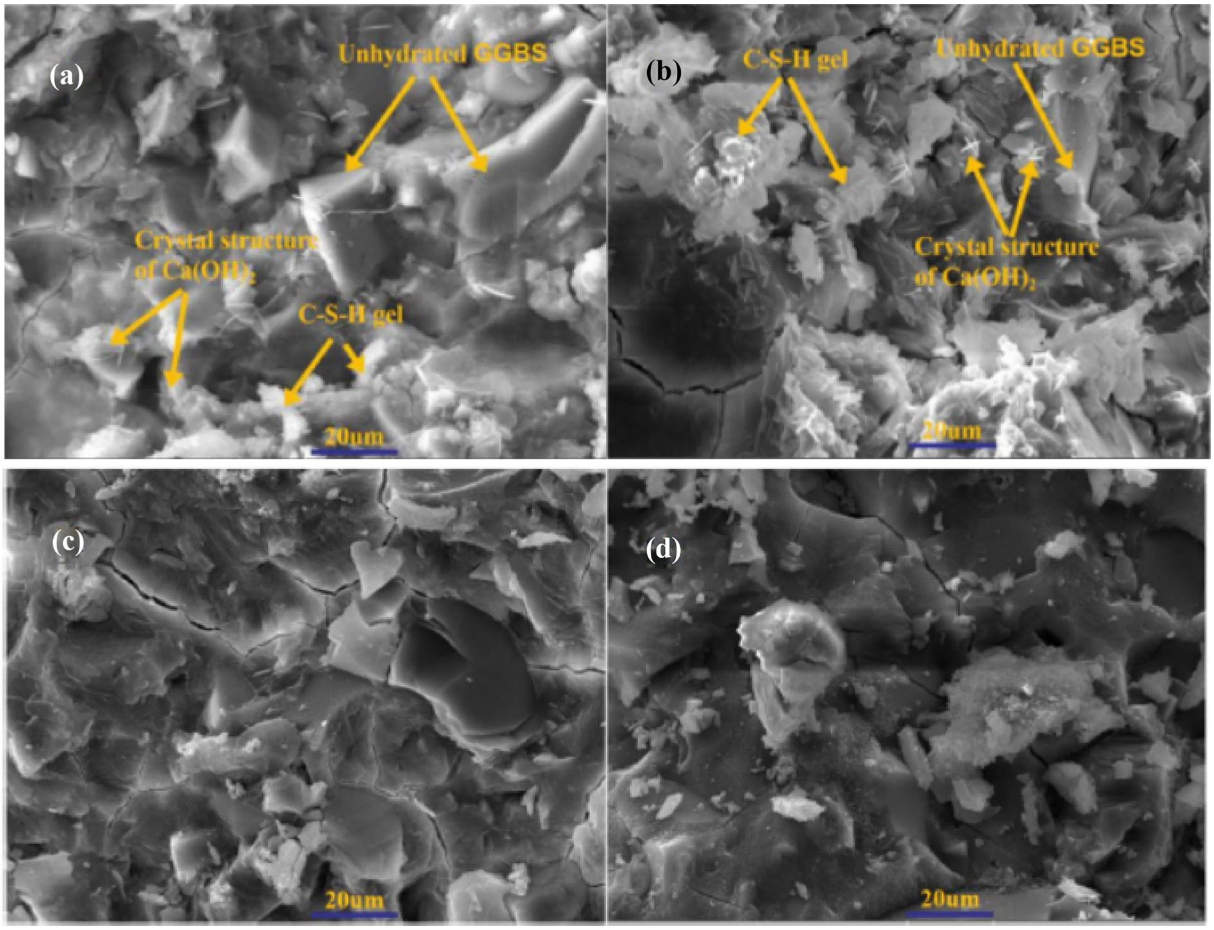

Fig. 8 SEM images at the age of 7 days for AAS mortar samples cued at − 10 (**a**), AAS + 3% CaO cured at − 10 °C (**b**), AAS cured at 20 °C (**c**), AAS + 3% CaO cured at 20 °C (**d**) (Ju et al., 2020)

with increasing activator concentration. The flow of the mixtures activated with 4% and 16% activator concentration showed 138.8% and 72.5% flow, respectively. Increasing activator concentration led to shortening the setting time. The obtained compressive strength at the age of 28 days was 17.97, 23.89, 28.1 and 24.13 MPa when the activator concentration was 4%, 8%, 12% and 16%, respectively. The obtained thermal conductivity was 0.678–0.783 W/mK when 4% activator concentration was used, whilst it was 0.696 to 0.799 W/mK, 0.752 to 0.862 W/mK and 0.66 to 0.841 W/mK when 8%, 12% and 16% concentration of activator was used, respectively. Park et al., (2016a) activated slag pastes with 5% CaO. The specimens were cured at 23 °C with 99% RH until testing date. The obtained 7 and 28 days compressive strength was ~ 20.5 and ~ 39 MPa, respectively. Dahal et al., (2023) activated slag with 5% CaO to prepare ultra-high-performance concrete (UHPC). The specimens were cured at 23 °C with 99% RH for 24 h, then, at 90 °C for 48 h. The mixture showed 265% flow. The obtained compressive strength was 110 MPa, whilst the tensile strength was 9 MPa. In a similar investigation, Oinam et al., (2023) obtained ~ 180 MPa compressive strength and ~ 12.75 MPa tensile strength of UHPC prepared with slag/SF activated with 5% CaO, from slag weight.

Burciaga-Díaz et al., (2023) activated slag pastes with 6% CaO. Some specimens were cured at 20 ± 2 °C with 80% RH for 90 days, whilst the other were cured at 60 °C for 24 h, then at 20 °C up to 90 days. The obtained 1, 3, 7, 14, 28 and 90 days compressive strength was ~ 0, ~ 3.75, ~ 8.5, ~ 17.5, 20 MPa for ambient curing, respectively, whilst it was ~ 5, ~ 5, ~ 5.5, ~ 7, ~ 7.5 and ~ 12.5 MPa for heat curing, respectively. Kim et al., (2013) activated slag pastes with either 6.25% CaO or 6.25% $Ca(OH)_2$. The specimens were cured at 25 °C with 99% RH until testing. The obtained compressive strength when CaO was used as an activator was higher than that of $Ca(OH)_2$. When CaO was used as an activator, the 1, 3, 7, 14, 28 and 56 days compressive strength was 3.3, 18, 31, 34, 42 and 53 MPa, respectively, whilst it was 3.8, 11, 18, 23, 23 and 24 MPa, respectively, for the specimens activated with $Ca(OH)_2$. They attributed the superior strength of the specimens activated with CaO to its larger initial heat compared to $Ca(OH)_2$, of which the liberated heat generated by CaO was − 64.45 kJ/mol, whilst it was − 17.8 kJ/mol for $Ca(OH)_2$. Wang et al., (2018) activated slag pastes with 7.5% CaO. The specimens were cured at 20 ± 1 °C with ≥ 90% RH. The obtained 7 and 28 days compressive strength was ~ 15 and 22 MPa, respectively. Park et al., (2016b) activated slag/stone powder sludge mortars with 2%, 5% and 10% CaO. The specimens were cured at 23 °C with 99.9% RH. As the amount of CaO increased as the compressive strength increased. At the age of 3, 7 and 28 days, specimens containing 10% CaO showed ~ 11, ~ 16.5 and ~ 27 MPa. Tian et al., (2021) activated two types of slag by 8% CaO. The pastes were cured at room temperature. The obtained initial setting time was 360 and 390 min, whilst the final setting time was 480 and 520 min. The 3 days compressive strength was 4.49 and 0.45 MPa, whilst the 28 days compressive strength was 9.3 and 5.64 MPa. Jeong et al., (2016) prepared pastes by activating various slag types by 10% CaO. The specimens were cured at 23 °C with > 95% RH. The obtained 28 days compressive strength was in the range of 25–52 MPa. This depended on the slag type. The main hydration products were C–S–H, NaOH and different phases of ettringite. Gu et al., (2014) activated slag pastes with 10% CaO. Two different curing conditions were used named water curing and humidity curing (RH 99 ± 1%.). They used a temperature of 20 ± 2 °C for all curing conditions. In the case of water curing and the w/c ratio was 0.35, the obtained 7, 28 and 90 days was 25, ~ 32.5 and ~ 39 MPa, respectively, whilst it was ~ 25, ~ 31 and ~ 34 MPa for the specimens cured in humidity, respectively. Hermawan et al. (Djayaprabha & Nguyen, 2023) activated slag mortars with 15% CaO. The specimens were cured at ambient temperature. The obtained flow, fresh density, 3–56 days compressive strength and 3–56 flexural strength was 115%, 2134.88 kg/m^3, ~ 9– ~ 27 MPa and ~ 2.1– ~ 5.4 MPa, respectively. The obtained 3 and 56 days porosity was ~ 27% and ~ 23.75%, respectively.

Jung-Il et al., (2020) Suh et al., (2023) activated FA pastes with 15% CaO. The specimens were cured at 60 °C with 95% RH for 24 h. The obtained 1, 3, 7 and 28 days compressive strength was 1, 7.4, 8.3 and 12 MPa, respectively. Zhao et al., (2020a) activated 70% FA/13% cement pastes by 17% CaO. After 24 h of casting, the specimens were exposed to autoclave conditions at different temperatures of 140 °C. 180 °C and 210 °C for 3–12 h. The results showed higher compressive strength with higher autoclave temperature and longer autoclave period. When 140 °C of autoclaving was used for 3 and 12 h, the obtained compressive strength was ~ 4 and ~ 17 MPa, respectively. When 180 °C of autoclaving was used for 3 and 12 h, the obtained compressive strength was ~ 5.5 and ~ 26 MPa, respectively. Table 4 summarizes the main results of using CaO as a sole activator.

From the above discussions, it can be noted that CaO can be used as a sole activator. In most cases, CaO can be incorporated in the range of 4–10%. As the ratio of CaO increased as the compressive strength increased due to the formation of C–S–H. The incorporation of sole CaO activator decreased the flowability of the mixtures. The flowability decreased with increasing CaO ratio. This reduction in the flowability could be attributed to the increase in the calcium content with the incorporation of CaO. Another possible reason for this reduction is increasing the alkalinity of the mixture with the incorporation of CaO. The increase in the alkalinity led to a shortage of water (Rashad & Gharieb, 2021) (Gharieb & Rashad, 2022). The setting time was affected by the concentration of CaO. The setting time decreased with increasing the amount of CaO. This could be attributed to the formation of heterogeneous nucleation centers with the incorporation of CaO, which can decrease the setting time (Deventer et al., 2007). In addition, when CaO mixed with water, it generates $Ca(OH)_2$, which leads to an increase in alkalinity and Ca^{2+} levels. As a result, the precursor becomes more soluble, leading to a decrease in setting time (Ju et al., 2020) (Rashad & Gharieb, 2021) (Gharieb & Rashad, 2022). It is important to note that, as indicated in Fig. 9, the majority of the mentioned studies (about 87.5%) focused on pastes, whilst those focused on concretes came in the second (about 11.76%).

3.2 CaO Combined with an Auxiliary Activator

Tian et al., (2021) incorporated 0.5–3% $Al_2(SO_4)_3$ into two types of slag activated with 8% CaO as an auxiliary activator to enhance the compressive strength. The pastes were cured at room temperature. In the first type of slag, the incorporation of 0.5%, 1% and 3% $Al_2(SO_4)_3$ decreased the initial setting time by 13.9%, 22.22% and 30.55%, respectively, whilst the final setting time was decreased by 4.17%, 12.5% and 22.92%, respectively. The incorporation of 0.5%, 1% and 3% $Al_2(SO_4)_3$ increased 3 days compressive strength by 2.45%, 4% and 5.34%, respectively, whilst the 28 days compressive strength was enhanced by 7.85%, 12.79% and 14.73%, respectively. In the second type of slag, the incorporation of 0.5%, 1% and 3% $Al_2(SO_4)_3$ decreased the initial setting time by 15.38%, 25.64% and 38.46%, respectively, whilst the final setting time was decreased by 9.62%, 15% and 26.92%, respectively. The incorporation of 0.5%, 1% and 3% $Al_2(SO_4)_3$ increased 3 days compressive strength by 48.9%, 80% and 95.55%, respectively, whilst the 28 days

Table 4 Effect of CaO as a sole activator on the properties of different matrices

References	Precursor	Sole activator	Ratio	Type	Curing condition	Main results
Yum et al., (2019)	Slag	CaO	4	Paste	23 °C with 99% RH	- The flowability, initial setting time and final setting time was 16.5 mm, 540 min and 1140 min - The 3, 7 and 28 days compressive strength was 7.15, 16.25 and 27.5 MPa - The 3 and 28 days total porosity was 39.45% and 38.51%
Yum et al., (2020)	Slag	CaO	4	Paste	23 °C with 99% RH	- The 3, 7 and 28 days compressive strength was 7.15, 16.25 and 27.5 MPa - The 28 days total porosity was 36.8%
Kolhe et al., (2022)	Slag	Calcium carbide (source for CaO)	4–16	Paste	23 ± 2 °C with 65% RH	- Increased CaO concentration decreased flowability, shortened setting time and increased compressive strength and thermal conductivity
Park et al., (2016a)	Slag	CaO	5	Paste	23 °C with 99% RH	- The 7 and 28 days compressive strength was ~ 20.5 and ~ 39 MPa
Dahal et al., (2023)	Slag	CaO	5	UHPC	23 °C with 99% RH for 24 h, then, at 90 °C for 48 h	- The flow of the mixture was 265% - The compressive strength and tensile strength was 110 and 9 MPa
Oinam et al., (2023)	Slag	CaO	5	UHPC	23 °C with 99% RH for 24 h, then, at 90 °C for 48 h	- The compressive strength and tensile strength was 180 and 12.75 MPa
Burciaga-Díaz et al., (2023)	Slag	CaO	6	Paste	20 ± 2 °C with 80% RH for 90 days	- The 1, 3, 7, 14, 28 and 90 days compressive strength was ~ 0, ~ 3.75, ~ 8.5, ~ 17.5, 20 MPa
	Slag	CaO	6	Paste	60 °C for 24 h, then at 20 °C up to 90 days	- The 1, 3, 7, 14, 28 and 90 days compressive strength ~ 5, ~ 5, ~ 5.5, ~ 7, ~ 7.5 and ~ 12.5 MPa
Kim et al., (2013)	Slag	CaO	6.25	Paste	25 °C with 99% RH	- The 1, 3, 7, 14, 28 and 56 days compressive strength was 3.3, 18, 31, 34, 42 and 53 MPa
Wang et al., (2018)	Slag	CaO	7.5	Paste	20 ± 1 °C with ≥ 90% RH	- The 7 and 28 days compressive strength was ~ 15 and 22 MPa
Tian et al., (2021)	Slag	CaO	8	Paste	Room	- The initial setting time was 360 and 390 min, whilst the final setting time was 480 and 520 min - The 3 days compressive strength was 4.49 and 0.45 MPa, whilst the 28 days compressive strength was 9.3 and 5.64 MPa

Table 4 (continued)

References	Precursor	Sole activator	Ratio	Type	Curing condition	Main results
Park et al., (2016b)	Slag	CaO	2, 5 and 10	Paste	23 °C with 99.9% RH	- The compressive strength increased with increasing CaO concentration - The 3, 7 and 28 days compressive strength for the specimens activated with 10% CaO was ~ 11, ~ 16.5 and ~ 27 MP
Jeong et al., (2016)	Slag	CaO	10	Paste	23 °C with > 95% RH	- The 28 days compressive strength was in the range of 25–52 MPa according to the slag type
Gu et al., (2014)	Slag	CaO	10	Paste	Water 20 ± 2 °C	- The 7, 28 and 90 days was 25, ~ 32.5 and ~ 39 MPa
	Slag	CaO	10	Paste	20 ± 2 °C with 99 ± 1% RH	- The 7, 28 and 90 days was ~ 25, ~ 31 and ~ 34 MPa
Djayaprabha and Nguyen, (2023)	Slag	CaO	15	Paste	Ambient	- The flow and fresh density was 115% and 2134.88 kg/m^3 - The 3–56 days compressive strength and 3–56 flexural strength was ~ 9- ~ 27 MPa and ~ 2.1- ~ 5.4 MPa
Jung-Il et al., (2020) Suh et al., (2023)	FA	CaO	15	Paste	60 °C with 95% RH for 24 h	- The 1, 3, 7 and 28 days compressive strength was 1, 7.4, 8.3 and 12 MPa
Zhao et al., (2020a)	70% FA/13% cement	CaO	17	Paste	Autoclaved at 140 °C. 180 °C and 210 °C for 3–12 h	- Higher compressive strength with higher autoclave temperature and longer autoclave period

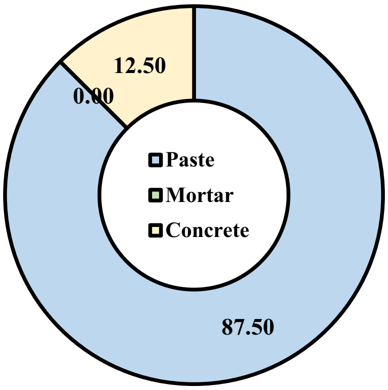

Fig. 9 Relative study number of different matrices activated by sole CaO

compressive strength was enhanced by 35.11%, 56.91% and 63.29%, respectively. Wang et al., (2021) used CaO as a part of the activator with Na_2SO_3 to activate MK geopolymer binders. They found that the ratio of Na_2SO_3 to CaO which gave the highest compressive strength was 1: 0.82. Wang et al., (2018) used 2.5% CaO/5% Na_2CO_3 as an activator instead of 7.5% CaO to activate slag pastes. The specimens were cured at 20 ± 1 °C with RH ≥ 9 0%. The obtained 3, 7 and 28 days compressive strength was ~ 17.2, ~ 22 and 27.6 MPa, respectively, which represent an enhancement of 197%, 46.67% and 25% compared to those activated with 7.5% CaO, respectively. The hydration products were C–S–H and hydrotalcite. Burciaga-Díaz et al., (2023) activated slag pastes with 2% CaO + 2% Na_2CO_3, 3% CaO + 3% Na_2CO_3 and 4% CaO + 4% Na_2CO_3. Some specimens were cured at 20 ± 2 °C with 80% RH for 90 days, whilst the other were cured at 60 °C for 24 h, then at 20 °C up to 90 days. The results showed higher compressive strength of the specimens activated with the combination of CaO and Na_2CO_3 compared to those activated with sole CaO. The heat curing increased the compressive strength at the age of 1 and 3 days, but showed adverse effect on the compressive strength at the ages of 7, 28 and 90 days. Zhao et al., (2020b) reported that the setting time of 80% slag/20% CaO pastes can be shortened with the incorporation of 1% Na_2SO_4, of which the incorporation of 1% Na_2SO_4 reduced the initial and final setting time by 11% and 17.5%, respectively. The incorporation of 1% Na_2SO_4 increased the 1, 3, 7, 28 and 60 days compressive strength of the pastes by 3.66, 2.38, 1.1, 1.05 and 1.07 folds, respectively. Yum et al., (2019) activated slag with 4% CaO coupled with either 0.5–5% $Ca(NO_3)_2$ or 0.5–5% $NaNO_3$. The specimens were cured at 23 °C with 99% RH. The incorporation of 0.5–5% $Ca(NO_3)_2$ increased the flowability by 7.88–26.1%, whilst the incorporation of $NaNO_3$ increased it by 9.1–19.39%. The incorporation of 0.5% $Ca(NO_3)_2$ shortened the initial and final setting time by 11.11% and 2.63%, respectively, whilst the incorporation of 1–5% $Ca(NO_3)_2$ prolonged the initial and final setting time by 44.44–72.22% and 10.53–15.79%, respectively. The incorporation of 0.5–5% $NaNO_3$ shortened the initial and final setting time by 16.67–27.78% and 2.63–7.89%, respectively. The incorporation of 0.5–5% $Ca(NO_3)_2$ increased 3, 7 and 28 days compressive strength by 89.79–126.43%, 21.17–45.97% and 11–20.59%, respectively. The incorporation of 0.5%, 1%, 3% and 5% $NaNO_3$ increased the 3 days compressive strength by 104.89%, 123.1%, 92.73% and 69.79%, respectively, whilst the 28 days compressive strength was decreased by 9.6%, 14.39%, 19.52% and 23.55%, respectively. The incorporation of 0.5%, 1% and 3% $NaNH_3$ increased the 7 days compressive strength by 24%, 25.29 and 3.45%, respectively, whilst the incorporation of 5% $NaNO_3$ decreased it by 3.57%.

Liu et al., (2022a) Liu et al., (2022b) activated slag pastes with 5% CaO + 5% $CaSO_4$. The specimens were cured at 20 ± 1 °C with ≥ 90% RH. The obtained 1, 3, 7 and 28 days was ~ 2, ~ 13, ~ 25 and ~ 32.5 MPa, respectively. Menchaca-Ballinas and Escalante-Garcia, (2019) activated waste glass powder/CaO mortars with different concentrations of NaOH (1.5%, 3% and 6% Na_2O). The waste glass powder has different fineness (400, 500 and 600 m^2/kg). The CaO was introduced at ratios of 10%, 15% and 20% as a substitution for waste glass powder. Different curing conditions were used. The results showed that the optimum conditions that gave the highest 28 days compressive strength (15.5 MPa) were: 80% waste glass powder has 600 m^2/kg surface area coupled with 20% CaO activated with 6% Na_2O initially cured at 60 °C for 24 h. Gu et al., (2014) found 8% enhancement in the 7 days compressive strength of slag pastes activated with 10% CaO by partially replacing CaO with 50% MgO (0.5 CaO/0.5 MgO), whilst the 28 and 90 days compressive strength was decreased by 9.2% and 7.7% when water curing at 20 ± 2 °C and w/c ratio of 0.35 were used, respectively. Jung-Il et al., (2020) used 2–8% MgO and 2–8% magnesium formate as auxiliary activators for FA pastes activated with 15% CaO. The specimens were cured at 60 °C with 95% RH for 24 h. The results showed that the incorporation of magnesium formate ($Mg(HCOO)_2$) is more effective than MgO in enhancing the compressive strength. The compressive strength increased with increasing the amount of auxiliary activator. The incorporation of 8% MgO enhance the 1, 3, 7 and 28 days compressive strength by 7.1, 1.59, 1.89 and 1.85 times, respectively, whilst the incorporation of 8% magnesium formate increased it by 2.5, 2.17, 4.16 and 3.74 times, respectively. The 28 days total porosity was decreased by 15.1%, 22.7% and 28.38% with the incorporation of 2%, 6%, and 8% MgO, respectively, whilst the incorporation of 2%, 6%, and 8% magnesium formate decreased it by 38.65%, 38.43% and 19.65%, respectively. In a similar investigation, Suh et al., (2023) used 2–8% magnesium nitrate ($Mg(NO_3)_2$) as an auxiliary activator for FA pastes activated with 15% CaO. The compressive strength increased with the incorporation of magnesium nitrate, but 6% gave the highest compressive strength. The incorporation of 6% magnesium nitrate increased the 1, 3, 7 and 28 days compressive strength by 5.7, 3.62, 5.1 and 4.14 times, respectively.

Zhao et al., (2020a) activated 70% FA/13% cement by 17% CaO. The CaO was partially replaced by MgO at levels ranging from 3 to 30%. After 24 h of casting, the specimens were exposed to autoclave conditions at different temperatures of 140 °C. 180 °C and 210 °C for 3–12 h. The results showed higher compressive strength with higher autoclave temperature and longer autoclave period. When the autoclave temperatures were 140 °C, 180 °C and 210 °C and the autoclave period was 12 h, the compressive strength was enhanced by 219.3%, 155.8% and 239.4% compared to those autoclaved for 3 h when MgO ratio was 15%. Contrarily, the incorporation of MgO increased the expansion. Yum et al., (2020) used 1–5% calcium formate ($Ca(HCOO)_2$) as an auxiliary activator for slag activated with 4% CaO. The specimens were cured at 23 °C with 99% RH. The incorporation of calcium formate increased the 3 days compressive strength by 1.3 to 2 times, whilst the 28 days was increased by 1.1 to 1.4 times greater than that activated with the sole CaO. The incorporation of 1%, 3% and 5% calcium formate decreased the 3 days total porosity by 17.4%, 32% and 40.33%, respectively, whilst the 28 days total porosity was decreased by 6.5%, 53% and 30.43%, respectively. Park et al., (2016a) activated slag pastes with 5% CaO. The slag was partially replaced with 10% and 15% gypsum. The specimens were cured at 23 °C with 99.9% RH. The results showed an enhancement in the compressive strength by ~ 50% with the inclusion of 10% gypsum, whilst 15% gypsum reduced it by ~ 30%. Hermawan et al. (Djayaprabha & Nguyen, 2023) activated slag mortars by 15% CaO and 15% CaO coupled with 2.5–10% SO_3. The specimens were cured at ambient temperature. The 28 days compressive strength was enhanced by 18.7%, 43.3%, 62.9% and 9.5% with the inclusion of 2.5%, 5%, 7.5% and 10% SO3 compared to those activated by sole CaO, whilst the 28 days flexural strength was enhanced by 6.2%, 5.72%, 44% and 23.64%, respectively. The porosity did not change with the inclusion of 2.5–7.5% SO_3, whilst the inclusion of 10% SO3 increased it compared to those activated with the sole CaO. The flow of the mixtures did not change with the inclusion of SO_3, whilst the fresh density was increased by 1.05%, 1.12%, 1.83% and 1.44% with the inclusion of 2.5%, 5%, 7.5% and 10% SO_3, respectively. Table 5 summarizes the effect of auxiliary activators on the properties of different matrices activated with CaO.

From the above discussions, it can be noted that CaO can be used as a part of an activator. To enhance the early strength and properties of matrices activated with CaO, auxiliary activators were used. The compressive strength of different matrices activated with CaO can be enhanced by adding a suitable ratio of $Al_2(SO_4)_3$, Na_2SiO_3, Na_2CO_3, Na_2SO_4, $CaSO_4$, NaOH, MgO, calcium formate, gypsum, and SO_3. The incorporation of $Al_2(SO_4)_3$ up to 3% shortened the setting time and enhanced the compressive strength due to the acceleration of hydration reaction, more dissolution of slag and formation more C–S–H and ettringite (Tian et al., 2021). The incorporation of a suitable ratio of Na_2SO_3 can enhance the compressive strength due to the formation of $CaSiO_3$ which can improve the degree of geopolymerization as illustrated in the following equations (Wang et al., 2021):

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2}$$

$$\mathrm{Na_2SiO_3} + \mathrm{Ca(OH)_2} \rightarrow \mathrm{CaSiO_3} \downarrow + 2\mathrm{NaOH}$$

The incorporation of a suitable ratio of Na_2CO_3 can enhance the compressive strength due to the higher pH value caused by the formation of NaOH resulting from the reaction between CaO and Na_2SO_3 as shown in this equation:

$$\mathrm{CaO} + \mathrm{Na_2CO_3} + \mathrm{H_2O} \rightarrow \mathrm{CaCO_3} \downarrow + 2\mathrm{NaOH}$$

The seeding effect of $CaCO_3$ can accelerate the formation of C–S–H gel (Burciaga-Díaz et al., 2023) (Wang et al., 2018), whilst the filling effect of $CaCO_3$ can reduce the porosity (Wang et al., 2018). The incorporation of a suitable ratio of Na_2SO_4 can enhance the compressive strength due to the higher pH value of the slurry resulting from the reaction between Na_2SO_4 and $Ca(OH)_2$ as follows:

$$\mathrm{Na_2SO_4} + \mathrm{Ca(OH)_2} \rightarrow \mathrm{CaSO_4} + 2\,\mathrm{NaOH}$$

In addition, the ettringite can be formed with the incorporation of Na_2SO_4 (Zhao et al., 2020b). It was reported that the incorporation of ettringite can increase the early age strength (Rashad et al., 2012) (Rashad et al., 2013) (Rashad, 2015b). The incorporation of 2–8% magnesium formate increased the compressive strength and decreased total porosity of FA pastes activated with CaO due increasing CaO dissolution degree leading to formation more C–S–H (Jung-Il et al., 2020). The incorporation of 6% magnesium nitrate into FA pastes activated with CaO increased the compressive strength due to increasing CaO dissolution degree leading to formation more C–(A)–S–H (Suh et al., 2023). The incorporation of 3–30% MgO, it is preferable not to exceed 20%, into FA/cement activated with CaO increased the compressive strength due to the formation and crystallization of C–S–H encouraged by Mg^{2+} (Zhao et al., 2020a). Contrarily, the incorporation of MgO increased the expansion due to the formation of $Mg(OH)_2$ (Zhao et al., 2020a). The incorporation of 0.5–5% $Ca(NO_3)_2$ into slag pastes activated with 4% CaO enhanced the 3–7 days compressive strength supplied additional Ca ions, whilst the incorporation of 0.5–5% $NaNO_3$ increased the 3 days compressive strength due to increased pH, which leading to more dissolving slag and formation C–S–H. contrarily, at the age of 28 days the inclusion of $NaNO_3$ decreased C–S–H (Yum et al., 2019). The incorporation of 1–5% calcium format, 3% was the optimal, increased the compressive strength due to the greater formation of C–S–H, more slag dissolution and the formation of C2AH8 (Yum et al., 2020). The incorporation of a suitable ratio of gypsum can enhance the compressive strength due to the pore-size refinement effect, smaller pores and the formation of ettringite crystals that can fill the pores with the inclusion of 10% gypsum producing denser microstructure (Fig. 10c, d). On the other hand, the inclusion of 15% gypsum produced a more porous matrix (Fig. 10e, f) (Park et al., 2016a). The incorporation of SO_3 can enhance the compressive strength and flexural strength due to the formation of the crystalline compounds of gypsum and ettringite (Djayaprabha & Nguyen, 2023). It is important to note that, as indicated in Fig. 11, the majority of the mentioned studies (about 88.24%) focused on pastes, whilst those focused on mortars came in the second (about 11.76%).

4 General View and Recommendation for Future Work

Generally, CaO can be incorporated into AAMs in three main forms: as a part of a precursor or as an additive for AAMs; as a sole activator or as an activator coupled with an auxiliary activator. Most of the past studies preferred to use CaO as an activator coupled with an auxiliary activator (38.63%), whilst 36.36% and 25% preferred to use CaO as a sole activator and as an additive/apart of a precursor, respectively (Fig. 12). However, in general view, the incorporation of CaO into AAMs as an additive/a part of a precursor significantly decreased the workability and setting time. There are scattered and contradictory results about the effect of CaO on compressive strength, but most of them reported a positive effect. In

Table 5 Effect of auxiliary activators on the properties of different matrices activated with CaO

References	Precursor	Auxiliary activator	Ratio/amount	Type	Curing condition	Effect
Tian et al., (2021)	Slag	$Al_2(SO_4)_3$	0.5–3%	Paste	Room	- Decreased setting time - Increased compressive strength
Wang et al., (2021)	MK	Na_2SO_3	$Na_2SO_3/CaO = 1/0.82$	Paste	Room	- Increased compressive strength
Wang et al., (2018)	Slag	Na_2CO_3	$Na_2CO_3/CaO = 5/2.5$	Paste	20 ± 1 °C with RH ≥ 90%	- Increased compressive strength by 197%, 46.67% and 25% at the ages 3, 7 and 28 days
Burciaga-Díaz et al., (2023)	Slag	Na_2CO_3	2–4%	Paste	20 ± 2 °C with 80% RH	- Increased compressive strength
	Slag	Na_2CO_3	2–4%	Paste	60 °C for 24 h	- Increased compressive strength
Zhao et al., (2020b)	Slag	Na_2SO_4	1%	Paste	20 ± 2 °C	- Decreased initial and final setting time by 11% and 17.5% - Increased 1, 3, 7, 28 and 60 days compressive strength by 3.66, 2.38, 1.1, 1.05 and 1.07 folds
Liu et al., (2022a) Liu et al., (2022b)	Slag	$CaSO_4$	5%	Paste	20 ± 1 °C with ≥ 90% RH	- The obtained 1, 3, 7 and 28 days was ~ 2, ~ 13, ~ 25 and ~ 32.5 MPa, respectively
Menchaca-Ballinas and Escalante-Garcia, (2019)	Glass powder	NaOH	6% Na_2O	Mortar	60 °C for 24 h	- Increased compressive strength
Gu et al., (2014)	Slag	MgO	MgO/CaO = 0.5/0.5	Paste	20 ± 2 °C (water)	- Increased 7 days compressive strength by ~ 8%, but decreased 28 and 90 days compressive strength by ~ 9.2% and ~ 7.7
Jung-Il et al., (2020)	FA	MgO	2–8%	Paste	60 °C with 95% RH for 24 h	- Increased compressive strength - Decreased total porosity
		Magnesium formate	2–8%	Paste	60 °C with 95% RH for 24 h	- Increased compressive strength - Decreased total porosity
Suh et al., (2023)	FA	Magnesium nitrate	2–8%	Paste	60 °C with 95% RH for 24 h	- Increased compressive strength
Zhao et al., (2020a)	FA/cement	MgO	3–30%	Paste	Autoclaved at 140, 180, 210 °C for 3–12 h	- Increased compressive strength and expansion
Yum et al., (2019)	Slag	$Ca(NO_3)_2$	0.5–5	Paste	23 °C with 99% RH	- Increased flowability - 0.5% shortened setting time, whilst 1–5% increased it - Increased 3–28 days compressive strength
		$NaNO_3$	0.5–5	Paste	23 °C with 99% RH	- Increased flowability - Shortened initial setting time - 0.5% and 1% shortened final setting time, whilst 3% and 5% increased it
Yum et al., (2020)	Slag	Calcium formate	1–5%	Paste	23 °C with 99% RH	- Increased compressive strength - Decreased total porosity
Park et al., (2016a)	Slag	Gypsum	10%	Paste	23 °C with 99.9% RH	- Increased compressive strength by ~ 50%

Table 5 (continued)

References	Precursor	Auxiliary activator	Ratio/amount	Type	Curing condition	Effect
	Slag	Gypsum	15%	Paste	23 °C with 99.9% RH	- Decreased compressive strength by ~ 30%
Djayaprabha and Nguyen, (2023)	Slag	SO_3	2.5–10%	Mortar	Room	- Increased compressive and flexural strengths - Increased fresh density - No effect on the flow - No effect on the porosity up to 7.5% SO_3, whilst 10% SO_3 increased it

this issue, about 50% of the available studies reported a positive effect of CaO on the compressive strength of AAMs, whilst about 20% of these studies reported a negative effect. On the other hand, about 30% of the available studies reported a positive effect or a negative effect. This mainly depended on the ratio of CaO and/or curing conditions. In most cases, the incorporation of CaO up to 7.5% into AAMs showed a positive effect on the mechanical strength, but 5% seemed to be the optimum ratio. Higher ratios of CaO than 7.5% may decrease the mechanical strength. In spite of there are too limited studies focused on the effect of CaO on the durability of AAMs, these studies confirmed lower porosity, lower water absorption, lower chloride diffusion, higher resistance to wet/dry cycles and acid attack with the incorporation of CaO up to 7.5%, but 5% CaO seemed to be the optimum ratio. Efficiently, 5–10% CaO can be used as a sole activator for different precursors without any additional or auxiliary activator. To enhance the compressive strength of CaO-activated materials, especially at different ages, suitable ratios of different auxiliary activators such as Na_2CO_3, Na_2SiO_3, Na_2SO_4, NaOH, gypsum and MgO can be used. It is worth stating that most of the available studies reported the effect of CaO on the properties of AAMs focused on slag precursor (about 47.35%) followed by FA precursor (about 20.1%), MK precursor (about 10.52%), glass powder precursor (about 5.26%), perlite precursor (about 5.26%), slag/stone powder precursor (about 5.26%) and FA/kaolinite precursor (about 5.26%) as shown in Fig. 13. Generally, it can be observed from Fig. 14 that about 47.22% of these studies focused on compressive strength, about 13.89% focused on setting time, about 8.33% focused on workability as well as water absorption and porosity. On the other hand, less attention is paid on the effect of CaO on other properties of AAMs such as flexural strength, shrinkage/length change, reaction kinetics, wet/dry cycles, acid resistance and chloride diffusion (Fig. 14). Unfortunately, there are no available studies related to the effect of CaO on the carbonation resistance, corrosion resistance, freeze/thaw resistance, fire resistance, seawater resistance, sulfate resistance, splitting tensile strength, elastic modulus and impact strength of AAMs. These topics can be used for upcoming studies.

5 Concluding Remarks

This article reviewed the obtainable studies focused on the effect of CaO on the properties of AAMs. The foremost findings can be mentioned as follows:

1. The incorporation of CaO in the matrix decreased the workability due to the higher dissolution of aluminosilicate during geopolymerization process with the higher alkalinity of the mixture caused by CaO. This process is associated with a shortage of water in the alkaline mixture.
2. The incorporation of CaO in the matrix decreased setting time due to the heat released during mixing CaO with water as well as the higher alkalinity of the matrix due to the formation of $Ca(HO)_2$.
3. There are notable variations in the results of the mechanical strength. These variations mainly depended on the ratio of CaO, precursor type, activator type, activator concentration, curing conditions and testing age
4. In spite of there are contradictory results about the effect of CaO on the compressive strength of AAMs, most of them reported higher compressive strength, especially at the early ages. The incorporation of CaO up to 5% in the matrix is more effective than the incorporation of higher ratios.
5. The enhancement in the strength with the incorporation of CaO could be attributed to the heat released during mixing CaO with water, which can promote hydration. At the same time, $Ca(OH)_2$ can be formed during the interaction between CaO and water, which can increase pH value and generate C–S–H.
6. In most cases, heat curing has a negative effect on the strength of the specimens containing CaO. This

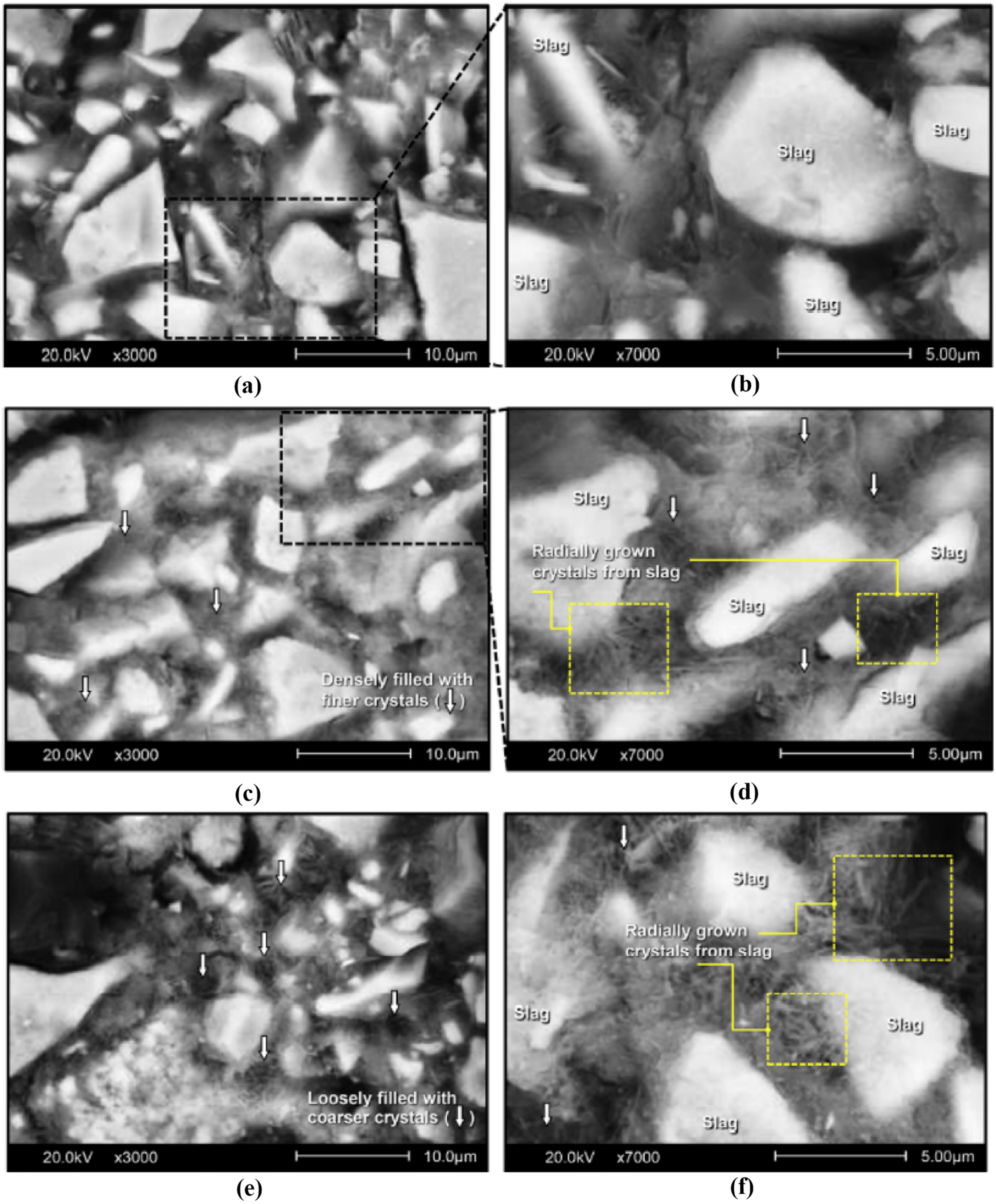

Fig. 10 BSE images of slag paste samples activated with sole CaO (**a**, **b**), CaO coupled with 10% gypsum (**c**, **d**) and CaO coupled with 15% gypsum (**e**, **f**) (Park et al., 2016a)

negative effect could be attributed to the higher porosity caused by evaporation of water due to heat curing even though heat curing accelerated the dissolution of the aluminosilicate and polymerization reaction.

7. In most cases of AAMs, the incorporation of CaO at ratios higher than 7.5% may reduce the strength

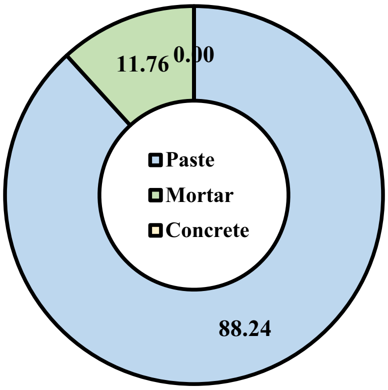

Fig. 11 Relative study number of different matrices activate

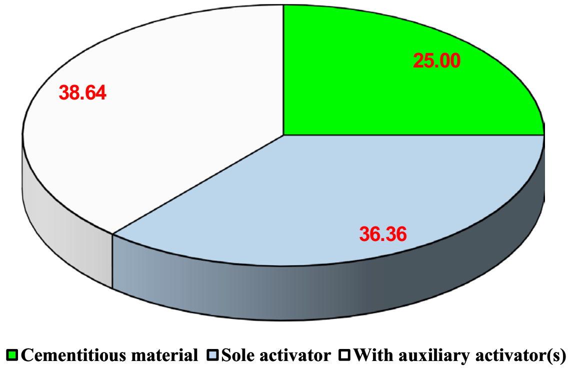

Fig. 12 Relative number of studies employed CaO as a cementitious material, a sole activator and an activator combined with an auxiliary activator

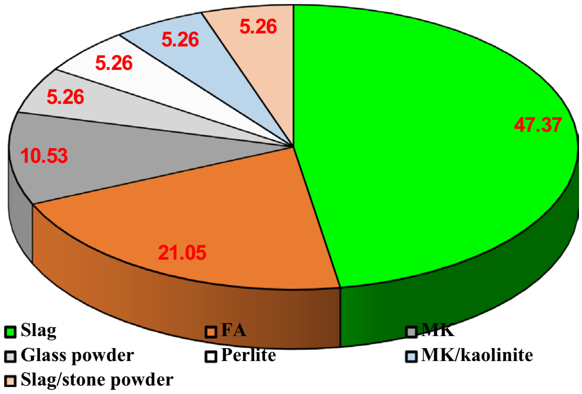

Fig. 13 Relative study number of precursors containing CaO

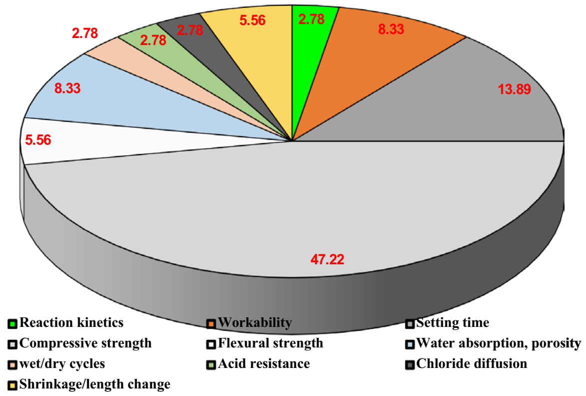

Fig. 14 Study number ratio of the effect of CaO on the properties of AAMs

due to the excessive alkalinity and the formation of porous microstructure.

8. With high efficiency, the incorporation of 3–5% CaO in AAMs can decrease water absorption and total porosity, whilst the resistivity of the specimens against wetting/drying cycles and acid attack can be increased. The higher durability could be attributed to the accelerated and more hydration products caused by CaO that can reduce the micropores, produce denser and more compact microstructure that can act as a barrier against the diffusion of harmful materials. In addition to the ability of CaO to promote the hydration process and packing effect.
9. The available studies related to the effect of CaO on the shrinkage and length change of AAMs are not enough to mention a reasonable conclusion.
10. CaO can be used as a sole activator. The commonly used ratios were 4–10%. As the ratio of CaO increased as the compressive strength increased, but decreased workability and shortened setting time.
11. Suitable ratios of auxiliary activators such as $Al_2(SO_4)_3$, Na_2CO_3, Na_2SiO_3, Na_2SO_4, NaOH, gypsum and MgO can be used to enhance the compressive strength of CaO-activated materials, especially at the early ages. Incorporating $Al_2(SO_4)_3$ up to 3% decreased setting time and increased compressive strength. Incorporating SO_3 as an auxiliary activator can enhance the strength. The optimal ratio was 7.5%. Incorporating 1–20% MgO enhanced the compressive strength, but increased expansion. Incorporating 3% calcium formate or 8% magnesium formate increased compressive strength and decreased total porosity, whilst incorporating 6% magnesium nitrate increased compressive strength. The incorporation of 0.5–5% $Ca(NO_3)_2$ increased 3–28 days compressive strength. The incorporation of $NaNO_3$ increased the 3 days compressive strength, but decreased the 28 days compressive strength.

12. Comparing the results of compressive strength of CaO-materials containing auxiliary activators, 1% Na_2SO_4 showed the best activator which enhanced the 1, 3, 7, 28 and 60 days compressive strength by 3.66, 2.38, 1.1, 1.05 and 1.07 folds, respectively.
13. There are shortages in the literature about the effect of the effect of CaO on other properties of AAMs such as flexural strength, shrinkage/length change, reaction kinetics, wet/dry cycles, acid resistance and chloride diffusion.

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