Construction and Building Materials 256 (2020) 119380

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mix design and mechanical properties of geopolymer and alkali activated concrete: Review of the state-of-the-art and the development of a new unified approach

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HIGHLIGHTS

- 184 published studies reported on concrete with AAC binder are reviewed.
- The fundamental compositions of binders and activators are investigated.
- A database is constructed containing 1756 AAC mixes from 111 studies.
- A unified model is developed to predict the compressive strength of AAC.
- Mechanical properties of AAC are assessed using code-based models.

ARTICLE INFO

Article history:
Received 24 January 2020
Received in revised form 21 April 2020
Accepted 27 April 2020
Available online 11 May 2020

Keywords:
Geopolymer and alkaline activated binder concrete
Unified model
Mechanical properties
Sodium silicate
Sodium hydroxide

ABSTRACT

This study presents a comprehensive overview of the design and properties of concrete with alkali-activated binder (AAC). 184 published studies reported on concrete with AAC binder were reviewed critically. A database is constructed containing 1756 individual AAC mixes from 111 studies from the literature, which covers a wide range of AAC mixing parameters and engineering properties. The effects of a set of critical factors (and ratios), including those less understood such as utilizing alkaline activator other than sodium silicate (SS) and sodium hydroxide (SH), adding setting retarder and water reducer, and curing regime, are addressed and the underlying mechanism discussed. The fundamental chemical and mineralogical compositions of source materials and alkaline activators are investigated and used as a solid basis to develop a unified approach for proportioning AAC mixes. Furthermore, by synthesizing the results of the database the relationship between the compressive strength and the mechanical and physical properties of AAC is established. Models provided in major design guidelines for predicting the mechanical properties of ordinary Portland cement concrete (OPCC) are assessed and then modified for their extended applications to AAC. Finally, based on this review, limitations of the existing studies are identified and recommendations laid down for potential future research on AAC.

1. Introduction

Ordinary Portland cement (OPC) is commonly used as the primary binder to produce conventional OPC-based concrete (OPCC). However, the production of OPC is resource- and energy- intensive, and is responsible for the emission of 1.35 billion tonnes of CO_2 annually — which contributes to 6–9% of total anthropogenic greenhouse gas emissions [1,2]. Now, more than ever, there is a growing environmental awareness of the harmful impacts during the making and use of OPCC. This consequently drives the cement and concrete industry to look for innovative alternatives to OPCC for ensuring environmental sustainability. Besides, there is also an urgent need for finding approaches to reuse industrial- and agricultural- by-products and wastes. Only by this way can a circular economy in construction be created. Under this background, a gradual but massive shift is taking place in the industry, in tandem with enormous research activities aimed at generating greener

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https://doi.org/10.1016/j.conbuildmat.2020.119380

cement-based productions. Developing alkali-activated (AA) cementitious materials is a prominent case in point, through which the need for OPC can be greatly reduced.

A large volume of research work has been conducted to investigate and quantify the properties of AA binders at paste, mortar and concrete levels. While the reaction mechanism and conceptual model of AA binders have been extensively reported elsewhere [3–9] and hence are not repeated here, our understanding of the behaviour of AA concrete (AAC) is less than complete. An extensive literature review has identified several limitations and areas that have received less research attention; these include:

1) The effects of using retarder and water reducing agents, combining activators, and the chemical composition of both the liquid and solid phases of an AA binder have been primarily considered at the paste and mortar levels;
2) The terminologies of liquid-to-solid ratio, water-to-solid ratio and alkaline activator-to-solid ratio for AAC mix designs have been used interchangeably or as synonyms. These parameters have also been used as analogies for the water-to-binder ratio for OPCC mixes, and the well-known inverse relationship between water-to-solid ratio and compressive strength of OPCC has been erroneously utilized to guide to develop AAC mix proportions;
3) The majority of existing studies have reported the preparation of AAC using unary or blended aluminosilicate source materials which is only available locally and with a unique chemical makeup. Plotting the chemical composition of source materials for AAC binder in a ternary diagram (Fig. 1) indicates that these industrial- and agricultural-by-products and wastes exhibit a wide variation in their chemical constituents. Therefore, the reactivity of these aluminosilicate precursors in alkaline activations cannot be simply evaluated based on their broad typologies;
4) The effects of chemical composition of AAC ingredients on AAC properties have been studied separately for source materials and alkaline solutions. The efficiency in producing AAC is largely controlled not only by the mix proportions, but also by the composition of aluminosilicate precursors, alkalis and silicates. The limitations stated in 3) and 4) hinder the transfer and generalization of AAC mix designs developed in individual experimental campaigns. More fundamental properties of the wide-range of source materials and activators, for instance, oxides governing the reactivity, may potentially help to develop a unified design-based approach;
5) The assessments of the applicability of code-based models, which are developed for OPCC, to predict the mechanical properties of AAC have only been assessed on relatively small subsets of test results. A database that covers extensive experimental results is required to reliably modify these models for perfecting AAC mechanical properties.

The overarching aim of this work is to provide a state-of-art review of engineering properties of concrete with an AA binder. A total of 184 published references are reviewed in the present study. Factors affecting the fresh and hardened engineering properties of AAC are systematically assessed along with the related underlying mechanism governing AAC's behavioural characteristics. Beyond simply summarizing the content reported in the existing studies on AAC, a large experimental database containing the results of 1756 individual AAC mixes compiled from across 111 studies are constructed. This database is used to develop a unified approach based on the fundamental chemical composition of solid precursors and liquid substances of AAC mixes for assessing the influential factors on hardened properties of AAC in an assigned curing regime. Furthermore, using the results reported in the database, the relationships between the compressive strength and the mechanical and physical properties of AAC are established and the code-based models presented in the major design guidelines for mechanical properties of OPCC are assessed and further modified to predict the properties of AAC. Finally, based on the overview of engineering properties of AAC, limitations in this research area are identified and recommendations delineated to further promote

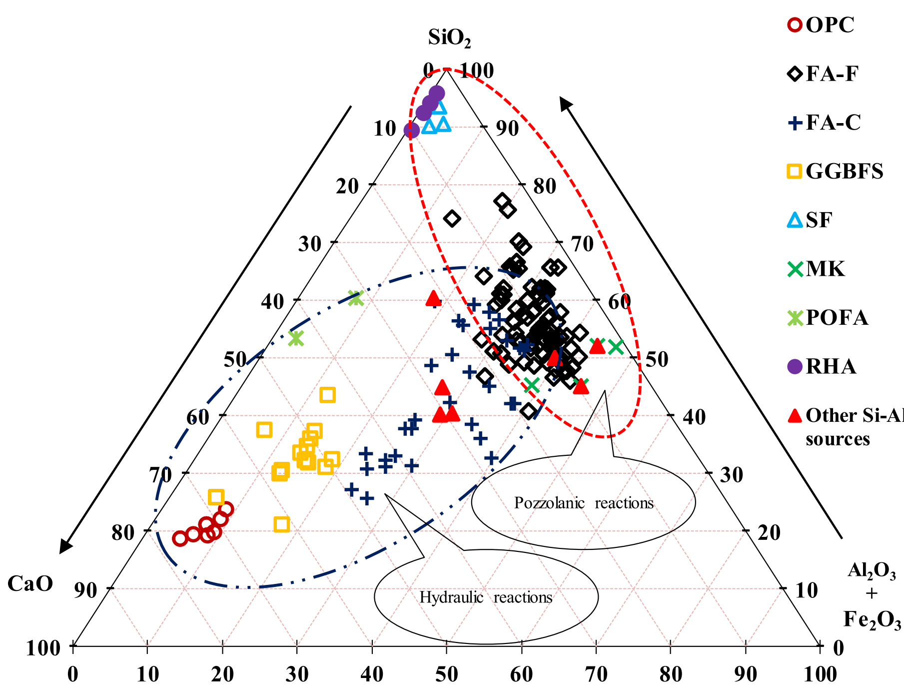

Fig. 1. Ternary diagram of source materials.

investigations and applications of AAC in civil engineering practice. Significantly, the work presented in this study will provide new insight into the mix design, property evaluation, and preparation technology of AAC.

2. An overview of concrete with alkali activated binders

This section presents an overview of concrete in which the binder is activated by different types and combinations of alkaline solutions and admixtures. Parameters and major findings reported in existing studies on AAC are summarized and the efficiency of different combinations of alkaline activators and retarders are investigated.

2.1. Concrete with sodium silicate and sodium hydroxide activated binder

Extensive research on alkali activated pastes, mortars and concrete has shown that duel alkaline activators consisting of sodium hydroxide (SH) and sodium silicate (SS) are highly efficient in activating both high and low calcium-containing aluminosilicate binders. In these duel alkaline activators SH is the main activator (also known as the reaction catalyst) and provides OH– ions while the SS acts as the auxiliary activator (also known as the structure forming element) to provide soluble silica. Based on a review of literature that describes the development of geopolymer or alkali activated binders published between the year 2000 to early 2019, 163 individual studies [10–172] have been identified to report on the behaviour of concrete prepared using SS + SH activated binders. Table 1 summarizes the parameters investigated in each study and the key findings relating to the engineering properties of the concrete.

2.2. Concrete with binder activated by other type of chemicals

Although the vast majority of studies on alkali activated concrete are based on the use of combined SS and SH activators, an additional 11 studies [89,111,173–181] were found to investigate the effects of other types or combinations of activators on properties of AACs. Table 2 summarizes the parameters investigated and the major findings of these 11 studies. Based on the information summarised in Tables 1 and 2, it can be generally concluded that reaction catalysts with calcium ions (Ca^{2+}), for instance $Ca(OH)_2$, have improved hardened mechanical properties, but a reduced slump of an AAC concrete compared to using catalysts containing sodium ions (Na^+). Further, concrete produced using a main activator containing lithium (Li^+), barium (Ba^{2+}), aluminium (Al^{3+}) or magnesium (Mg^{2+}) ions exhibit inferior properties compared to those with sodium ions (Na^+). Ignoring the economic considerations, the results in Table 2 also indicate that at a given dosage and concentration, reaction with potassium ions (K^+) is more efficient than that with sodium ions (Na^+), yielding higher compressive strengths. This finding arises because potassium-based activators are more alkaline than sodium-based activators, and the higher basicity favours the dissolution and polycondensation process, subsequently improving the mechanical strength of the concrete. An exception to the above generalisation is the results reported by [89], in which AAC produced using potassium-based activators exhibited inferior properties compared to those using sodium-based activators. As suggested by the authors, this is likely caused by the difference in the size of sodium and potassium cations, where the smaller size of potassium cations benefits the formations of zeolitization [182,183]. As can be seen from the information summarised in Table 2, because of the small quantity of experimental investigations identified (11 studies), no clear conclusion can be drawn about the effect of the auxiliary activator on the compressive strength of AAC. However, the results reported in [178] suggest that the contribution of a structure-forming element to the strength of concrete not only depends on the solubility of the auxiliary activator but also the basicity of the associated main activator.

2.3. Retarders for AAC

Flash setting in AAC occurs because of either the heat generated from the dissolution of solids in the alkaline solutions, or the high calcium content of the source materials. The uncontrolled rapid setting is a critical issue in AAC as many investigations have reported a significantly reduced setting time of AAC than required for practical applications. This problem constitutes one of the current barriers preventing more widespread utilization of AAC in either cast-in-situ or precast scenarios [184–186]. Many attempts have been made to avoid flash setting of binders in AAC, with the majority adopting the approach of adjusting the mix proportions of the concrete or the binder constituents to attain more desirable rheology. Approaches to adjusting the mix proportions include: reducing calcium content in binder; adding extra water; varying total liquid-to-solid ratio, SS/SH ratio, SH concentration or silica modulus of SS solution (e.g. SiO_2/Na_2O weight ratio). Although changes in mixing proportions have been found to delay setting, compromised mechanical properties of AAC have also resulted.

With the aim to prevent flash setting while maintaining the mechanical properties, several studies have focused on the addition of retarders [33,50,187–195]. Table 3 summarizes the information collated from the 10 studies found in the literature on delaying the setting of AAC binder using retarders. It is worth noting that in most instances the retarders applied to AAC mixes are the same as those commonly used for conventional OPCC, including natural sugar/glucose, phosphoric acid (H_3PO_4), Gypsum ($CaSO_4{\cdot}H_2O$) and citric acid ($C_6H_8O_7$). However, due to the differences in reaction mechanism and kinetics between the AAC and OPC binders, the conventional retarders only affect the setting of high calcium-containing binders in AAC, whereas they are less effective at delaying setting of AAC binders with low calcium content. This is simply because these conventional retarders only prolong the time to form hydrates associated with the reactions in which calcium ions participated. Besides those retarders for conventional OPCCs, the results reported in Karthik et al. [193,194] indicate that the application of terminalia chebula combined with natural sugars including molasses, palm jaggery, and honey is a feasible method for prolonging the setting time AACs. The mechanism of retardation in this instance is the formation of reaction products involving the retarders covering the surface of the cementitious materials, thereby delaying interaction with the alkali and prolonging setting time.

3. Assessments of influential factors on the fresh and hardened properties of aac

Having summarized the key findings (Table 1) in each study on AAC with SS and SH activated binders, the effects of some critical factors on the fresh (e.g. workability and setting time) and hardened (e.g. compressive strength) engineering properties of AAC are further assessed in this section, with a particular focus on the identifications of essential mechanisms governing the actions.

3.1. Slump

Fig. 2(a)–(e) presents the effects of AAC mixing parameters, including sodium silicate to sodium hydroxide weight ratio (SS/-

Table 1
Summary of key findings reported in studies on SS + SH based AAC.

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[10]	Bakharev et al.	2000	Effects of chemical admixtures including Superplasticiser based on modified naphthalene formaldehyde polymers, air-entraining agent, water-reducing, shrinkage-reducing admixtures at dosages of 6 ± 10 ml/kg, and gypsum			Air-entraining agent, shrinkage-reducing admixtures, and gypsum reduces drying shrinkage of AACs; Lignosulphonate-based admixture slightly reduces shrinkage, while naphthalene-based superplasticiser results in increased shrinkage and a reduced f_c of AAC
[11]	Hardjito and Rangan	2005	l/b; SH concentration; SS/SH ratio; Curing time & temperature; Specimen rest time; Water content; Mixing time; SP content			A higher SH concentration, SS/SH ratio, Curing temperature (within 30° to 90°), H_2O to Na_2O ratio or a longer specimen rest time (up to 5 days) results in a higher f_c; Over 2% of SP addition results in a slightly decrease in f_c; f_c of AACs does not significantly affect by curing age after undergoing an initial heat curing; AACs have similar physical and mechanical properties compared to OPCs with similar compressive strength; A lower l/b ratio results in a higher f_c, Prolonged mixing time (up to 6 mins) increases f_c
[12]	Fernández-Jiménez et al.	2006	–	Pull-out tests		AACs have rapidly developed initial strength; lower drying shrinkage; and good steel bond strength compared to those of OPC based concrete with a similar f_c
[13]	Sumajouw and Rangan	2006	–	Reinforced concrete beams and columns		For a given f_c, an AAC beam performs similar to an OPC beam
[14]	Wallah and Rangan	2006	Durability tests of AACs			Heat-cured fly ash-based AACs undergo low creep; The creep coefficient of AACs is only 50% of those of OPCs; Heat cured fly ash-based AACs undergo little drying shrinkage whereas ambient cured AACs is over 1500 microstrains after 3 months; Sulfuric acid resistance of AACs is significantly better than OPCs
[15]	Olivia et al.	2008	l/b ratio; a/b ratio			f_c decreases with an increase in l/b ratio or a/b ratio
[16]	Mishra et al.	2008	Curing time ; SH concentration			A higher SH concentration, or a longer curing time (up to 48 hrs) results in enhanced mechanical properties and durability of AACs
[17]	Andi Arham Adam	2009	Na_2O content; M_s			A higher Na_2O content or M_s results in a higher f_c and a lower porosity
[18]	Kong and Sanjayan	2010	Aggregate size			An increase in maximum aggregate size (up to 20 mm) results in a higher $f_{c;}$ Conventional superplasticizer does not improve workability and reduces f_c of AACs
[19]	Reddy et al.	2010	SH concentration			A higher SH concentration results in a higher f_c and a lower slump
[20]	Wongpa et al.	2010	RHA/FA ratio; Paste content			A higher SiO_2/Al_2O_3 ratio or PV content (0.38–0.68) results in lower f_c and water permeability. For a given f_c, an AAC exhibits a higher water permeability compared to that of a OPC
[21]	Ahmed et al.	2011	Water addition; Curing time & temperature	Self-compacting concrete		An addition of water in an AAC improves workability and results in more significant bleeding and segregation as well as a decreased fc; A higher curing temperature or a longer curing time results in a higher f_c.
[22]	Ariffin et al.	2011	POFA/FA ratio; SS/SH ratio; l/b ratio; SH concentration			A higher SH concentration or a higher SS/SH ratio results in a higher f_c
[23]	Bhikshma et al.	2011	ac/b ratio			An increase in ac/b ratio results in enhanced mechanical properties of AACs
[24]	Diaz-Loya et al.	2011	FA type			Relationships between f_c and other mechanical properties of AACs are in similar manner to those of OPCs
[25]	Edouard	2011	Durability tests of AACs			Geopolymerization product of low calcium AACs is more homogeneous and well-bonded to aggregates than OPCs. AACs have superior durability related properties over OPCs
[26]	Memon et al.	2011	Curing temperature & time	Self-compacting concrete		A higher curing temperature or a longer curing time results in a higher f_c

Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[27]	Nuruddin et al.(b)	2011	SH concentration; SP content	Self-compacting concrete	Optimum SP and SH concentration content are 6% and 12 M,respetively for slump and f_c of FA-based AACs	12 M SH performs better than 14 M SH in developing f_c of FA-based AACs
[28]	Nuruddin et al.(c)	2011	l/b ratio; Curing time & temperature;	Self-compacting concrete	Optimal curing time and temperature are 48 h + 70° for f_c	A lower l/b ratio or a longer curing time results in a higher f_c and a lower water absorption
[29]	Olivia and Nikraz	2011	a/b ratio; ac/b ratio; l/b ratio			A lower a/b ratio, a lower ac/b ratio or a higher l/b ratio results in a lower f_c
[30]	Pan et al.	2011	Curing time; SS/SH ratio	Fracture properties established by conducting beam tests (notched)		For a given f_c, AACs have a higher brittleness than the companion OPCs
[31]	Abdul Aleem and Arumairaj	2012	Paste volume			A increase in paste volume generally results in a higher f_c of AACs
[32]	Bernal et al.	2012	MK/GGBFS ratio; SiO_2/Al_2O_3 ratio			A higher SiO_2/Al_2O_3 ratio results in improved mechanical strength and durability of AACs
[33]	Chi	2012	ac/b ratio		Developed three grades of concrete C20-C30; 60°+ 80% RH is the optimal curing condition for f_c	A higher Na_2O content results in improved mechanical strength and durability of AACs
[34]	Joseph and Mathew	2012	l/b ratio; SS/SH ratio; SP ratio; Fine/coarse aggregate ratio; Aggregate content; Curing temperature			AACs' compacting factor increases with an increase in l/b ratio; An increase in total aggregate content (up to 70%), fine to coarse aggregate ratio (up to 0.35), SS/SH ratio (up to 0.25), SH concentration (up to 10 M), curing temperature (up to 100°) or a curing time results an increase in fc; A higher l/b ratio results in a lower f_c
[35]	Kotwal	2012	ac/b ratio; SH concentration; SS/SH ratio			An increase in SH or SS proportion results in decreased slump and flow of AACs; Excessive OH– ions accelerates dissolution but decreases polycondensation
[36]	Kusbiantoro et al.	2012	RHA/FA ratio; Curing method			RHA replacing FA in AACs results in denser gel structure, which in turn enhances mechanical properties of the concrete. A higher curing temperature results in a higher f_c
[37]	Mane and Jadhav	2012	Elevated temperature	Fire performance	OPC vs AAC under elevated temperature	For a comparable f_c, AACs exhibits superior performance over OPCs when subjected up 500°
[38]	Montes and Allouche	2012	SH concentration; SS/SH ratio; M_s of SS		The optimum M_s of SS for f_c is 2.5	A higher SH concentration or a lower SS/SH ratio results in a higher f_c
[39]	Olivia and Nikraz	2012	ac/b ratio; SS/SH ratio; Curing temperature & time; Aggregate content		Taguchi method	f_c of AACs increases with an in curing temperature/time or SS/SH ratio, and a decreases in ac/b ratio
[40]	Sujatha et al.	2012	Paste volume	Slender column tests	Two grades of AACs developed C30 and C50	A higher paste volume results in a higher f_c; AAC slender columns perform similar to OPC columns on load bearing capacity but with a slightly reduced ductility
[41]	Supraja and Kanta Rao	2012	SH concentration; Curing method			A higher SH concentration or curing with a higher temperature results in a higher f_c of AACs
[42]	Vijai et al.	2012	OPC/FA ratio; Curing temperature			A higher OPC/FA ratio or curing temperature results in a higher f_c
[43]	Deb	2013	GGBFS/FA ratio; SS/SH ratio; SH concentration; Curing method; Paste volume			An increase in GGBFS/FA ratio improves the early-age strength an durability of FA-based AACs; An addition of water or SP results in a decrease in f_c;
[44]	Demie et al.	2013	SP content	Self-compacting concrete	SP inclusion should be over 6% of binder content to significantly influences slump	An increase in SP content improve rheological properties, microstructure and f_c
[45]	Jamkar et al.	2013	FA fineness			FA with a higher fineness results in a improved workability and develops a higher f_c of AACs
[46]	Jeyasehar et al.	2013	ac/b ratio; SH concentration	Reinforced concrete beams	AAC and OPC beams have comparable performance for a given strength grade	A lower SH concentration leads to a higher f_c; f_c increases with an increase in ac/b ratio (up to 0.5)

(*continued on next page*)

Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[47]	Jaydeep and Chakravarthy	2013	SH concentration			A higher SH concentration results in a higher f_c of AACs
[48]	Kar et al.	2013	GGBFS/FA ratio; Ms ratio; Curing temperature		The optimum Ms ratio of SS for f_c is 1.4	An increase in GGBFS/FA ratio or curing temperature leads to improved mechanical properties and durability of AACs.
[49]	Sundar Kumar et al.	2013	GGBFS/FA ratio; SH concentration; Curing method			An increase in GGBFS/FA ratio, SH concentration or curing temperature leads to improved mechanical properties of AACs.
[50]	Lee and Lee	2013	SH concentration; SS/SH ratio; GGBFS/GGBFS ratio			An increase in GGBFS/FA ratio, SS/SH ratio or SH concentration leads to a decrease in setting time and an increase in f_c
[51]	Mathew et al.	2013	BA/FA ratio			A higher BA/FA ratio results in a lower f_c of AACs
[52]	Memon et al.(a)	2013	SF/FA ratio	Self-compacting concrete		An inclusion of SF in a FA-based AAC mix significantly improves the mechanical properties (up to 10% SF/FA ratio) and reduces rheological properties of the concrete
[53]	Memon et al.(b)	2013	SH concentration	Self-compacting concrete	The optimum SH concentration for f_c is 12 M	A higher SH concentration (up to 12 M) results in a higher f_c and reduced rheological properties of AACs
[54]	Parthiban et al.	2013	GGBFS/FA ratio; ac/b ratio			A higher GGBFS/FA ratio or ac/b ratio results in a higher slump and an improved f_c of AACs;
[55]	Patankar et al.	2013	l/b ratio; water addition		The optimum l/b ratio for fc should be within 0.25–0.35	A higher l/b ratio results in a lower f_c and improved workability of AACs
[56]	Radlińska et al.	2013	SH concentration; Curing temperature		Durability properties: AAC vs OPC	A higher SH concentration or curing temperature results in a higher f_c of AACs; AACs have a slightly lower elastic modulus than that of OPCs with a similar strength; AACs exhibit slightly better durability related properties than OPCs
[57]	Rashad	2013	GGBFS/FA ratio			A higher GGBFS/FA ratio leads to enhanced mechanical properties, a reduction in workability and more significant drying shrinkage of AACs
[58]	Reddy et al.	2013	SH concentration		AACs and OPCs of a similar strength grade exhibit comparable performance in marine environment	A higher SH concentration results in a higher f_c of AACs
[59]	Sarker et al.	2013	ac/b ratio; l/b ratio	Fracture properties established by conducting beam tests (notched)		A higher ac/b ratio or a lower l/b ratio results in a higher f_c; Failure of AAC under flexure is more brittle than that of OPC with a similar f_c
[60]	Sanni and Khadiranaikar	2013	SS/SH ratio; ac/b ratio		The optimum SS/SH ratio for mechanical properties is 2.5	A decrease in ac/b ratio reduces slump but enhances mechanical properties of AACs
[61]	Shrestha	2013	SH concentration; curing time/temperature/method; type of FA	Reinforced concrete pipes		An increase in SH concentration, curing temperature, curing time, or water content (at SH concentration of 14 M) results in a higher f_c; CaO content in FA governs the strength of the corresponding concrete under a given curing condition
[62]	Vora and Dave	2013	l/b ratio; SS/SH ratio; Curing temperature & time; Specimen's rest time		SP inclusion should be over 4% of binder content to significantly contribute to slump	An increase in SS/SH ratio, l/b ratio or SP content reduces fc of AACs whereas an increase in SH concentration, curing time or curing temperature enhances f_c of AACs; 1 day rest period enhances f_c of AACs; A higher l/b ratio or SP content results in improved workability AACs
[63]	Yost et al.	2013	AAC beams vs OPC beams	RC beam tests		AAC beams perform similar to OPC beams in terms of load carrying capacity and failure modes; At ultimate load, a AAC beam is in a more brittle manner compared to its companion OPC beam
[64]	Barnard et al.	2014	GGBFS/FA ratio; SS/SH ratio; l/b ratio; SH concentration		The optimum SS/SH ratio for f_c is 1.18; The optimum Fine to coarse aggregate ratio for f_c is 0.4	Mechanical properties of AACs increase with an increase in GGBFS/FA ratio, SH concentration, while decreases with an increase in SS/SH ratio, or l/b ratio; Slump decreases with an increase in GGBFS/MK ratio, SH concentration or total aggregate content
[65]	Ferreira et al.	2014	Type of solution; ac/b ratio; SH concentration	Precast facade panels		f_c increases with an increase in SiO_2/Na_2O or curing temperature

Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[66]	Krishnaraja et al.	2014	GGBFS/FA ratio			A higher GGBFS/FA ratio results in reduced setting time and slump flow, and improved mechanical properties
[67]	Kumar et al.	2014	SH concentration; SP content; Curing temperature & time; Specimen rest time		Less than 2% SP addition leads to significantly improved slump but nearly no effect on f_c of AACs	A higher SH concentration, SS/SH ratio, curing temperature, a longer curing time or specimen rest time (up to 3 days) results in improved mechanical properties
[68]	Kumaravel	2014	GGBFS/FA ratio			An increase in GGBFS/FA ratio results in a higher f_c of AACs
[69]	Malviya and Goliya	2014			Durability properties: AAC vs OPC	For a given f_c, AACs perform better than OPCs in resisting acid attack
[70]	Nagral et al.	2014	Curing temperature & time; Water addition & l/b ratio	Self-compacting concrete	Over 100° curing temperature is detrimental to f_c of AACs	A higher curing temperature (up to 90°) or a longer curing time results in a higher f_c. An addition of water in an AAC mix results in a decrease in fc and an improved slump
[71]	Nath and Sarker	2014	GGBFS/FA ratio; ac/b ratio; Curing temperature; SS/SH ratio			A higher GGBFS/FA ratio results in reduced setting time and slump flow while an increase in f_c; A higher curing temperature results in a higher f_c; A higher l/b ratio results in a decrease in f_c and an improved workability; An increase in SS/SH ratio results in reduced setting time and a slightly reduction in f_c
[72]	Parthiban and Mohan	2014	SH concentration; SS/SH ratio; Mixing time			A longer mixing time decreases workability of AACs; An inclusion of SP does not have a remarkable effect on AAC properties; A higher SH concentration (up to 12 M), or SS/SH ratio (up to 2) results in a higher f_c
[73]	Patil et al.	2014	Curing method			AACs with heat curing exhibit higher f_c than ambiently-cured AACs
[74]	Yusuf et al.(a)	2014	l/b ratio; Water content; H2O/Na2O molar ratio			A higher H_2O/Na_2O molar ratio results in a lower f_c
[75]	Yusuf et al.(b)	2014	POFA/GGBFS ratio; Curing time & temperature		The optimum curing temperature for f_c is 60°; The optimum GGBFS/POFA for f_c is 20%	A longer curing time results in a higher f_c
[76]	Yusuf et al.(c)	2014	SH concentration; curing method		The optimum SS/SH (at SH of 10 M) ratio for f_c is 2.5	The chemical composition of source materials as well as the proportion of SH and SS in an AAC mix significantly affect the f_c of the corresponding AAC regardless the curing method; f_c increases with an increase in SH concentration (up to 10 M)
[77]	Albitar et al. (a)	2015	l/b ratio; SP content			SP addition leads to only a slight decrease in f_c; A higher l/b ratio leads to a lower fc
[78]	Albitar et al. (b)	2015	GLSS/FA ratio, Curing time			A higher GLSS/FA ratio or a shorter curing time results in a decrease in f_c
[79]	Aravindan et al.	2015	SH concentration; Curing method		Over 100° curing temperature is detrimental to f_c of AACs	Application of 12 M SH in an AAC mix results in a higher f_c compared to the use of 16 M SH in short term (before 28 days)
[80]	Behfarnia et al.	2015	SH concentration; ac/b ratio; SS/SH ratio; Paste volume		Taguchi method; The optimum SH concentration for the mechanical properties is 6 M.	A higher ac/b ratio, or SH/SS ratio results in a lower f_c of AACs
[81]	Bidwe and Hamane	2015	SH concentration; ac/b ratio		Developed three grades of concrete C20-C30	f_c of AACs increases with an increase in SH concentration or ac/b ratio
[82]	Castel et al.	2015	Curing time & temperature	Bond tests		A higher curing temperature or a longer curing time results in enhanced mechanical properties of AACs; Chemical adhesion of AACs to the steel surface is similar to the one observed on OPCs
[83]	Gunasekara et al.	2015	Type of FA; l/b ratio			f_c of an AAC strongly correlates with its slump flow or UPV
[84]	Herwani	2015	SH concentration		The optimum SH concentration is 12 M	A higher SH concentration generally results in a higher f_c and a less significant drying shrinkage of AACs
[85]	Hussin et al.	2015	Elevated temperature	Fire performance	OPC vs AAC under elevated temperature	For a similar f_c, AACs exhibit less significant strength loss when subjected to elevated temperature compared to OPCs
[86]	JOSEPH	2015	Elevated temperature	Fire performance	OPC vs AAC under elevated temperature	For a similar f_c, AACs exhibit less significant strength loss when subjected to elevated temperature compared to OPCs
[87]	Lavanya and Jegan	2015	ac/b ratio		Developed four grades of concrete C20-C35	A lower ac/b ratio results in a lower f_c

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Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[88]	Nath and Sarker	2015	OPC/FA ratio; SS/SH ratio; ac/b ratio; Curing temperature			A higher OPC/FA ratio or a lower ac/b ratio results in a higher f_c; Slump flow and setting time of ACCs increase with an increase in l/b ratio, and decreases with an increase in OPC/FA ratio or SS/SH ratio; An increase in SS/SH ratio increases slump flow and delays setting
[89]	Okoye et al.	2015	Curing temperature; MK/FA ratio; SP content		Over 100° curing temperature is detrimental to f_c of AACs	NaOH solution performs better than KOH solution in developing f_c of AACs; An increase in SP content reduces f_c of AACs
[90]	Omar et al.	2015	SH concentration; SS/SH ratio; Paste volume, Curing time			A higher SH concentration, curing temperature (up to 60°) or SS/SH ratio results in improved mechanical properties and durability of AACs; An increase in H_2O/Na_2O results in a lower f_c
[91]	Parthiban and Vaithianathan	2015	MK/GGBFS ratio; SH concentration			A higher MK/GGBFS ratio or SH concentration results in a higher f_c
[92]	Ramani and Chinnaraj	2015	RHA/GGBFS			An increase in RHA/GGBFS ratio leads to reduced mechanical properties of AACs
[93]	Shojaei et al.	2015	SH concentration; ac/b ratio; SS/SH ratio;		The optimum ratio of ac/b ratio and SH/SS ratio are 0.5 and 1, respectively; The optimum ratio of SH concentration is 6 M	A higher ac/b ratio or SS/SH ratio results in a higher f_c
[94]	Junaid et al.	2015	l/b ratio; ac/b ratio; Curing time & temperature		Mixing design method	A higher ac/b ratio, curing temperature or a longer curing time results in a higher f_c while an increase in l/b ratio results in a lower f_c
[95]	Thomas and Peethamparan	2015	Binder content; Curing method	Compressive stress–strain behavior	GGBFS-, FA- based AACs vs OPCs	An increased binder content or curing temperature results in reduced f_c; FA-based AACs perform similar to OPCs in their mechanical properties where as GGBFS-based AACs are more brittle than OPCs
[96]	Topark-Ngarm et al.	2015	SH concentration; Curing method	Railway sleepers		A higher SH concentration (up to 15 M) or SS/SH ratio results in a higher f_c; Oven curing leads to a higher f_c compared to ambient curing
[97]	Vignesh and Vivek	2015	GGBFS/FA ratio			A higher GGBFS/FA results in a higher f_c
[98]	Wardhono	2015	FA based GPC vs. GGBFS based GPC			For a given f_c, GGBFS-based AACs exhibit better mechanical properties compared to FA-based AACs in short term
[99]	Xie and Ozbakkaloglu	2015	l/b ratio			f_c of AACs decreases with an increase in l/b ratio
[100]	Abhilash et al.	2016	GGBFS/FA ratio			A higher GGBFS/FA ratio results in a higher f_c
[101]	Aliabdo et al.(a)	2016	l/b ratio; OPC/FA ratio; SH concentration; SS/SH ratio; Curing time & temperature			A higher OPC/FA ratio leads to decreased slump; Increased paste volume leads to a higher f_c; An increase in OPC/FA ratio, curing temperature (up to 70°) or time results in improved mechanical properties and durability of AACs
[102]	Aliabdo et al.(b)	2016	Water addition; SP content; SH concentration; l/b ratio; SS/SH ratio			An increase in SP content results in reductions in mechanical properties and durability of AACs; A lower l/b ratio, a higher SS/SH ratio or a higher SH concentration (up to 16 M) results in a higher f_c
[103]	Assi et al.	2016	Water addition, FA type			The chemical composition of source materials affect mechanical properties and durability of AACs regardless curing method
[104]	Castel et al.	2016	Curing time & temperature			A higher curing temperature or a longer curing time results in a higher f_c and improved durability (shrinkage and creep) of AACs
[105]	Haddad and Alshbuol	2016	ac/b ratio; l/b ratio; SS/SH ratio; SH concentration; Curing time & temperature		Over 80° curing temperature is detrimental to f_c of AACs; The optimum ratio of SH concentration is 14 M	f_c of AACs increases with an increase in ac/b ratio (up to 0.45), SH concentration (up to 14 M), or SS/SH ratio (up to 3); An increase in l/b ratio results in a lower f_c
[106]	Jawahar and Mounika	2016	GGBFS/FA ratio			An increase in GGBS/FA ratio enhances mechanical properties of AACs

Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[107]	Kumar and Ramesh	2016	MK/GGBFS ratio			Mechanical properties of AACs first decreases with an increase in MK/GGBFS ratio up to 50% then increases with a further increase in MK/GGBFS ratio
[108]	Mahendran and Arunachelam	2016	FA/Copper slag ratio; Curing method			An increase in FA/Copper slag ratio or curing temperature generally results in a higher f_c and enhanced durability of AACs
[109]	Muthadhi et al.	2016	ac/b ratio; Curing method; SH concentration			An increase in SH concentration enhances mechanical properties of AACs
[110]	Muthuanand and Dhanalakshmi	2016	MK/FA ratio			An increase in MK/FA ratio results in enhanced mechanical properties of AACs
[111]	Nagalia et al.	2016	Curing method, time & temperature; SH concentration;		Different Activators	NaOH solution performs better than KOH, LiOH and Ba(OH)2 solution in developing higher f_c of AACs
[112]	Nguyen et al.	2016	ac/b ratio	Flexural behaviour of beams (FPB)	Mixing design method	An increase in ac/b ratio results in a higher f_c
[113]	Noushini et al.	2016	Curing method & temperature & time	Compressive stress–strain behaviour		An increase in curing time or temperature enhances mechanical properties of ACCs
[114]	Noushini and Castel	2016	Curing time & temperature			An increase in curing time or temperature of enhances mechanical properties of AACs; There is strong correlations between f_c and durability properties of AACs
[115]	Okoye et al.	2016	SF/FA ratio			A higher GGBFS/FA (up to 20%) enhances mechanical properties and reduced slump of AACs
[116]	Pavithra et al.	2016	l/b ratio		Mixing design method	f_c of AACs increases with a decrease in l/b ratio
[117]	Pouhet and Cyr	2016	H_2O/Na_2O ratio	Reinforced concrete beams	The optimum H_2O/Na_2O ratio is 17 M	f_c of AACs increases with a decrease in paste content
[118]	Rajarajeswari and Dhinakaran	2016	ac/b ratio; Curing temperature; SS/SH ratio		Over 80° curing temperature is detrimental to f_c of AACs	An increase in SS/SH ratio or curing temperature (up to 80°) leads to an increase in f_c of AACs; A higher ac/b ratio results in a lower f_c of AACs
[119]	Shalini et al.	2016	RHA/FA ratio; Effect of RHA, GGBFS and FA blend			An increase in RHA/FA ratio results in a lower f_c; With 10% GGBFS inclusion, an increase in RHA/FA ratio results in a lower f_c
[120]	Shehab et al.	2016	OPC/FA ratio; SH/SS ratio; l/b ratio;		The optimum H_2O/Na_2O ratio is 17 M	A higher l/b ratio or SH/SS ratio results in a lower f_c; A higher OPC/FA ratio (up to 50%) results in a higher f_c
[121]	Shinde and Kadam	2016	Curing method; SH concentration		The optimum OPC/FA ratio is 50%	An increase in SH concentration or curing temperature results in a higher f_c
[122]	Singh et al.	2016	Paste content; SH concentration	Compressive stress–strain behaviour	The optimum SH concentration is 14 M	f_c of AACs increases with an increase in SH concentration (up to 14 M) or an increase in paste content
[123]	Venkatesan and Pazhani	2016	RHA/GGBFS ratio; Curing temperature			Mechanical properties and durability of AACs enhance with an increase in curing temperature, and with a decrease in RHA/GGBFS ratio (over 10%)
[124]	Vinai et al.	2016	Paste volume; Water addition; ac/b ratio			A higher ac/b ratio results in a lower f_c; An increase in paste volume results in a higher f_c
[125]	Yadav	2016	SH concentration			An increase in SH concentration reduces workability and enhances mechanical properties of AACs
[126]	Gunasekara et al.	2017	FA type			The chemical composition of FA significantly affects mechanical and durability-related properties of AACs
[127]	Hadi et al.	2017	ac/b ratio; SS/SH ratio; Binder content; SH concentration		Taguchi method	A higher SH concentration, SS/SH ratio, or binder content (up to 450 kg/m^3) results in a higher f_c; A lower ac/b ratio results in a higher f_c
[128]	Hung et al.	2017	SH concentration		Developed three grades of concrete C20-C35	A higher SH concentration results in a higher f_c
[129]	Ibrahim et al.	2017	SS/SH ratio; ac/b ratio		A SS/SH ratio over 2.5 is detrimental to f_c of AACs	A increase in ac/b ratio results in a higher f_c and delayed initial and final setting time; A higher SS/SH ratio (up to 2.5) results in a higher f_c

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Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[130]	Kumar and Ramesh	2017	MK/GGBFS ratio; SH concentration			An increase in MK/GGBFS ratio or a decreased SH concentration leads to a less change in strength, better acid resistance and a decrease in f_c
[131]	Kothari	2017	M_s. of SS; GGBFS/FA ratio			A decrease in M_s. of solution results in a faster setting, less significant drying shrinkage and a higher f_c
[132]	Malleswara Rao and Hamantha Raja	2017	MK/GGBFS ratio			An increase in MK/GGBFS ratio results in reductions in mechanical properties of AACs
[133]	Manickavasagam and Mohankumar	2017	SH concentration; Curing method		The optimum SH concentration is 12 M	An increase in SH concentration (up to 12 M) leads to an increase in f_c of AACs
[134]	Mehta	2017	l/b ratio; SS/SH ratio; SH concentration; paste content; fine/coarse aggregate ratio; Curing temperature		A OPC/FA ratio over 20% is detrimental to f_c of AACs	An increase in OPC/FA ratio (up to 20%) results in improved mechanical properties and durability of AAC;
[135]	Mehta and Siddique	2017	OPC/FA ratio		A OPC/FA ratio over 20% is detrimental to f_c of AACs	An increase in OPC/FA ratio (up to 20%) results in a higher f_c of AACs;
[136]	Mehta et al.	2017	OPC/FA ratio; SH concentration; Curing temperature		Taguchi method; A SH concentration over 15 M or curing temperature over 80° is detrimental to f_c of AACs	A higher OPC/FA, SH concentration (up to 15 M) or Curing temperature (80°) enhances f_c of AACs
[137]	Mohankumar and Manickavasagam	2017	Paste volume; SH concentration			An increase in paste volume or SH concentration leads to enhanced mechanical properties of AACs
[138]	Nath and Sarker (a)	2017	OPC/FA ratio; GGBFS/FA ratio; l/b ratio; Paste volume			An increase in the calcium compounds in AACs enhances mechanical properties of AACs; The addition of extra water reduces f_c of AACs
[139]	Nath and Sarker (b)	2017	ac/b ratio; GGBFS/FA ratio	Fracture properties established by conducting beam tests (notched)	Water content over 35% of alkaline solution adversely affects mechanical properties of AACs	An increase in GGBFS/FA ratio or ac/b ratio results in improved mechanical properties of AACs
[140]	Neupane et al.	2017	Paste volume			A higher binder content results in a higher f_c; Ambiently cured AACs exhibits similar drying shrinkage compared to that of OPCs
[141]	Padmakar and Kumar	2017	MK/GGBFS ratio			An increase in MK/GGBFS ratio results in enhanced mechanical properties of AACs
[142]	Prakash	2017	ac/b ratio	Flexural behaviour of beams (FPB)	Developed four grades of concrete C20-C35	A higher ac/b ratio results in a higher f_c; Correlations between f_c and other mechanical properties of AACs are similar to those of OPCs of a same fc
[143]	Prasad and Kumar	2017	FA/GGBFS ratio; SH concentration			An increase in FA/GGBFS ratio or a lower SH concentration results in reductions in mechanical properties of AACs
[144]	QUADAR and SAMDANI	2017	ac/b ratio; SH concentration			An increase in SH concentration or a decrease in ac/b ratio results in enhanced mechanical properties of AACs
[145]	Rafeet et al.	2017	l/b ratio; GGBFS/FA ratio; Paste volume fraction		Mixing design method; A paste volume within 30–33% does not significantly affect f_c of AACs	An increase in GGBFS/FA ratio or a decrease in l/b ratio leads to a higher f_c of AACs; A higher l/b ratio results in a delayed setting
[146]	Ramujee and PothaRaju	2017	Water content		Developed three grades of concrete C20-C60	An increase in water content results in a lower f_c of AAC
[147]	Rostami and Behfarnia	2017	SF/GGBFS ratio			An increase in SF/GGBFS ratio results in enhanced mechanical and durability related properties of AACs
[148]	Sharma and Ahmad	2017	SH concentration; ac/b ratio; Curing temperature		A curing temperature over 100° is detrimental to f_c of AACs	A higher SH concentration (up to 18 M), ac/b ratio or curing temperature (up to 90°) results in a higher f_c
[149]	Talha Junaid	2017	GGBFS/FA ratio			An increase in GGBFS/FA ratio results in a faster setting and a generally enhanced mechanical properties of AACs
[150]	Takekar and Patil	2017	Curing method; GGBFS/FA ratio			A higher GGBFS/FA or curing temperature results in a higher f_c
[151]	Veerendra Babu et al.	2017	SH concentration			An increase in SH concentration results in enhanced mechanical properties and durability of AACs
[152]	Wardhono et al.	2017	FA- and GGBFS- based GPC			GGBFS-based AAC exhibits better early age stiffness compared to FA-based AAC
[153]	Zhang et al.(a)	2017	Curing temperature; OPC/FA ratio		A OPC/FA ratio over 5% is detrimental to f_c of AACs	An increase in OPC/FA ratio (up to 5%) results in reduced slump and improved mechanical properties of AACs

Table 1 (*continued*)

Ref.	Authors	Year	Parameters studied	Structural tests	Remarks	Major findings
[154]	Zhang et al. (b)	2017	Curing method			A higher curing temperature is vital for developing f_c of AACs; It suggests that to rest AAC at ambient temperature then to conduct heat curing benefits development of f_c of AACs
[155]	Al-Tais and Annapurna	2018	FA/VA ratio; RHA/VA ratio; GGBFS/VA ratio			An increase in FA/VA ratio or GGBFS/VA ratio leads to a higher f_c of AACs, whereas a higher RHA/VA ratio adversely affects f_c of AACs
[156]	Assi et al.	2018	FA particle size; FA source			FA with finer particle size leads to an increase in f_c and enhanced microstructure
[157]	Chithambaram et al.	2018	Total aggregate content; SH concentration; Curing temperature		A curing temperature over 90° is detrimental to f_c of AACs; The optimum aggregate content is 76%;	A higher SH concentration or aggregate content results in a lower slump
[158]	Ding et al.	2018	GGBFS/FA ratio; SH concentration; SS modulus; l/b ratio	Fracture properties established by conducting beam tests (notched)		The mechanical properties of AAC increase with a increase in SH concentration, Ms or GGBFS/FA ratio while decrease with an increase in l/b ratio
[159]	Fang et al.	2018	SH concentration; SS/SH ratio; ac/b ratio			Workability or setting time of AAC decrease significantly with a increase in SH concentration as well as a decrease in ac/b ratio; Mechanical strengths of AACs increase significantly with an increase in SH concentration or a decrease in ac/b ratio
[160]	Mallikarjuna Rao and Gunneswara Rao	2018	Binder content; FA/GGBFS ratio; ac/b ratio; Curing method		f_c increases with an increase in ac/b ratio to 0.5; A further increase in ac/b ratio results in a decreases in f_c	f_c of AACs increases with a increase in curing temperature SH concentration or GGBFS/FA ratio while decreases with an increase in ac/b ratio (over 0.5); An higher GGBFS/FA ratio results in a lower slump
[161]	Mehta and Siddique	2018	RHA/ GGBFS ratio		The optimum RHA/GGBFS ratio is 15%	An increase in RHA/GGBFS ratio up to 15% enhances mechanical properties and durability of AACs
[162]	Nagaraj and Babu	2018	SH concentration, SS/SH ratio			An increase in SH concentration reduces workability and increases f_c of AACs; An increase in SS/SH ratio concentration increases workability and f_c of AACs
[163]	Oyebisi et al.	2018	CCA/GGBFS ratio			An increase in CCA/GGBFS ratio results in reduced mechanical properties of AACs
[164]	Patel and Shah (a)	2018	RHA/FA ratio			For a given mix proportion, an increase in RHA/FA ratio (up to 5%) leads to enhanced mechanical properties and a further increase in RHA/FA ratio reduces mechanical properties of AACs
[165]	Patel and Shah (b)	2018	SH concentration; FA-based AACs vs GGBFS-based AACs; Curing temperature		The optimum SH concentration is 12 M	For a given mix proportion, FA as the source materials results in improved flow of AACs and reduced f_c compared to GGBFS; An increase in SH concentration leads to reduced slump of AACs and a higher f_c (up to SH at 12 M)
[166]	Phoo-ngernkham et al.	2018	SH concentration; ac/b ratio		Mixing design method	Setting time of AACs decreases with an increase in l/b ratio or SH concentration; A higher ac/b ratio or SH concentration leads to a higher f_c
[167]	Rai et al.	2018	SH concentration; ac/b ratio; SS/SH ratio; Curing temperature			f_c of AACs increase with an increase in curing temperature, SS/SH ratio, SH concentration (up to 14 M) or ac/b ratio.
[168]	Reddy et al.	2018	ac/b ratio		Mixing design method	A higher ac/b ratio results in a lower f_c
[169]	SUN et al.	2018	l/b ratio; Na_2O ratio; M_s of SS; unit water dosage		The optimum Na2O ratio, and M_s of SS are 8% and 1.6 respectively	An increase in l/b ratio leads to a lower fc; An increase in Na2O ratio (up to 8%), unit water dosage or Ms of SS (up to 1.6) leads to a higher fc;
[170]	Zhang et al.	2018	OPC addition; Curing method & temperature & humidity			A higher temperature can significantly improve f_c of AACs at early age
[171]	Aliabdo et al.	2019	SH concentration; SS/SH ratio; ac/b ratio; curing time & temperature		30° is the optimal curing temperature of GGBFS-based AACs	A higher SH concentration or curing temperature results in a higher f_c; A higher ac/b ratio or SS/SH ratio results in a lower f_c of GGBFS-based AACs
[172]	Hadi et al.	2019	GGBFS content; ac/b ratio; Additional water; SS/SH ratio			f_c decreases with an increase in ac/b ratio; A higher GGBFS content results in a higher f_c, reduced setting time and slump flow; An higher SS/SH ratio results in reduced setting time and a higher f_c

Table 2
Effects of different combinations of alkaline activators.

Ref.	Source	Year	Activator	Auxiliary activators	Source material (s)	Parameters studied	Remarks
[173]	Bondar et al.	2011	KOH	Na_2SiO_3	Natural pozzolan	Type of source materials; l/b ratio	No remarks on the effect of activators
[174]	Raijiwala et al.	2012	50%KOH + 50%NaOH	Na_2SiO_3	FA	Curing temperature	No remarks the on effect of activators
[175]	Yang et al.	2012	$Ca(OH)_2$	Na_2SiO_3	GGBFS	l/b ratio	Slump loss rate of $Ca(OH)_2$-based AACs is lower than OPCs; Use Na_2CO_3 as an auxiliary activator maintains 75% of slump after 2 hrs while Na_2SiO_3 based AACs have 50% of initial slump after 2 hrs
			$Ca(OH)_2$	Na_2CO_3	GGBFS		
[176]	Yang and Song	2012	$Ca(OH)_2$	Na_2SiO_3	GGBFS	l/b ratio	$Ca(OH)_2$ + Na_2SiO_3-based AACs exhibit improved mechanical properties than $Ca(OH)_2$ + Na_2CO_3-based AACs
			$Ca(OH)_2$	Na_2CO_3	GGBFS		
[177]	Bondar et al.	2013	KOH	Na_2SiO_3	Natural pozzolan	Type of source materials; l/b ratio	No remarks on effect of activators
[178]	Ambily et al.	2014	KOH	K_2SiO_3	Blended GGBFS, SF or/and FA		For a given mixing proportion, potassium hydroxide and potassium silicate based activators performs better than sodium hydroxide and sodium silicate based activators in terms of flowability and f_c
			NaOH	Na_2SiO_3	Blended GGBFS, SF or/and FA		
[89]	Okoye et al.	2015	KOH	Na_2SiO_3	FA + MK		For a given mixing proportion, sodium hydroxide and sodium silicate based activators performs better than potassium hydroxide and potassium silicate based activators in term of f_c
			NaOH	Na_2SiO_3	FA + MK		
[179]	Al-Majidi et al.	2016	K_2SiO_3		85% FA + 15% GGBFS		An increase in PS/binder ratio results in delayed setting and a decrease in f_c
[180]	Bilek et al.	2016	KOH	Na_2SiO_3	GGBFS	l/b ratio	No remarks on effect of activators
[111]	Nagalia et al.	2016	NaOH	Na_2SiO_3	FA	Different combinations of activators	NaOH > KOH > LiOH > Ba(OH)2 in developing f_c
			KOH	Na_2SiO_3	FA		
			$Ba(OH)_2$	Na_2SiO_3	FA		
			LiOH	Na_2SiO_3	FA		
			90% NaOH + 10% KOH	Na_2SiO_3	FA		90% NaOH + 10% KOH > 90% NaOH + 10% LiOH > 90% NaOH + 10% $Ba(OH)_2$ = 90% NaOH + 10% $Al(OH)_3$ > 90% NaOH + 10% $Mg(OH)_2$ in developing f_c
			90% NaOH + 10% Ba $(OH)_2$	Na_2SiO_3	FA		
			90% NaOH + 10% LiOH	Na_2SiO_3	FA		
			90% NaOH + 10% Al $(OH)_3$	Na_2SiO_3	FA		
			90% NaOH + 10% Mg $(OH)_2$	Na_2SiO_3	FA		
			50% NaOH + 50% KOH	Na_2SiO_3	FA		50% NaOH + 50% KOH > 50% NaOH + 50% LiOH > 50% NaOH + 50% $Ba(OH)_2$ = 90% NaOH + 10% Al(OH)3 > in developing fc
			50% NaOH + 50% Ba $(OH)_2$	Na_2SiO_3	FA		
			50% NaOH + 50% LiOH	Na_2SiO_3	FA		
			50% NaOH + 50% Al $(OH)_3$	Na_2SiO_3	FA		
[181]	Satpute et al.	2016	KOH	Na_2SiO_3	FA	Different combinations of activators	KOH + Na_2SiO_3 > KOH + K_2SiO_3 > KOH + $CaSiO_3$ in developing f_c; KOH + Na_2SiO_3 > NaOH + Na_2SiO_3 > Ca $(OH)_2$ + Na_2SiO_3 in developing f_c
			KOH	K_2SiO_3	FA		
			KOH	$CaSiO_3$	FA		
			NaOH	Na_2SiO_3	FA		NaOH + Na_2SiO_3 > NaOH + $CaSiO_3$ > NaOH + K_2SiO_3 in developing f_c; Ca(OH) 2 + K_2SiO_3 > NaOH + K_2SiO_3 > KOH + K_2SiO_3 in developing f_c
			NaOH	K_2SiO_3	FA		
			NaOH	$CaSiO_3$	FA		
			$Ca(OH)_2$	Na_2SiO_3	FA		$Ca(OH)_2$ + K_2SiO_3 > $Ca(OH)_2$ + Na_2SiO_3 > $Ca(OH)_2$ + $CaSiO_3$ in developing f_c; NaOH + $CaSiO_3$ > Ca(OH) 2 + $CaSiO_3$ > KOH + $CaSiO_3$ in developing f_c
			$Ca(OH)_2$	K_2SiO_3	FA		
			$Ca(OH)_2$	$CaSiO_3$	FA		

SH), concentration of sodium hydroxide, superplasticizer (SP)-to-binder weight ratio, mineral replaced FA ratio and total liquid-to-binder ratio, on the workability of fresh AAC using experimental results collected from the literature.

The effect of SS/SH ratio on the slump of AAC is shown in Fig. 2 (a) using the results reported in [17,50,65,71,102,159]. The slump of ACC is found to generally increase with a reduction in SS/SH ratio when the SS/SH ratio over 1, while below this threshold (SS/SH ratio = 1) a higher SS/SH ratio leads to an increased slump. This behaviour likely arises because SS solution as the auxiliary activator is more viscous than most of the main alkaline solutions (e.g. NaOH or KOH) [159], hence when added at high proportions (e.g. SS/SH ratio over 1), the overall slump of the concrete is dramatically affected. Moreover, an increase in SS/SH ratio increases the soluble silica content, which subsequently accelerates the rate of the polymerization and hence increases the overall viscosity of the fresh mix [71].

As is evident from the results depicted in Fig. 2(b) [19,90,102,159], an AAC mix with a SH activator of higher molarity exhibits a lower slump. This can be attributed to the increased viscosity of SH with an increased molarity and also to the accelerated leaching of silica and alumina from source materials under a higher pH condition [96].

The effect of conventional chemical admixtures (e.g. superplasticizer) on the slump of AAC is shown in Fig. 2(c) using the results reported in [62,67,77,102]. As in an OPC based concrete, SP plays a role as a dispersant, driven by the electrostatic repulsion at an interparticle level, helping to disperse the particles thereby improving workability [196,197]. Similar to its performance in an OPC based concrete, increasing the dosage of SP in an AAC leads to an improved slump, as illustrated in Fig. 2(c). It is noteworthy that in a FA-based AAC, SP is observed to improve the workability of the concrete more effectively than in an OPC based concrete (refer to the more rapid increase in slump of the FA-based AAC with only a small increment of SP content as shown in Fig. 2(c)). This behaviour occurs because the polycondensation or formation of hydrates in a FA-based AAC does not require the participation of water, hence SP acts to disperse FA particles in the mix and helps release unbonded water from the flocs during the mixing process, further helping to fluidize the fresh concrete [198].

Fig. 2(d) illustrates the experimental results reported in [43,57,71,101,115,135,153] that present the influences of mineral incorporations on the slump of AAC in which FA is the primary binder. It can be seen when partially replacing FA by high-calcium minerals (e.g. OPC or GGBFS) the slump of concrete reduces with increasing content of the minerals. When FA replaced with silica-rich materials (e.g. SF) only a slight reduction in the slump of the corresponding AAC is observed. These phenomena can be explained by the fact that the increased content of calcium bearing compounds increases the rate of hydration (as opposed to polymerization), while also consuming free water [135,199], which subsequently increases the viscosity of the entire mix and minimizes the effect of particle dispersion. Even considering the finer particle size of SF, the blend of silica-rich materials with FA does not significantly change the kinetics and the rate of reaction in an AAC concrete at its very green stage and hence has a minimal effect on the slump.

The effect of the total liquid-to-binder ratio on the slump of AAC is examined using the results from [55,65,71,160] in Fig. 2(e). This ratio is commonly analogous to the effect of water-to-cement ratio on the slump of OPC based concrete, and as with OPC based concrete it is seen that the slump of an AAC generally improves with

Table 3
Effects of retarders.

Ref.	Authors	Source	Retarder	Activator	Source material(s)	Parameters studied	Remarks
[187]	1991	Douglas et al.	Lime slurry	SS	GGBFS		Lime slurry is added to a AAC mix at a weight ratio of 1:1 to GGBFS
[188]	2008	Al-Otaibi	Lime slurry	SS	GGBFS		Lime slurry is added to an AAC mixes in a weight ratio of 1:1 to Na2O ratio in activator
[189]	2010	Nuruddin et al.	Sugar/Glucose	SS + SH	FA	Sugar/FA content of 1,2 or 3%	With 1% glucose addition, final setting time of AACs delays from 20 mins to 30 mins and its f_c increases of 18.8%
[190]	2011	Nuruddin et al.	Sugar/Glucose	SS + SH	FA	Sugar/FA content of 3%	
[33]	2012	Chi	Phosphoric acid (H_3PO_4)	SS + SH	GGBFS	Phosphoric acid/Na_2O weight ratio of 4,5 or 6%	An increase of Na2O concentration decreases slump of AACs with H3PO4. Meanwhile, an increase of 1% Na2O needs the increase of H3PO4 of 20% for achieving the approximate initial setting time of 120 min.
[50]	2013	Lee and Lee	Phosphoric acid (H_3PO_4)	SS + SH	80%FA + 20% GGBFS	Phosphoric acid/binder weight ratio of 0.5, 1, 1.5, 2 or 2.25%	H3PO4 cannot effectively delay setting of blended FA and GGBFS based AACs
[192]	2015	Albitar et al.	Gypsum	SS + SH	50%FA + 50% granulated lead smelter slag	5%, 10% or 15% gypsum addition	Gypsum cannot effectively delay setting of blended FA and GGBFS based AACs
[193]	2017	Karthik et al. (a)	Terminalia chebula combined with one of natural sugars including molasses, palm jaggery, honey	SS + SH	60%FA + 40% GGBFS	Both bio-additives were added 0.8% by the weight of aluminosilicate minerals.	Prolonged initial and final setting time are achieved by all the combinations of the retarders
[194]	2017	Karthik et al. (b)	Terminalia chebula combined with one of natural sugars including molasses, palm jaggery, honey	SS + SH	60%FA + 40% GGBFS	Both bio-additives were added 0.8% by the weight of aluminosilicate minerals.	
[195]	2018	Askarian et al.	Citric acid ($C_6H_8O_7$)	SS + SH	Blended OPC, FA and GGBFS	Citric acid/OPC weight ratio of 0.4%	Citric acid can be added to retard AACs setting by minimize impacts of OPC and slag hydration

increasing total liquid-to-binder ratio. This behaviour occurs because the increased content of liquid helps disperse the dry particles in the mix and reduce the friction and interactions between the particles.

3.2. Initial and final setting time

As noted previously, binders in AAC have a higher tendency to undergo a flash set which hinders the practical application. It is therefore necessary to evaluate and understand the effects of the mixing parameters of AAC on the initial and final setting time such that future mix designs can be improved. Fig. 3(a)–(d) depict the effects of SS/SH ratio, concentration of sodium hydroxide, mineral replaced FA ratio, and total liquid-to-binder ratio on the initial and final setting time of AAC.

It can be seen from experimental results [50,71,96,159] shown in Fig. 3(a) that, in general, no significant change in either the initial or final setting time occurs when the SS/SH ratio used for the concrete mix is lower than 2. Conversely, when the SS/SH ratio is over 2, setting time is strongly dependent on SS/SH ratio. As reported in [71,200], at a higher SS dosage, the increased SS/SH ratio accelerates the rate of dissolution of source materials, subse-

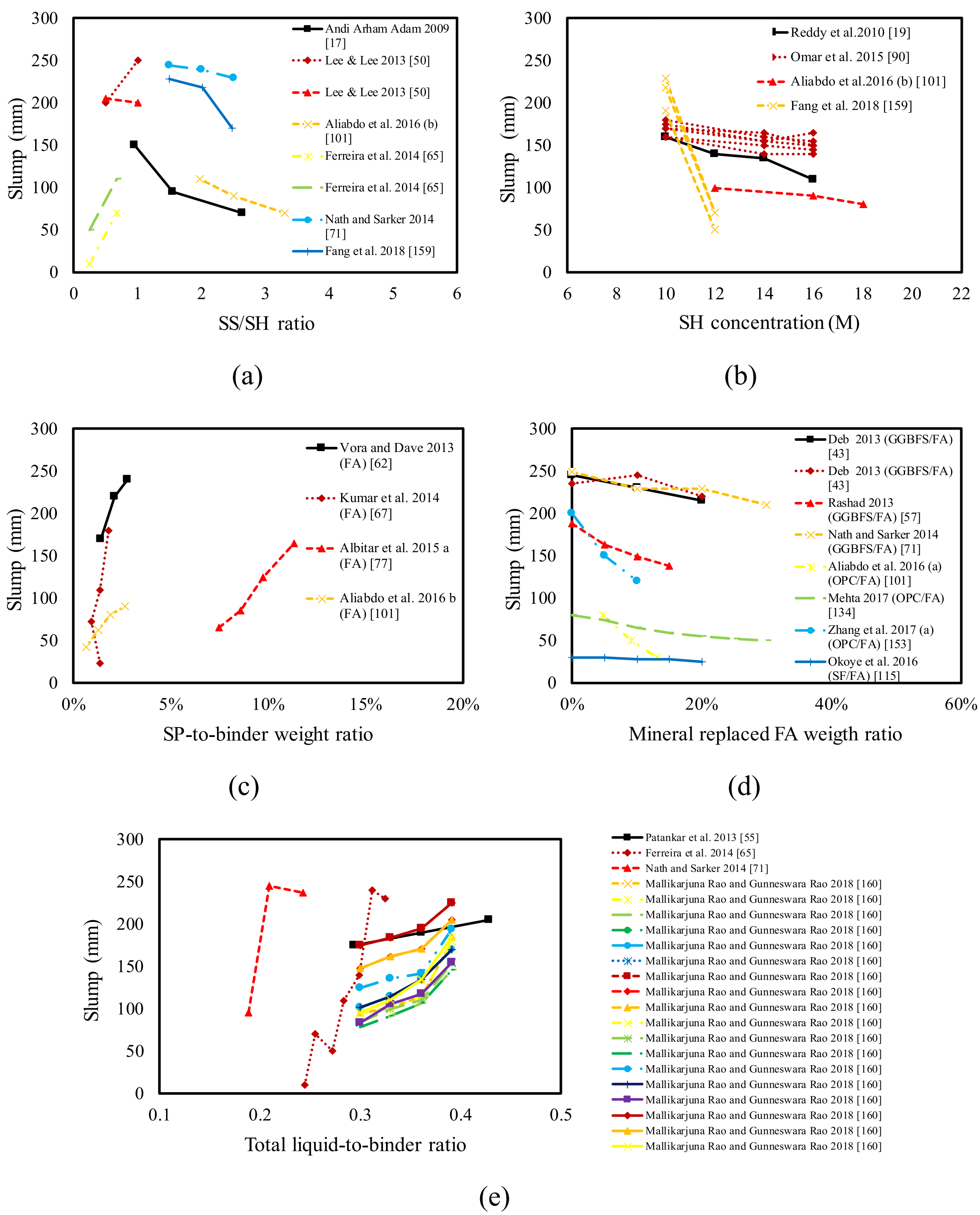


Fig. 2. Effects of factors on fresh properties of GPCs: a) sodium silicates-to-sodium hydroxide ratio (SS/SH); b) concentration of sodium hydroxide; c) SP-to-binder ratio; d) mineral-to-fly ash ratio; e) total liquid-to-binder ratio.

quently altering the reaction kinetics and the condensation process, which results in rapid initial and final setting.

Fig. 3(b) shows the effect of SH concentration on setting time using the results reported in [50,159], where an SH morality over 10 M shortens the setting time of the concrete. This phenomenon is due to both the increased dissolution of Si^{4+} and Al^{3+} from the source material at a higher pH environment and the change in silica modulus (SiO_2/Na_2O) in the dual activators consisting of SH and SS [200,201]. For an AAC mix with SH at a lower molarity (e.g. lower than 6 M as shown in Fig. 3(b)), no significant influence of SH concentration on setting time is observed. This is because of the relatively slow rate of dissolution and polycondensation or formation of hydrates. It is however worth mentioning that flash setting can occur in AACs even when using SH at low molarity, e.g. the results presented in [159] (Fig. 3(b)) show a final set of less than 60 min with an SH concentration of less than 6 M. This finding can be attributed to the high calcium content in the source materials (slag) used for these mixes.

The influences of silica or calcium additive on setting time assessed using the results reported in [71,127] and is presented in Fig. 3(c). It can be seen that an increased content of high-calcium aluminosilicates (e.g. FA, MK or SF added into the binder in a GGBFS-based AAC as reported in [127]) a slightly prolonged setting, whereas a higher content of calcium-rich additive in silica-alumina-rich primary source materials (e.g. GGBFS added into the binder in a FA-based AAC as reported in [127]) results in a more rapid setting of the binder. These phenomena indicate that the setting time of the binder in AAC is sensitive to the content of calcium compounds. That is, for a given mix, the efficiency and rate of the reactions in AAC are greatly affected by the proportion of calcium compounds in them. The underlying mechanism of this action is that the addition of a calcium containing compound to a low-calcium binder (unary or blended) increases the rate and extent of calcium dissolution allowing for the formation of cementitious C-S-H hydrates or amorphously structured polymeric products (e.g. C/N-A-S-H) via polymerization [99,184].

Regardless of the alkali content, SS/SH ratio, or the concentration of SH, an increase in overall liquid content (i.e. amount of water and alkaline liquids) to binder ratio in an AAC binder concrete mix delays setting significantly, as clearly shown in Fig. 3 (d) according to the experimental work in [71,159]. This mainly results from the effect of the water in the alkaline liquid interfering with the dissolution of the aluminosilicate source and the subsequent polycondensation [184]. Note that this is different to the mechanism occurring in an OPC based binder, in which part of the mixing water is chemically bonded in hydration products, in the polycondensation phase in AAC, then the water involved in dissolutions of source materials is released and thus halts the rate of reaction, resulting in a prolonged setting time of AAC binders [202,203].

3.3. Compressive strength

Compressive strength is an essential indicator of the quality of concrete. In this section, the effects of the critical factors on the compressive strength of AAC, including different forms of liquid

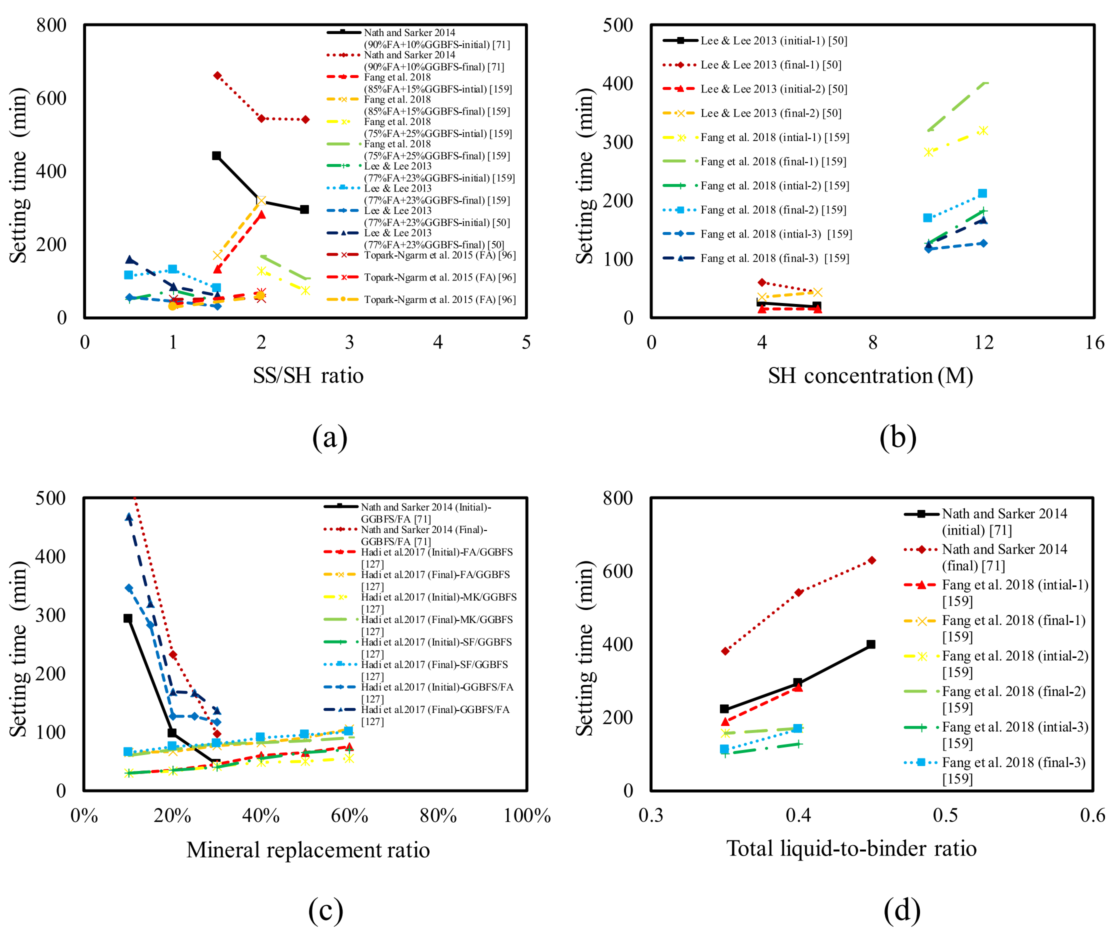


Fig. 3. Effects of factors on initial and final setting time of GPCs: a) sodium silicates-to-sodium hydroxide ratio (SS/SH); b) concentration of sodium hydroxide; c) mineral-to-fly ash ratio; d) total liquid-to-binder ratio.

to-binder ratios (total liquid-to-binder ratio (l/s), water-to-binder ratio (w/s) and sodium alkaline solution-to-binder ratio (a/s)), combined effects of alkaline activator components (silicate-to-sodium hydroxide ratio (SS/SH) and concentration of sodium hydroxide), concrete mixing parameters (sp-to-binder ratio, binder-to-total aggregate volume ratio, fine-to-coarse aggregate volume ratio) and curing regime (curing temperature, and heat curing time and delayed handling time of concrete) are reviewed.

3.3.1. Effects of different liquid substances

Fig. 4(a)–(c) illustrates the effects of different liquid-to-binder ratios on the compressive strength of AAC. It has been reported in some previous studies on AAC, e.g. [55] that, the effect of liquid-to-binder ratio on the compressive strength of AAC is analogous to that of water-to-binder ratio on the compressive strength of an OPC-based concrete. However, this simplification may not fully represent the actual reaction mechanisms and kinetics driven

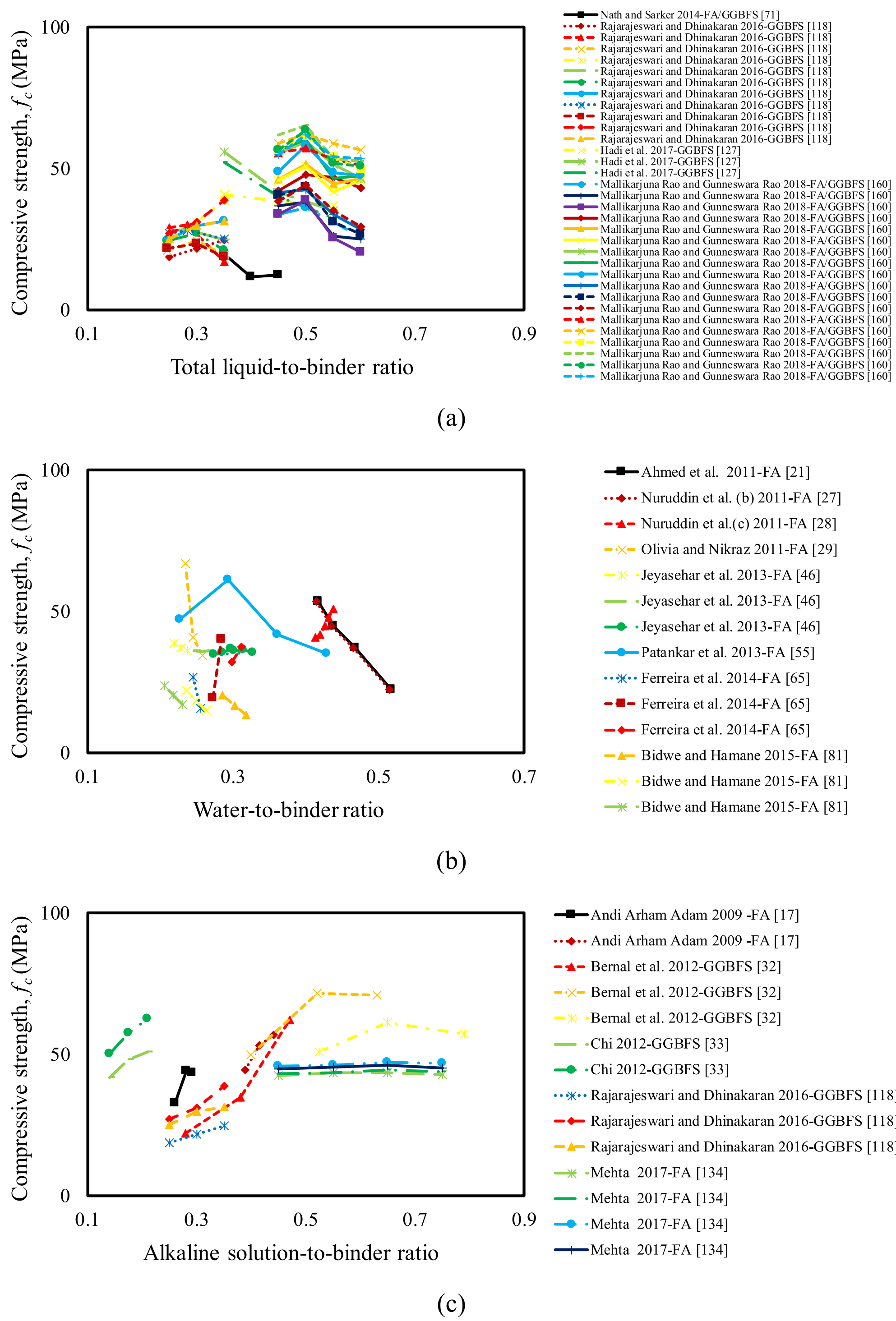
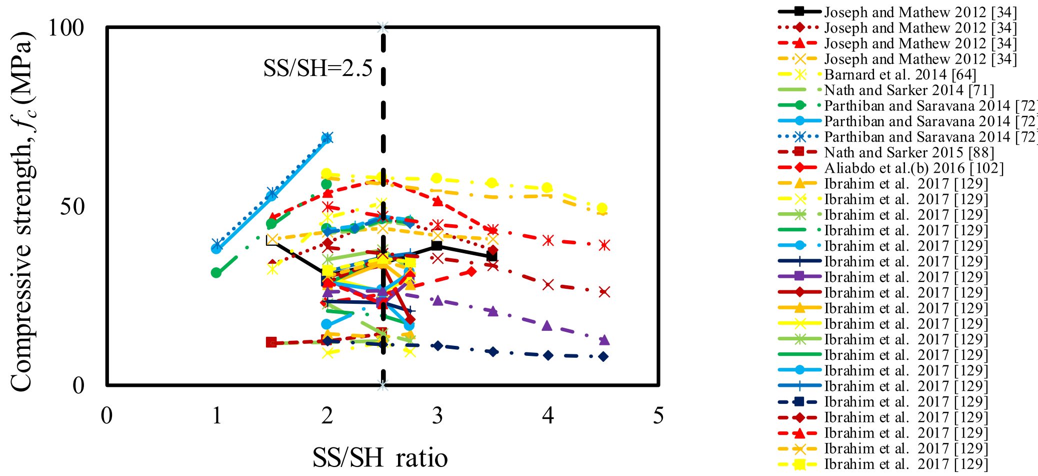
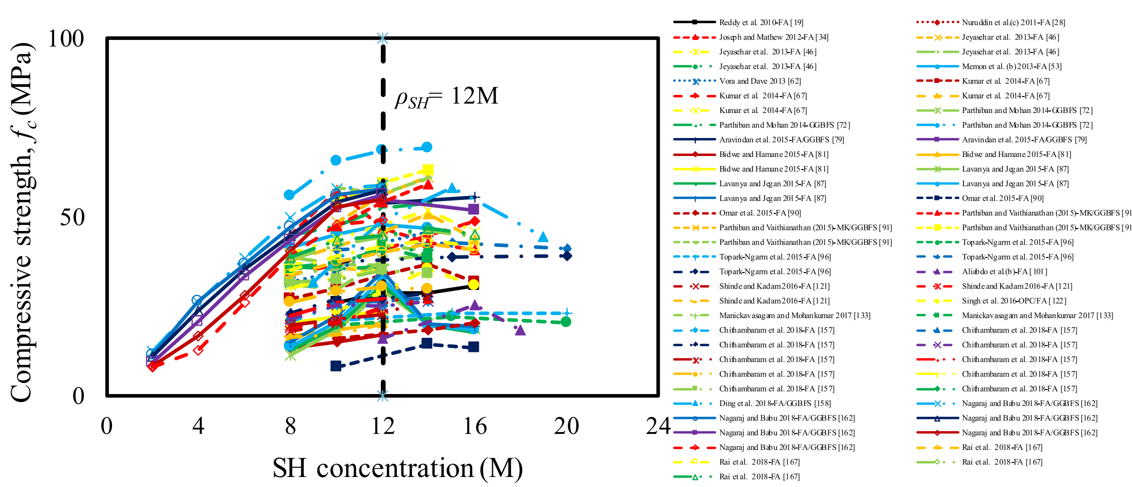


Fig. 4. Effects of factors on compressive strength of GPCs: a) water-to-binder ratio; b) alkaline solution-to-binder ratio; c) total liquid-to-binder ratio; d) sodium silicates-to-sodium hydroxide ratio (SS/SH); e) concentration of sodium hydroxide; f) curing temperature; g) heat curing time; h) binder-to-total aggregate ratio; i) fine-to-coarse aggregate ratio; j) sp-to-binder ratio; k) specimen rest time.



(d)



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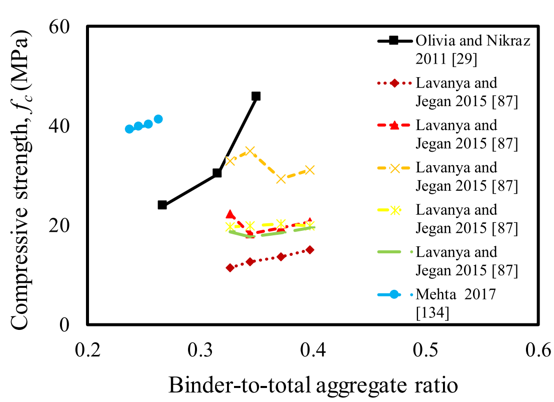
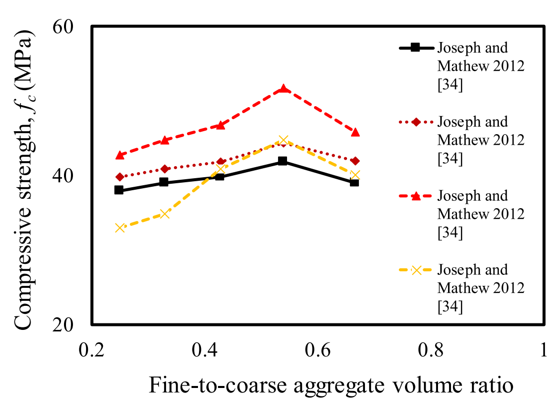


(f)



(g)

Fig. 4 (*continued*)

by the liquids in AAC. That is, the liquid added to OPC typically is a single chemical composition (H_2O), while the liquids used in the preparation of an AAC are commonly a blend of alkalis (e.g. NaOH), soluble silica sources (e.g. sodium silicate), and water. The major types of reactions governing the strength developments in AAC- and OPC- binders are hence different, namely hydration of OPCs and mostly polymerization of the binders in AAC, and the kinetics of both the reactions are greatly affected by the nature, proportions and compositions of the liquid substances used for the concrete mixes. In this section, the effects of liquid substances on the

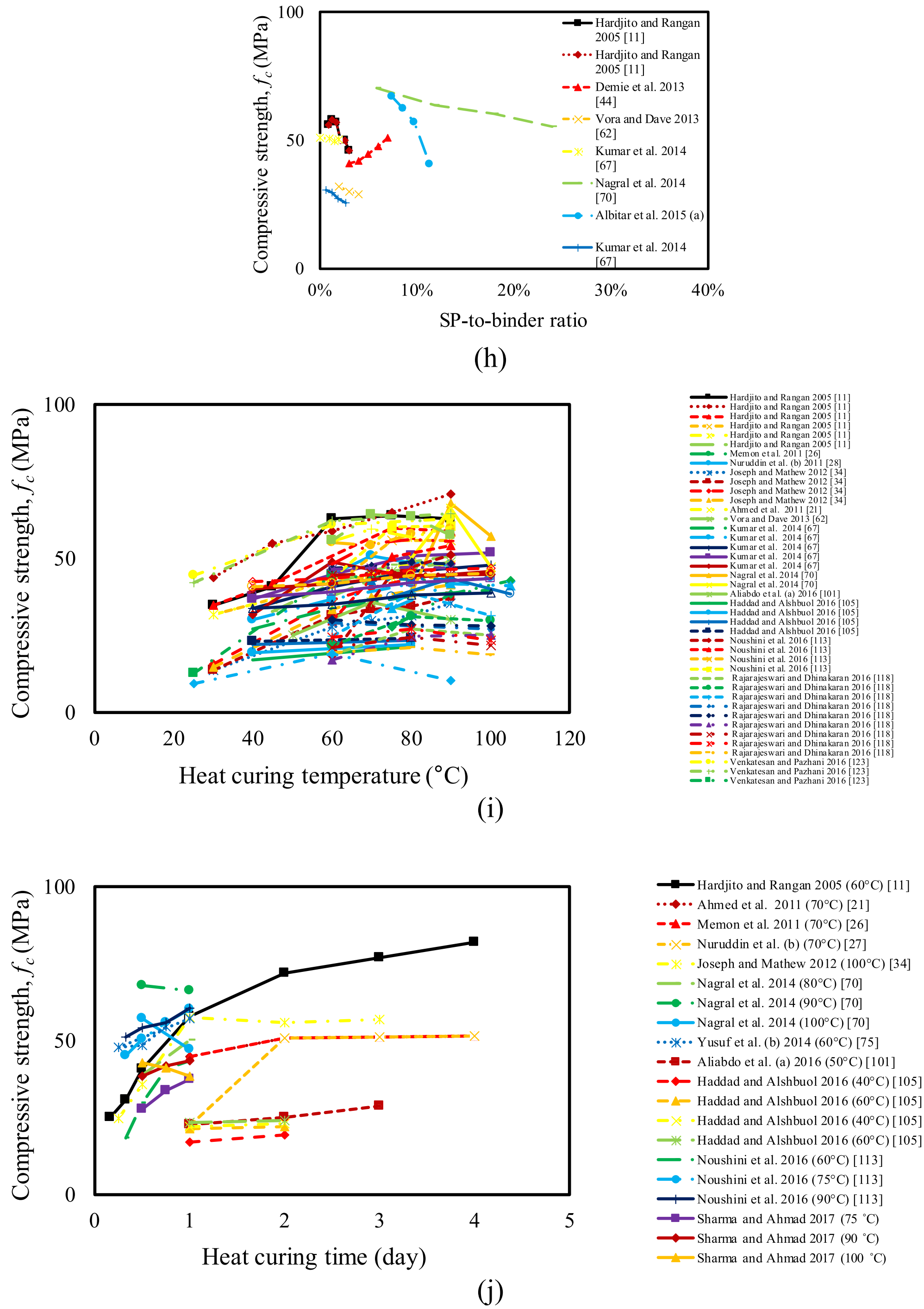
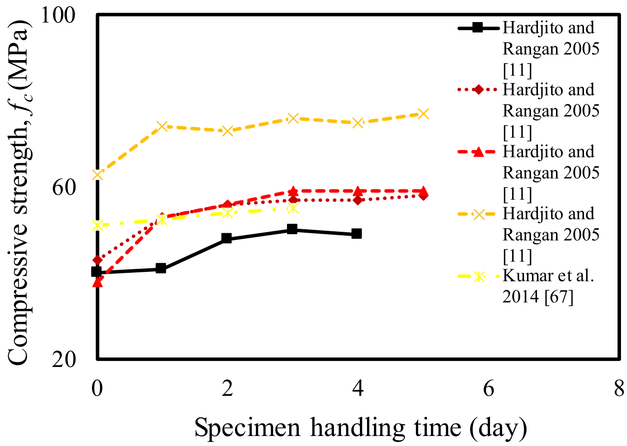


Fig. 4 (*continued*)

compressive strength of AAC are assessed at three different levels: 1) total liquid that contains alkali, soluble silica source and water; 2) water alone; and 3) alkaline activators that provide alkali cations (e.g. a blend of alkali and soluble silica source).

3.3.1.1. Effect of total liquid-to-binder ratio. Fig. 4(a) shows the experimental results collected from [71,118,127,160] that report the effect of the total liquid-to-binder ratio on the compressive strength of AAC. As can be seen from the figure, when considering all the liquids in an AAC mix as a whole, there is no clear relationship between the compressive strength of the concrete and the corresponding total liquid-to-solid ratio. This suggests that the total liquid-to-binder ratio of an AAC mix is not a proper indicator of the compressive strength of concrete, or at least it does not play the same role as does the water-to-binder ratio in an OPC based concrete.

3.3.1.2. Effect of water-to-binder ratio. For a given proportion of alkali (main activator) and soluble silica source (auxiliary activator), the effect of water content on the compressive strength of AAC is shown in Fig. 4(b) using the experimental results collected from [21,27–29,46,55,65,81]. This analysis shows that there is also no clear relationship between the compressive strength of AAC and the water-to-solid ratio used in the corresponding mixes. Note



(k)

Fig. 4 (*continued*)

that, the amount of water used to calculate the water-to-solid ratio includes mixes with extra water, SP, and the alkaline activators. Unlike the water in an OPC-based binder, which acts as the driving force of the primary chemical reaction (hydration) [199,204], water in an AAC mix only partially contributes to the initial dissolution of source materials and later the polycondensation process [11,205]. Hence it does not strongly affect the resulting compressive strength. Excessive water, which is mostly physically bonded in AAC, does however tend to increase the porosity of the concrete and therefore may result in inferior mechanical and durability properties [11,17,99]. This phenomenon is reflected by the experimental results presented in Fig. 4 (b).

3.3.1.3. Effect of total alkaline activators-to-binder ratio. To study the effect of total alkaline activator-to-binder ratio on the compressive strength of AAC, results from the experiments [17,32,33,118,134] prepared with a given total liquid-to-binder ratio, constant water content and different contents of alkaline activators are shown in Fig. 4 (c). It can be seen that by eliminating the effects of total liquid-to-binder ratio and the content of water, the compressive strength of an AAC generally increases with an increase in the total alkaline solution-to-binder ratio. This finding highlights that alkaline activators most strongly drives the strength developments of AAC.

The review presented in this subsection (3.3.1) indicates the effects of liquids in OPCC and AAC are completely different. The well-known inverse relationship between water-to-binder ratio and compressive strength of OPCC cannot guide the mix proportion design of AAC to attain the designated strength. The effects of liquids in AAC mixes on the properties of the concrete products need to be assessed from more fundamental views, such as the type of components of liquids and the chemical composition of the liquids.

3.3.2. Effects of components of alkaline liquids

Alkaline activators for AAC are commonly a mixture of soluble silica (e.g. sodium silicate), alkali (e.g. sodium hydroxide) and water. In this section, the specific effects of the components of the liquids in terms of sodium silicates-to-sodium hydroxide ratio (SS/SH) and concentration of sodium hydroxide on the compressive strength of the concrete are further examined. Fig. 4(d) and (e) present the combined effect of SS/SH ratio and the combined effect of water and sodium hydroxide (i.e. the concentration of sodium hydroxide), respectively. It can be seen from Fig. 4(d) and (e) that based on the experimental results collected from [34,64,71,72,88,102,129,134,162] and [19,28,34,46,52,62,67,72,79,81,87,90,91,96,102,121,122,133,157,158,162,167], respectively, an increase in SS/SH ratio or SH concentration up to a threshold limit, results in an increase in the compressive strength of AAC. When the SS/SH ratio or the SH concentration exceeds this threshold (in most cases SS/SH ratio > 2.5 and SH concentration > 12 M depending on the physical and mineralogical properties of the source materials as well as the concrete mixing proportions), further increases in SS/SH or SH concentration results in a reduction in compressive strength.

It is known that the mechanical strength of AAC binders is greatly affected by the level of dissociations of silica and alumina from source materials as well as the content of the soluble silica species from sodium silicate solutions. Firstly, consider when the SS/SH ratio exceeds the threshold noted above, the presence of high content of cyclic silicate species hinders the process of polycondensation and subsequently reduces the mechanical strength of the corresponding binder/concrete. Moreover, insufficient sodium hydroxide in the mix prevents the dissolution of reactive silica and alumina from binders to complete the condensation process [206,207], thereby reducing the strength of the concrete.

Now consider the influence of SH concentration on compressive strength. Leaching of silica and alumina from source materials is increased with SH molarity, this causes the formation of more polymeric networks and results in a higher compressive strength. When the concentration of SH solution exceeds the identified threshold (e.g. commonly 2.5 for low calcium FA-based AAC mixes), further increase in SH molarity reduces the stability of oligomeric silicate species (e.g. $Si_4O_8(OH)_6{}^{2-}$, $Si_4O_8(OH)_4{}^{4-}$)) and species equilibrium shifts to the formation of the mononuclear silicate species (e.g. $SiO_2(OH)_2{}^{2-}$, $SiO(OH)^{3-}$) and generates excessOH^-. These excess hydroxide ions, in turn, reduce the effectiveness of the polycondensation process and subsequently decreases compressive strength [208–213].

3.3.3. Effects of concrete mixing parameters and curing regimes

In addition to the influences of different quantities of liquid in AAC, parameters including concrete mix proportions and the curing regime also influence compressive strength as follows.

3.3.3.1. Effects of concrete mix proportions. Fig. 4(f) and (g) present the experimental results from [29,87,134] and [34], respectively showing the influence of the interactions among paste, coarse and fine aggregates. The effects of the paste-to-total aggregate volume ratio and fine-to-coarse aggregate volume ratio on the compressive strength of AAC are nearly identical to their effects on the compressive strength of OPCC even though the types of binder and the reaction kinetics of the two concrete types are completely different. At a low to moderate strength grade, which is common for AAC, an increase in paste volume to a moderate amount increases the compressive strength of the concrete as a result of improved aggregate packing enabled by the paste. This is true for a paste-to-binder ratio lower than 0.4, which is the same as the range reported for OPCCs [199,204] and neglecting the long-term effects of AAC binder on aggregates (e.g. alkaline-silica reaction). As shown in Fig. 4(g), an increased content of fine aggregate in AAC enhances the homogeneity of the matrix and hence improves the mechanical properties of the concrete.

Due to the undesirable slump and setting of AAC discussed in Sections 3.1 and 3.2, chemical admixtures such as high range water reducers (superplasticizers), are often used to improve the fresh properties of AAC. Commercially available superplasticizers are not specially developed for AAC and hence the modification of AAC flow by SP is quantified based on visual inspections during the mixing procedure or via multiple trial tests. In most reported

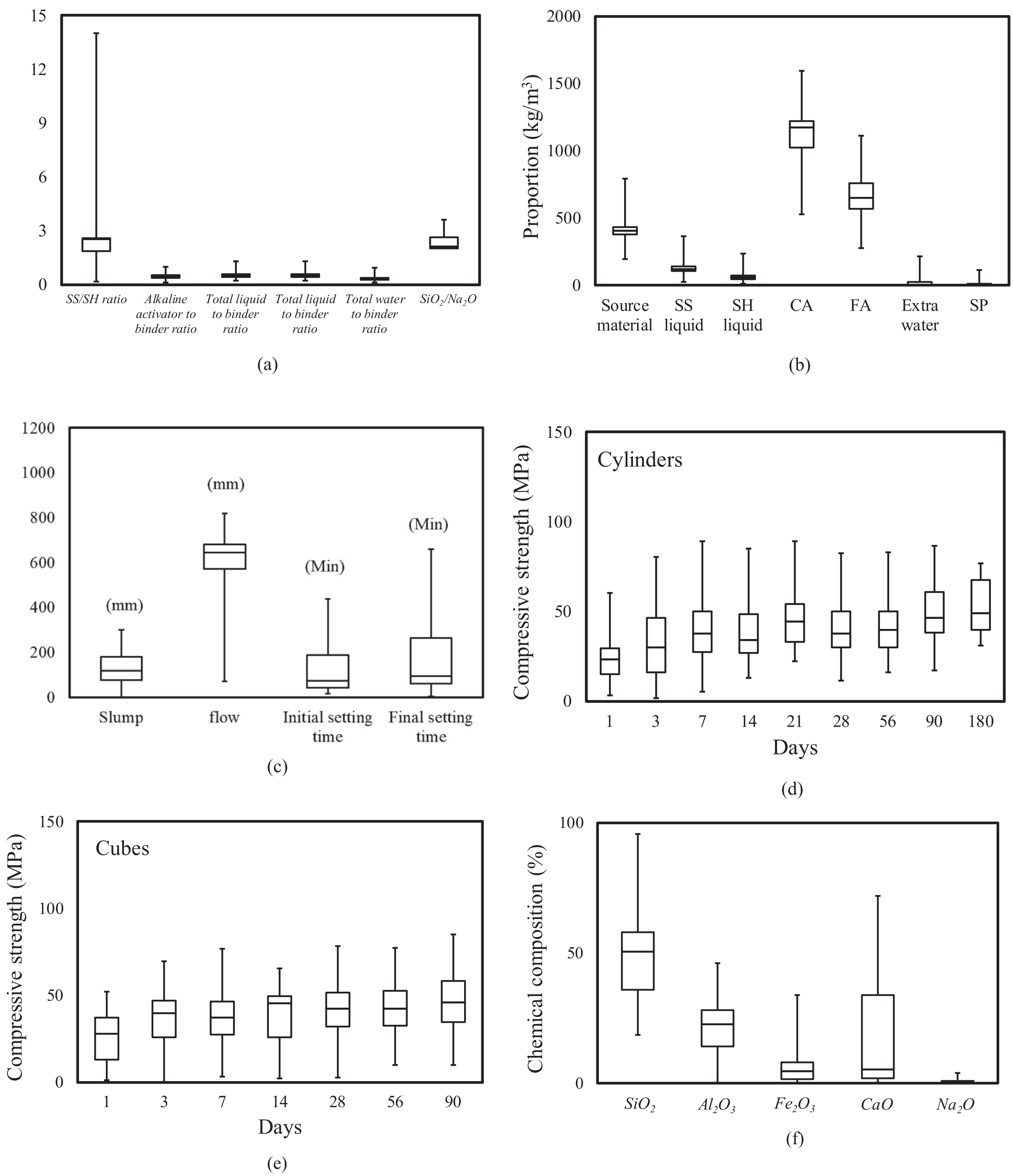


Fig. 5. Statistics of database: a) critical mixing ratios; b) critical mixing proportion; c) fresh properties; d) cubic compressive strength; e) cylindrical compressive strength; f) chemical proportion of source material.

investigations, superplasticisers are added into an AAC mix together with extra water until visibly desirable workability [78,99,192]. However, it would be more beneficial to utilize SP in a designated amount (e.g. a fixed SP-to-binder ratio as in OPCCs), to control unexpected flash setting, higher viscosity of the alkaline activator, or other influential factors that an AAC mix is sensitive to, such as ambient temperature, moisture of surrounding environment or rate of airflow.

Uncontrolled addition of chemical admixtures hinders systematic investigation of the impact of the superplasticizer on the hardened properties of AAC. Fig. 4(h) illustrates a subset of the experimental results [11,44,62,67,70,77] to isolate the effect of SP content in terms of the SP-to-binder weight ratio on the compressive strength of AAC. Regardless of the chemical basis of SPs, in general, it can be seen from the figure that the compressive strength of AAC generally decreases with an increase in the amount of SP used. This can be explained by an increase in pores or voids forming in the matrix as SP content is increased, as well as changes in the initial rate of dissolution of the aluminosilicate sources by the addition of water to the mix (approximately 60–70% of SP volume can be considered to be water). These mechanisms are similar to those well-known effects of the SP on the

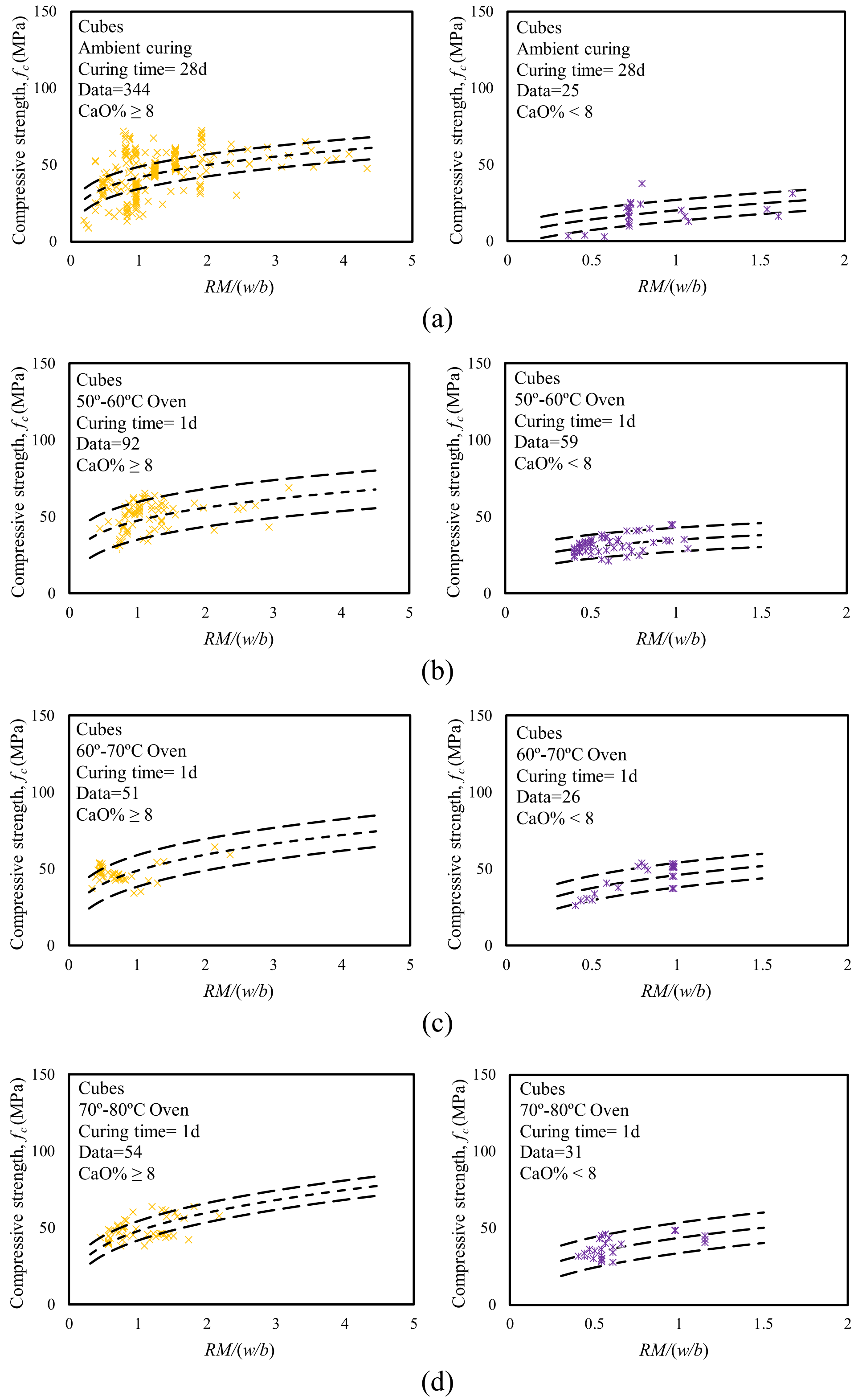
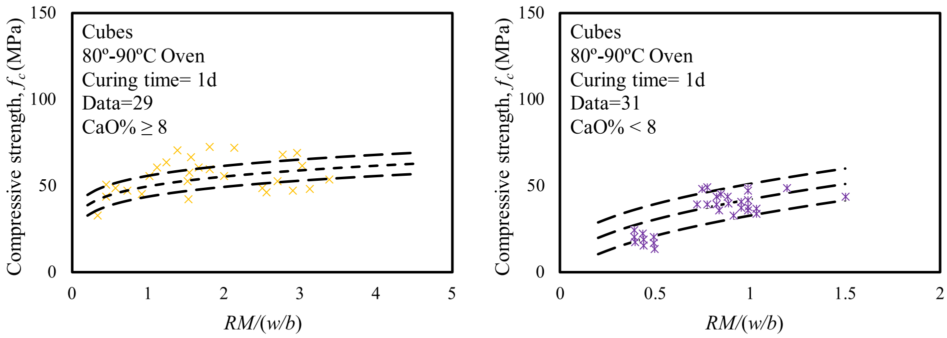


Fig. 6. A unified approach for assessing cubic compressive strength of GPCs under: a) ambient curing; b) 50–60 °C oven curing; c) 60–70 °C oven curing; d) 70–80 °C oven curing; e) 80–90 °C oven curing.

properties of OPC based concrete. Note that some opposite trends are shown in Fig. 4(h), in which the compressive strength of AAC increases with an increase in the SP content. This is mainly attributed to a more compacted microstructure of AAC due to the enhanced workability by the additional SP, leading to the refinement of the pore structures in conjunction with the facilitation of the evacuation of air [214–216]. For instance, the increase in the compressive strength with increasing SP content reported in Demie et al. [44] and shown in Fig. 4(h) is mainly due to their AAC mixes designed to attain self-consolidating, and the increase



(e)

Fig. 6 (*continued*)

in SP content subsequently improves the compaction of concrete and leads to the increase in the strength of the concrete.

3.3.3.2. Effects of heat curing. Unlike OPCCs which are predominately cured under ambient or standard fog room conditions, the curing of AAC, in particular those prepared using lower calcium source materials, requires a higher temperature to promote the formation of a spaced 3D structure and enhanced bonds that characterise a high performing material [70]. Fig. 4 (i) illustrates the influence of the curing temperature on the compressive strength of AAC using the results reported in [11,21,26,27,34,62,67,70,101,105,113,118,123,134,148,167]. In this figure, it can be seen that the compressive strength of AAC does not always increase when subjected to an elevated temperature. A very higher curing temperature (e.g. over 90 °C) adversely affects the compressive strength of AAC. This is attributed to the continuous loss of moisture in the concrete when subjected to a high temperature, leading to more voids due to water evaporation, and cracks induced by self-desiccation and drying shrinkage of the binder [217]. It is also observed from Fig. 4 (i) that the efficiency of heat curing on the compressive strength of AAC is also affected by the strength grade of the concrete (refer to the vertical scatters of the compressive strength in Fig. 4 (i) for each given curing temperature). When subjected to an elevated temperature an AAC designed with a low target compressive strength exhibit less significant strength gain during curing compared to an AAC designed with a higher target compressive strength. Moreover, as can also be seen from the figure, the temperature that the decrease in the compressive strength of AAC initiated is also lower for a concrete designed with a lower compressive strength. These observations can be explained by the fact that an AAC mix designed with a lower target compressive strength has insufficient source materials and solutions to support the rapid reaction that occurs under higher temperature.

Fig. 4 (j) presents the effect of heat-curing duration on the compressive strength gain of AAC [11,21,26,27,34,70,75,101,105,113,148], where the development of the compressive strength of AAC is typically seen to be completed within the first 24 to 48 hr under heat curing. After this point, only a slight increase in the compressive strength occurs because near complete polymerization is typical within the first 24–48 h. Note that the results reported in [70] shown in Fig. 4 (j) are contrary to the above-established relationship between the compressive strength of AAC and the heat curing duration. These contradictory findings, in which the strength decreases with heat curing, were mainly caused by the relatively high curing temperature used (80 and 90 °C, respectively).

In addition to the curing temperature and duration, some studies have also suggested there is a need for resting or delayed handling of AAC under ambient conditions prior to the commencement of heat curing. Fig. 4 (k) shows the effect of the specimen rest time on the compressive strength [67,218], where it is observed that a longer resting time prior to heat curing results in improved compressive strength. The exact underlying mechanism governing the effect of the delayed handling time on the compressive strength of an AAC still remains unclear. The explanation offered by Davidovits [218] is that in the resting period, hydrogen produced via the reaction between the metallic components in source materials and the alkalis are released from fresh concrete, eliminates voids caused by the gas bubbles, which subsequently leads to a higher compressive strength of the concrete. Another potential explanation is that the initial rest allows for moisture distribution/diffusion in concrete. This helps to minimize localized cracks due to the loss of moisture during the high temperature curing process. These mechanisms are however believed to only partially explain the effect of AAC handling time on compressive strength owing to the lack of fundamental investigations to comprehensively characterize the effect of delay handling of AAC, hence further explorations are needed.

4. A unified approach for assessing the compressive strength of aac cured under different temperatures

4.1. Existing approaches for modelling the compressive strength of AAC using fundamental chemical compositions

In addition to the above review of the mix parameters of AAC, the chemical and mineralogical compositions of the source materials that form the binder in AAC is recognized to critically influence the properties of AAC. The source materials supply glassy silica and alumina that are activated by alkaline solutions to form a polymeric gel network and hence to support the development of mechanical properties. A comprehensive review by Reddy et al. [219] presented attempts to establish the relationships between the mechanical properties of AAC (compressive strength) and the chemical composition of the corresponding source materials and alkaline activator (i.e. the percentage of oxides from source materials including CaO, Al_2O_3, SiO_2, Fe_2O_3, the composition of oxides from alkaline activators including H_2O, Na_2O and SiO_2). In this work the individual or a combination of the critical oxides of the unary or blended source materials were plotted against the compressive strength of the AAC prepared using the binders. The work of Reddy et al. importantly identified the types and quantities of oxides required in an AAC mix to enhance its compressive strength. Despite identifying the importance of oxides, the approach

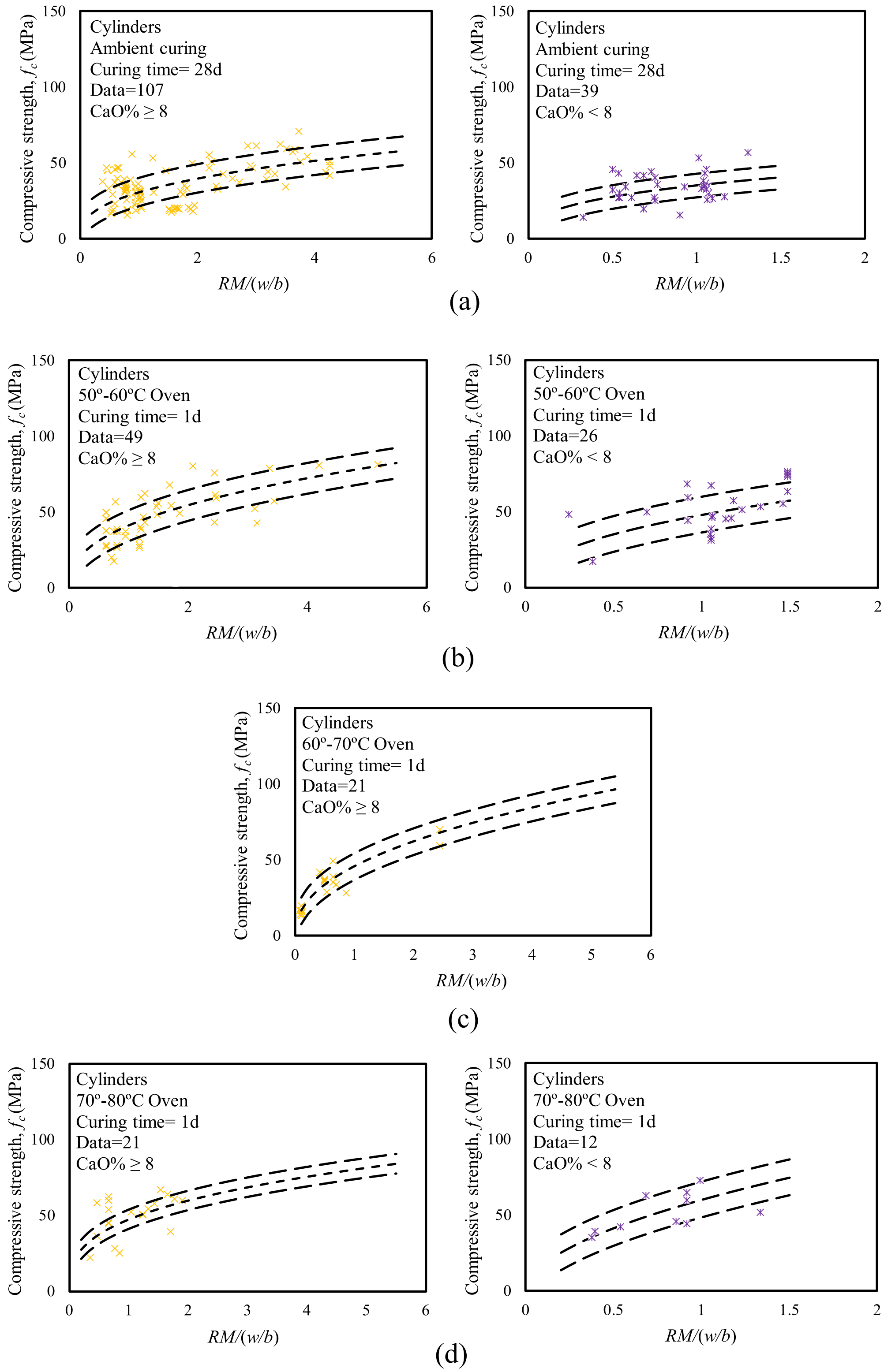
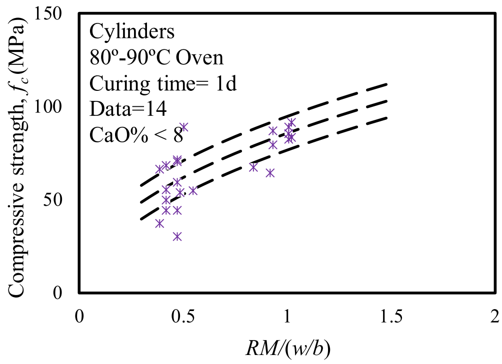


Fig. 7. A unified approach for assessing cylindrical compressive strength of GPCs under: a) ambient curing; b) 50–60 °C oven curing; c) 60–70 °C oven curing; d) 70–80 °C oven curing; e) 80–90 °C oven curing.

developed by Reddy et al. did not generate clear trends between the combinations of oxides and the compressive strength of the AAC. This may have been because the effect of each oxide from source materials was assessed individually rather than combining them based on reaction kinetics, or because the mixing parameters such as the proportions of binder and activator were not considered, or because the effect of curing regime on the compressive strength was ignored.

Thomas et al. [220] undertook a systematic stepwise regression analysis to model the compressive strength of AAC using the chemical composition of source materials and alkaline solutions including considerations of the key mixing and curing parameters, such



(e)

Fig. 7 (*continued*)

as the total liquid-to-binder ratio, as the inputs for the model. Although the data driven approach provided adequate predictions for the compressive strength of AAC, it failed to address the following problems. Only part of the chemical composition (e.g. only Na_2O and SiO_2) from source materials were considered in this method; and the effect of curing regime on the compressive strength was only considered generally (i.e. only ambient or oven curing where the effect of specific curing temperature was not considered); and the effects of individual liquids in alkaline solution (e.g. SS, SH and water) were not quantified in the model. Further, being based on the application of machine learning, some parameters included in the model do not have a physical meaning.

Loya et al. [221] developed an approach to predict compressive strength by assessing the effect of the reactivity of fly ash on compressive strength of AAC using the ratio between nonbridging oxygens (NBO) and tetrahedrons (T) based on the structure of the three-dimensional network of FA-based AAC products. A strong correlation was seen between the NBO/T ratio and the compressive strength of the AAC (38 datasets). A limitation of this study is that, except for the varied sources of fly ash (which provide a different chemical composition), only a single mix design and curing regime was considered.

Besides the three above mentioned methods which utilised a wide range of experimental results and considered the reaction kinetics and/or mixing proportions, there exist many other approaches reported in literature aiming to link the critical mix design parameters and the compressive strength of AAC (e.g. [222,223]). These approaches are however either developed based on individual or limited experimental campaigns, or significantly lack physical meanings (e.g. do not consider mix proportions, curing regime or reaction kinetic/mechanism and are therefore more limited in transferability and generalization). In the following subsections, based on a large experimental database, a unified design-oriented approach is introduced to establish the relationships between the key parameters for AAC mixes and the compressive strength of the concrete produced using the mixes.

4.2. Experimental database

Of the 163 studies reviewed, the results reported in 111 of them were selected to construct an experimental database to develop a unified approach to establish the relationship between fundamental mixing parameters of AAC mixes and their compressive strengths. When selecting the experimental results, the following criteria were subjected:

1) Detailed chemical compositions of the source materials and alkaline activators in terms of the weight proportions of oxides must have been provided;
2) Mix proportions of AAC must have been reported in detail;
3) Mixes containing unnatural and reactive aggregates, as well as superfine source materials (e.g. nano-materials) were excluded as their effects on the properties of AAC are not within the scope of this study;
4) Only AAC produced using the alkaline activators that are comprised of sodium silicate and sodium hydroxide were included because of the limited volume of data for other activators and the change in reaction efficiencies or kinetics; and
5) The compressive strength of AAC must be obtained by testing a standard cylindrical specimen with an aspect ratio of 2 or a cubic specimen with an aspect ratio of 1.

For each of the 1756 individual AAC mix proportions collated from these 111 studies detailed mix design and the associated physical and mechanical properties of the resulting AAC are reported in Table A1. The chemical composition and the physical (Blaine fineness and specific gravity) properties of the corresponding source materials are summarized in Table A2.

To provide an overview of the range of the database, the fresh and hardened concrete properties and the range of the critical chemical composition of source materials in these two databases are graphically shown in Fig. 5(a)–(e). In addition to those shown in the figures, the curing temperature of the AAC reported in Table A1 is varied from 20 to 120 °C; specimen handling time is varied from 0 to 5 days; the heat curing time is varied from 0 to 28 days; and the relative humidity for curing is varied from 0 to 100%.

4.3. Oxides governing the reactivity of source materials

The chemical composition of source materials reported in Table A2, are shown graphically in a ternary diagram in Fig. 1 to help identify the primary oxides that predominate the reaction kinetics in AAC. Silica (SiO_2) from the source materials and sodium silicate solution, and alumina (Al_2O_3) from the source materials are recognized as the two oxides most strongly influencing the properties of AAC. This is because the two species are activated by the alkaline solution to yield semi-crystalline polymeric products that consist of Si-O-Al and Si-O-Si bonds [219].

For source materials containing a higher content of calcium (e.g. OPC, GGBFS or class C FA), the presence of the calcium compound significantly changes the reaction kinetics and the corresponding reaction products. It is well-known that the introduction of calcium compounds in an AAC leads to an accelerated dissolution process. The formation of C-A-S-H hydrates in addition to the N-A-S-H network, with the C-A-S-H hydrates acting as nucleation sites promoting an increased rate of condensation and enhanced mechanical and durability properties [184]. When using the strict terminology for a concrete binder with chemically activated materials, the presence of calcium makes the resulting material 'alkali activated' rather than a 'geopolymer' [224]. However, because the terms of 'geopolymer concrete' and 'concrete with alkali activated binders' are commonly used interchangeably or even as synonyms, this argument is not further raised in this review work, and the effect of calcium is directly considered in the proposed unified approach which is reported in the following sections.

Finally, Fe_2O_3 is also recognized as a major contributor to the oxide composition in that it is present in the majority of source materials such as coal ash and slag. Based on the reports in [225], the presence of Fe_2O_3 inhibits the formation of C-A-S-H hydrates in the high calcium AAC system, however it improves the properties of products in low calcium AAC binder via replacing Al^{3+} by Fe^{3+} in octahedral sites as reported in [226].

4.4. Primary factors influencing compressive strength of AAC

Based on the parameters that significantly control the compressive strength of AAC identified in Section 3.3, the following factors are selected to assess their combined effect on the compressive strength of AAC:

1) Properties of alkaline solution (e.g. dosage and composition)
2) Reactivity of source materials based on their fundamental chemical compositions (e.g. oxides)
3) Oven curing temperature
4) Mixing proportion (e.g. ratio between pure water and binder)

Methods of how to apply these factors in the proposed unified method are presented in the following of this subsection. The effects of individual components in the alkaline solutions for an AAC are considered separately, where the activator is divided into three parts, including water, NaOH solid, and Na_2SiO_3 solid. The effects of the dual activators containing NaOH and Na_2SiO_3 on the compressive strength of AAC are further represented using the oxides SiO_2 and Na_2O in the solution. SiO_2 and Na_2O from the NaOH and Na_2SiO_3 solids are added to those of the unary and blended source materials when calculating the reactivity modulus (RM) of each binder. The total water in alkaline solution together with the extra water for AAC mixes and the proportion of water in the chemical admixture (e.g. commonly around 60–70% by weight) are considered as a whole.

As introduced in Section 4.3, the four oxides CaO, SiO_2, Al_2O_3 and Fe_2O_3, in conjunction with Na_2O which is majorly from alkaline solution with a trace from source materials, are recognized as the major contributors to the final chemical structure of geo-solids. Table A2 summarises the chemical composition of each source material, and because of the relatively small proportions of MgO and K_2O, the effects of these two oxides on the compressive strength of AAC are ignored. The reactivity of unary or blended binder of AAC are determined based on the weight proportion of total oxides present by defining the relativity modulus as:

$$RM = \frac{CaO + Na_2O}{SiO_2 + Al_2O_3 + Fe_2O_3} \tag{1}$$

In Eq. (1) the oxides in the denominator represent the alkalinity of the mixes, while the oxides in the numerator represent the ability to form a framework of polymeric products or hydrates. This definition is similar to that reported by [221,227,228]. To assess the effect of curing temperature on the compressive strength, all the data for oven-cured AAC were first divided into multiple subsets based on the range of their curing temperature, where each subset contains the experimental results within a 10 °C temperature interval (e.g. 50–60 °C, 60–70 °C, 70–80 °C, 80–90 °C and 90–100 °C). The results of those cured under ambient conditions are collected in another data subset. Because of the small quantity of results including steam or immersed curing as well as the effects of the fineness of binder materials, the experimental work associated with these three factors is not considered further.

After dividing the data into subsets, the combined effects of the selected parameters are investigated within each of the given temperature ranges. Due to the limited range of heat curing durations in each given temperature interval (the majority of studies adopt 24 hrs), the curing period is not considered a parameter in the proposed approach. Therefore, the results of AAC subjected to 1-day heat-curing are used in each of the sub-datasets for analysis. Similarly, because a resting time of 24 h is commonly applied for the majority of AAC, specimen handling time is also not considered

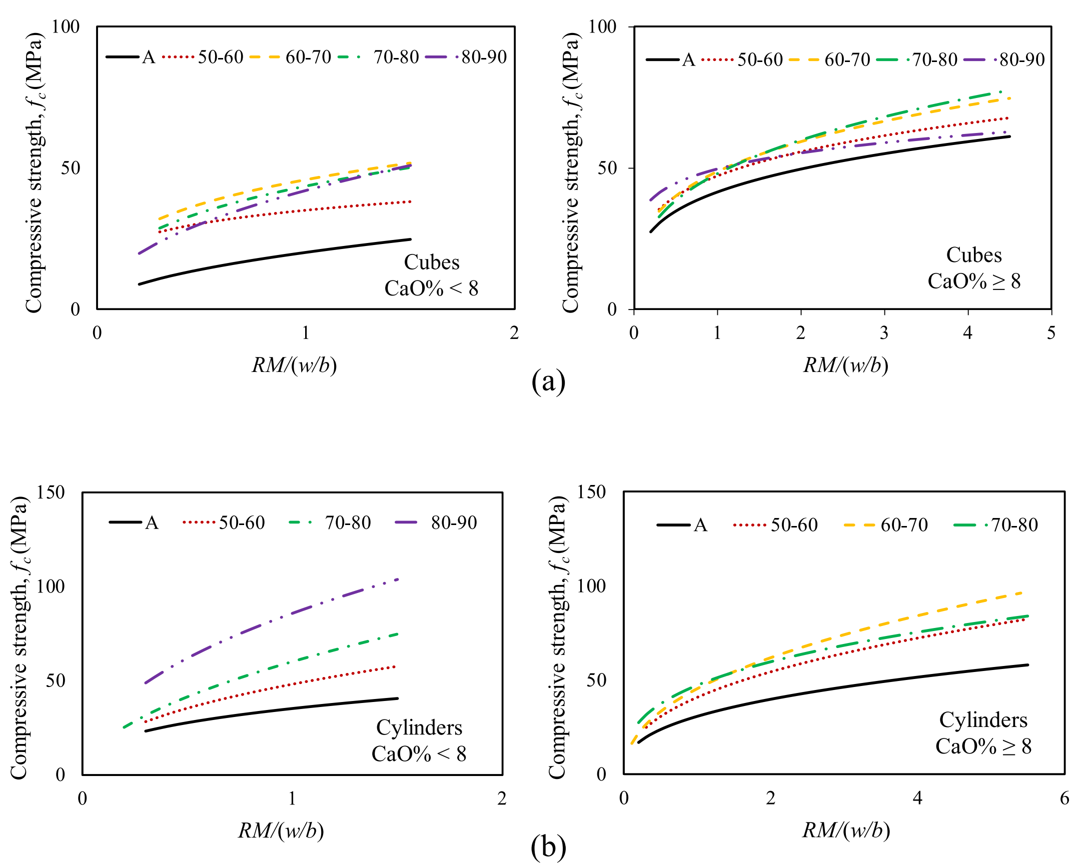


Fig. 8. Comparison among the global trends for compressive strength of GPCs cured under different temperatures: a) cubes; b) cylinders.

further. For the ambient-cured AAC, a 28-day compressive strength is selected to represent the hardened properties of the concrete.

Since it is known that, for a given range of curing temperature, the compressive strength of AAC increases with an increase in the binder reactivity (*RM*) and decreases with an increase in the water content in the mix, the combination of the two factors in the form of $\frac{RM}{(w/b)}$ is used to assess its effect on the compressive strength of AAC.

The generic form of this approach is a power function (Eq. (2)), where it should be noted that for calibration the database is split further into subsets for cylindrical and cubic specimens and for low and high calcium content. Moreover, because of the relatively small range of the binder-to-total aggregate weight ratio (mostly within 0.2–0.4) and the fine-to-coarse aggregate weight ratio (e.g. mostly within around 0.5–1.0), the effects of these two parameters are not considered further.

$$f_c = a\left(\frac{RM}{(w/b)}\right)^b \tag{2}$$

4.5. A unified approach for assessing the compressive strength of AAC at a given temperature interval

Fig. 6(a)–(e) illustrates the relationship between the selected parameters and the cubic compressive strength of AAC at each given temperature interval and the effects of the combined factors on the cylindrical compressive strength of AAC are shown in Fig. 7 (a)–(e). Through calibrating the results reported in the database, it is found that the CaO content of 8% is considered as a threshold. When the CaO content is below this value, the mechanical strength of AAC binder is mainly contributed by the geopolymeric products formed by SiO_2, Al_2O_3 and Fe_2O_3; while for the CaO content over 8% the effect of hydrates from the reactions of CaO, the compressive strength of AAC is more pronounced. This leads to the further subset of the database, and the results of concrete testing with binder containing CaO below or above 8%, are assessed separately. Note that to avoid the bias caused by a small sample size, the subplots containing less than 10 datasets are excluded for the comparisons.

It can be seen from both the figures that when subjected to the assigned conditions, there is a good correlation between the proposed factor $\frac{RM}{(w/b)}$ and the compressive strength of AAC. Fig. 6 (a) and 7 (a) also show that due to the variability of ambient curing condition there is a large scatter of the compressive strength of the AAC cured under ambient conditions compared to thermal-cured AAC. This can be explained by the wide ranges of values of factors associated with ambient curing, such as temperature, humidity and air flow.

The influence of curing temperature on the compressive strength of AAC is further investigated by comparing the trendlines for the companion assessments as presented in Fig. 8. It is evident from this comparison that, for high calcium AAC, a very high curing temperature (e.g. over 70 °C) causes a reduction in the compressive strength of AAC, whereas a higher curing temperature often improves the compressive strength of AAC or at least helps to maintain the compressive strength of AAC. This is mainly attributed to the degradation of concrete caused by the more significant drying shrinkage of C-S-H hydrates compared to that of the geopolymeric products N-A-S-H under a higher temperature [217]. The coefficients *a* and *b* of each global trendline in Figs. 6 and 7 are summarized in Table 4 and the statistics of fit are given in Table 5.

5. Relationships between the compressive strength and the engineering properties of AAC

In existing design codes compressive strength of concrete is an essential indicator that is commonly used to predict the mechanical properties of OPCCs. In this section, the relationships between the compressive strength and other engineering properties of AAC are established using the experimental results reported in the database in Table A1. The engineering properties of AAC investigated include the mechanical properties (elastic modulus (E_c), flexural strength/modulus of rupture (f_r), splitting/indirect tensile strength (f_{st}) and abrasion resistance); and the physical properties (porosity, water absorption capacity, water permeability, sorptivity, and ultrasonic pulse velocity (UPV)). It is worth mentioning that only the results obtained using similar specimens and test procedures are selected for these assessments, where the experimental results based on non-standard test procedures or special specimen geometries are excluded.

The code-based models reported in major design guidelines for the mechanical properties of OPCCs are selected to assess their

Table 4
Coefficients of the expressions for the proposed unified model.

Temperature interval	Cylinder				Cube			
	Low-calcium		High-calcium		Low-calcium		High-calcium	
	a	b	a	b	a	b	a	b
Ambient	35.12	0.35	30.71	0.37	20.06	0.50	41.59	0.26
50°–60°	48.09	0.44	41.10	0.41	35.00	0.21	47.31	0.24
60°–70°	–	–	45.83	0.44	45.85	0.30	48.67	0.28
70°–80°	60.23	0.54	47.39	0.34	43.59	0.35	48.07	0.32
80°–90°	85.61	0.47	–	–	41.90	0.47	50.86	0.76

Table 5
Performances of the proposed unified model.

Temperature	Cube-LC		Cylinder-LC		Cube-HC		Cylinder-HC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ambient	0.95	3.45	0.94	4.06	1.08	3.13	1.05	3.21
50°-60 °C	1.01	3.17	0.96	5.67	1.03	4.12	1.09	3.47
60°-70 °C	0.96	4.07	–		0.92	2.61	1.07	4.47
70°-80 °C	0.99	4.21	0.95	5.95	1.01	2.62	0.97	3.28
80°-90 °C	0.96	3.65	0.95	0.56	1.05	3.11	–	

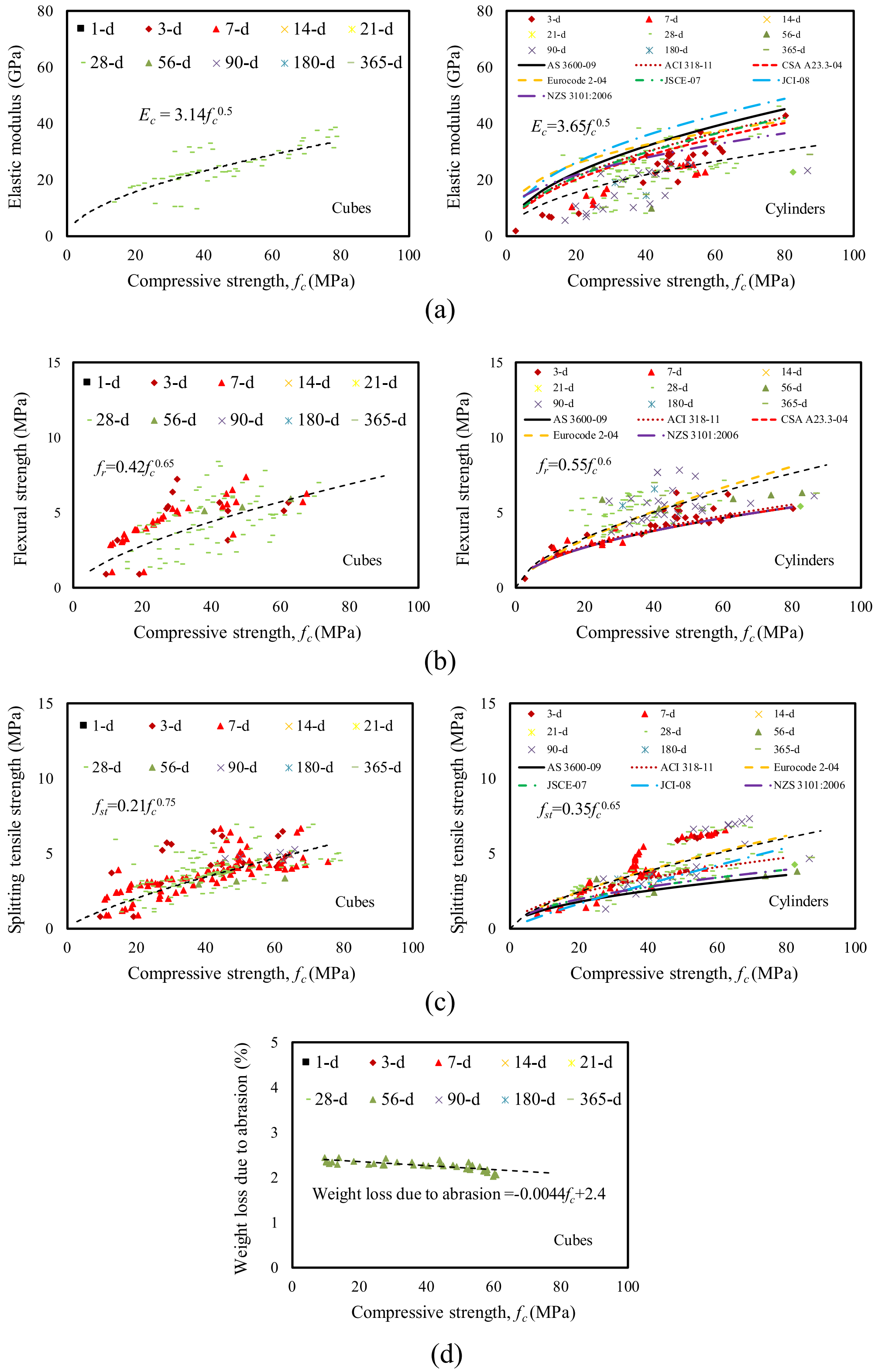


Fig. 9. correlations between mechanical properties and compressive strength of GPCs: a) elastic modulus; b) flexural strength; c) splitting tensile strength; d) abrasion resistance.

feasibility of predicting the relationships between the compressive strength and the engineering properties of AAC. Fig. 9(a)–(d) shows the relationships between the compressive strength and the mechanical properties of AAC. It can be seen that the elastic modulus (E_c), flexural strength (f_r) and splitting tensile strength (f_{st}) of AAC all increase with an increase in the compressive strength of the concrete. The weight loss due to abrasion reduces slightly with an increase in the compressive strength of the concrete, indicating an improved abrasion resistance of the concrete with a higher mechanical strength. The predictions using the expressions given

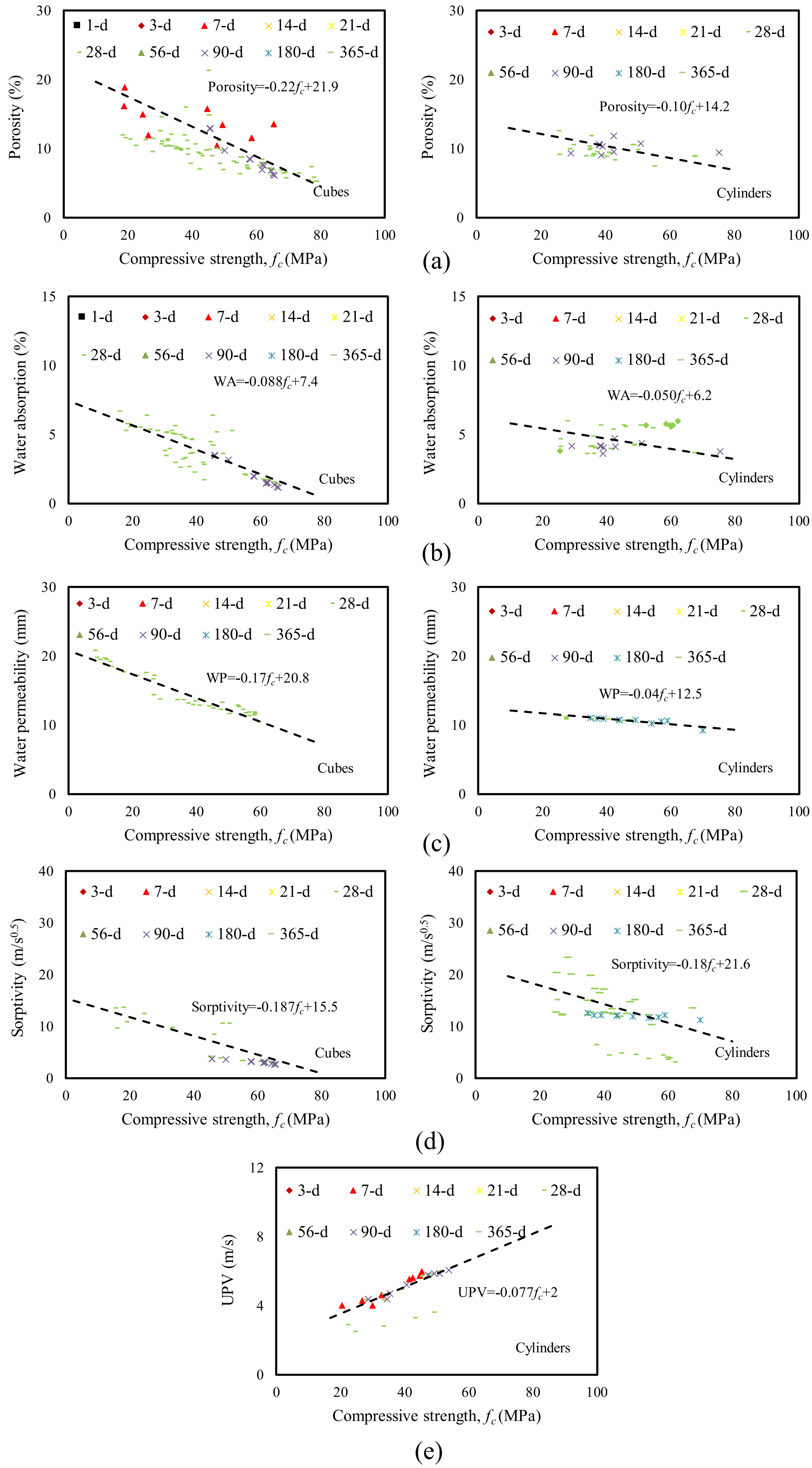


Fig. 10. correlations between physical properties and compressive strength of GPCs: a) porosity; b) water absorption; c) water permeability; d) sorptivity; e) UPV; f) RCPT.

in Australian Standard [229], ACI standard [230], Canadian Standard [231], European Standard [232], two Japanese Standards [233,234] and New Zealand Standard [235] as shown in Fig. 9 (a)–(c) indicate that the code-based models significantly overestimate the elastic modulus of AAC and most of them underestimate the flexural and splitting tensile strength of AAC, with only

Eurocode's [232] relationship between tensile and compressive strengths of AAC being well matched with the test results. The inaccuracy of the codes' predictions is mainly attributed to the higher porosity of AAC compared to that of the companion OPCCs with similar compressive strength [78,99]. The inferior mechanical properties of AAC compared to those of OPCCs hence indicate the necessities of modifying the expressions in the current design guidelines to incorporate AAC. The relationships between each mechanical property of AAC and the corresponding cubic and cylindrical compressive strength are determined using the data in Table A1 by assuming a power function. The expression of these models provides the best fit as shown in Fig. 9(a)–(c) for each mechanical property of AAC.

Fig. 10(a)–(d) clearly shows the relationships between the compressive strength and the physical properties of AAC. Formulas are also given to predict various physical properties of AAC using the compressive strength. It is evident from the figure that the increase in the compressive strength of AAC leads to decreases in the porosity, water absorption capacity, water permeability and sorptivity, whereas the UPV increases with increasing compressive strength of AAC. These observations can be explained by the refined pore structure of AAC with increased mechanical strength [78,236].

6. Conclusions and remarks

This study has presented a comprehensive review of the engineering properties of concrete with AA binders. A total of 184 studies on AAC mix design and mechanical properties are reviewed and the effects of the less-understood factors as the following are assessed:

- alkaline activators other than the combined SS and SH;
- the influence of retarders;
- total liquid to-binder ratio (l/s);
- water-to-binder ratio (w/s);
- sodium alkaline solution-to-binder ratio (a/s);
- silicate-to-sodium hydroxide ratio (SS/SH);
- concentration of sodium hydroxide;
- sp-to-binder ratio;
- binder-to-total aggregate volume ratio;
- fine-to-coarse aggregate volume ratio;
- curing temperature; and
- heat curing duration and delayed handling time.

In addition to the assessments based on the results reported in individual experimental campaigns, approaches reported in the literature to predict the compressive strength of AAC based on their mixing parameters and chemical composition are also reviewed to identify shortcomings. Based on 1756 AAC tests collated from 111 studies a novel mix design approach based on the definition of a reactive modulus is proposed. The approach adequately captures the difference in the reaction mechanism of binders in AAC containing low (less than8%) and high (>8%) calcium content and the influence of curing regime. The relationship between the compressive strength and the engineering properties of AAC are evaluated and the code-based design approaches for OPCC concrete are also applied to assess their feasibility to be directly used for designing AAC.

Based on the extensive review of the current state-of-the-art, the following limitations that hinder the application of AAC in civil engineering are identified:

1) Flash setting which limits the handling of AAC must be prevented. Numerous mix designs have been developed that do not achieve the minimum setting time required for practical application and to date there are no retarders to delay the setting of binder in AAC without significantly comprising its mechanical strength.
2) AACs can exhibit poor workability and as such an efficient high-range water reducer is needed specifically for AAC to improve its rheological properties. This is essential because the addition of water has been shown to significantly reduce the mechanical and durability properties of AAC.
3) The impacts or benefits of long-term heat curing or resting time of AAC together with their mechanisms need further exploration.
4) Although oven curing time is incorporated in the proposed approach, the effect of heat curing on the compressive strength of AAC is not well quantified as significant scatter of results exits. Future models for predicting the compressive strength of AAC may consider converting the curing temperature and curing period of AAC together with the volume to the total energy input to develop the strength of AAC.
5) Effects of fineness of the source materials and different curing method (e.g. steam or hot water curing at the same temperature of oven curing) on engineering properties of AAC requires further investigation.

It is suggested that future research may consider:

1) the development of high strength or self-compacting AAC as currently mix designs generally cover low and normal strength concretes.
2) the use of the mineralogical compositions of each source material to assess the reactivity of the unary or blended binders rather than the use of oxides. This may be advantageous because the mineralogical composition of source material can be more accurately represent the actual reactive composition and reaction kinetics.
3) According to the assessments of the relationship between the compressive strength and the engineering properties of AAC, the inferior properties of AAC suggest that structural level testing is required to help bridge the gap between material development and utilisation in practice.

CRediT authorship contribution statement

Tianyu Xie: Conceptualization, Data curation, Writing - original draft. **Phillip Visintin:** Conceptualization, Writing - review & editing. **Xinyu Zhao:** Conceptualization, Data curation, Writing - original draft. **Rebecca Gravina:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2020.119380.

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