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A critical review on structural behavior of alkali-activated concrete beams

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Abstract

The increasing demand for sustainable development in engineering practice has triggered researchers to explore solutions to reduce the CO_2 footprint caused by ordinary Portland cement (OPC) production. Alkali-activated concrete (AAC), made of by-products using alkali activation, is of great potential as a promising alternative to conventional concrete (CC). Despite vast studies on its material properties, there is still insufficient scientific research on the structural performance of AAC, which impedes its widespread application. In this paper, an overview of the fundamental behavior of AAC beams under different loading conditions is presented. The experimental investigations on mechanical performance of AAC beams are reviewed in terms of ultimate capacity, ductility and cracking behavior. Moreover, numerical methods to predict AAC structural response as well as the applicability of existing CC design codes are summarized. It is concluded that AAC beams show comparable short-term behavior with CC counterparts. Besides, the design codes for CC turn out to be applicable but conservative for most steel-reinforced AAC beams. Though short-term flexural behavior has been widely investigated for AAC beams, the challenge remains to clarify shear behavior and long-term behavior. Furthermore, reliable guidelines are needed to be developed, providing recommendations for future structural design.

1 Introduction

Huge demand for ordinary Portland cement (OPC), the essential component of concrete, leads to an annual increase in production. The manufacturing of OPC is responsible for up to 10% release of total CO_2 emissions, resulting in enormous impacts on the environment [1]. In recent decades, increasing awareness of the importance of sustainability leads to the development of more environmentally-friendly materials for the building industry. Among those, alkali-activated concrete (AAC), where OPC is replaced by binder made of by-products activated by alkali, has become a promising option. It is envisioned that this zero-cement technology can bring us a step further to the realization of sustainable construction by value-added use of recycled industrial waste and reduction of CO_2 footprint [2].

Considerable research on the material level illustrates that some of AAC mixtures have high compressive strength, good chemical and high temperature resistance, as well as good adhesion properties in general [3], contributing to increasing attention in the construction industry.

Some companies have already taken the first step to field application of AAC. In Australia, reinforced AAC has been applied in both precast and cast in-situ elements, including external wall panels, floor beams, slabs and bridge decks [4], etc. However, challenges still exist for promotion of AAC because of (among other things), the gap between the current knowledge of material properties and structural applications. It is of vital importance to fully understand the structural response of AAC members for the utilization of this innovative material in new structures.

The aim of this paper is to review the structural behavior of AAC beams. The experimental investigations of both monolithic and composite AAC beams are summarized. The numerical models available in the literature for performance prediction are included. It is highlighted that the similarity and difference between AAC beams and conventional concrete (CC) counterparts are investigated and the applicability of available design codes for steel-reinforced CC beams is further discussed. Based on the current findings, recommendations are proposed for future investigations in this field.

2 Methodology

Scopus [5], a widely-accepted database, is used for searching current research output including journal papers, conference proceedings and book chapters. The keywords are limited to (“geopolymer concrete ” or “alkali activated concrete”) and (“beam” or “girder”) and articles published before 21/03/2022 are recorded. Only the highly-related and accessible publications, which focus on the structural behavior of newly-built AAC beams, are chosen for critical review. Articles relevant to the experimental investigations of both monolithic and composite AAC beams are summarized and further analyzed in Section 3. Meanwhile, those involving modelling methods are included in Section 4. Furthermore, a small dataset including 38 steel-reinforced AAC beams subjected to flexure, is built for assessment of the applicability of current design codes on ultimate bending moment while for ultimate shear load of steel-reinforced AAC beams, only 2 relevant papers are reported in Section 4.2.

3 Experimental investigation of AAC beams

3.1 Monolithic AAC beams

In this review, monolithic AAC beams are classified with those produced by AAC and reinforcement only, including the steel or FRP-reinforced AAC beams and prestressed AAC beams. In Table 1, the number of publications as well as relevant monolithic AAC specimens using different precursors and under various loading conditions, are recorded. In total 78 AAC beams are cast using fly ash as the precursor. However, due to the lack of reactivity, ambient-temperature-cured fly-ash-based AAC illustrated low compressive strength and thus heat curing is necessary [6]. Although fly-ash-based AAC is promising for precast structural elements with a high-temperature curing environment, it is not suitable for cast in-situ members. The addition of slag was beneficial to the strength development of AAC at ambient temperature, but short setting time and poor workability impede its structural application [7]. In order to satisfy the requirement of practical construction, growing attention is paid to the beams produced by combined systems incorporating low-calcium (e.g. fly ash) and calcium-rich (e.g. slag) precursors, from which a balance of desired strength and workability can be obtained [8]. Regarding different loading conditions, AAC beams subjected to flexure are most widely tested while the shear behavior gains increasing attention. Besides, researchers started to explore the structural behavior of AAC beams under dynamic load [9], [10], but this paper is limited to static loading conditions.

Table 1 Publication (and specimen) number considering different precursors and loading conditions

Loading condition \ Precursor type	Fly ash	Slag	Other	Combination
Flexure	13 (59)	3 (14)	14 (17)	16 (58)
Shear	4 (19)	1 (21)	2 (13)	6 (49)
Torsion	0	0	0	1 (9)
Long-term effects	0	1 (2)	0	2 (5)
Dynamic	0	0	0	5 (27)

3.1.1 Flexural behavior of reinforced AAC beams

Studies on the short-term flexural behavior of reinforced AAC beams were undertaken since 2005 by Wallah and Rangan [11]. Four-point bending tests were conducted to investigate the flexural performance of steel-reinforced AAC beams in comparison with CC counterparts. Similar experiments with various AAC mixtures and different types of reinforcement were carried out in the following years, from which flexural behavior was found to be similar for reinforced AAC and CC beams in general.

Compared to CC beams, AAC beams showed generally higher ultimate capacity and similar crack patterns [12]–[15]. However, inconsistent results of deflection at failure were found. As recorded in [12], both reinforced fly-ash-based AAC and fly-ash/slag-based-AAC exhibited significantly larger deflection than CC beams. But there is no information about compressive strength of both AAC and CC provided in this paper. In contrast, Yost et al. [16] found that reinforced fly-ash-based AAC beams failed in a sudden and brittle mode while CC counterparts with the same strength class experienced a gradual decrease of load before eventual concrete crushing, and thus slightly higher displacement compared to AAC beams. Reasons for these observed discrepancies are still not clear.

Lower post-cracked stiffness was found in reinforced AAC beams cured under ambient conditions. Tran et al. [17] pointed out that the considerable drying shrinkage of ambient-cured AAC with high content of slag might lead to the formation of drying cracks, which further resulted in the loss of tension-stiffening. However, the influence of severe drying shrinkage on the structural behavior of AAC elements needs more investigation.

In addition, the influence of different aspects on flexural behavior of AAC beams was investigated, including the compressive strength of AAC [11], [18], types of reinforcement [13], [19], reinforcement ratio [20], [21] and the addition of fibers [17], [22], [23]. Similar to CC, the increase of compressive strength leads to higher initial stiffness while similar deflection and crack patterns are measured. Regarding different types of reinforcement, FRP-reinforced AAC beams showed comparable flexural behavior to FRP-reinforced CC beams [13]. In addition, the increase of reinforcement ratio also had a considerable impact on the enhancement of ultimate capacity of under-reinforced AAC beams while the ultimate strength mainly depended on the material properties of AAC when over-reinforced beams were designed [20]. Furthermore, comparable to CC, the usage of appropriate volume of fiber improves the cracking resistance, ultimate flexural capacity, and ductility of reinforced AAC beams as expected. Multiple and fine cracks were observed in the constant moment zone [24]. It should be noted that the post-crack stiffness of ambient-cured specimens was enhanced owing to the control of drying shrinkage when fibers were added [17].

3.1.2 Shear behavior of reinforced AAC beams

Limited amount of shear tests for reinforced AAC beams were conducted in the last decade. In general, AAC specimens with the same strength class as CC counterparts illustrate comparable crack distribution and shear strength [16], [25]. Tran et al. [26] reported that one slag-based AAC sample cured under an ambient condition exhibited lower stiffness and cracking load, resulting from severe shrinkage cracks. Such observation is in line with the phenomenon presented in the previous flexural tests [17]. Additionally, Wu et al. [25] found that AAC beams showed more brittle behavior and fewer cracks.

The factors that influence the shear behavior of reinforced AAC beams are similar to that of reinforced CC beams. The most widely investigated factors are shear span-to-depth ratio and stirrup spacing. A decrease of shear span-to-depth ratio results in a great increase of ultimate shear capacity in terms of the change of failure mode, confirming arching action in AAC beams [25], [27]. A smaller stirrup spacing contributed to the improvement of shear resistance was found in [28], [29] while insignificant impacts of stirrup spacing were reported in [30]. It was concluded that the explanation of these discrepancies needs further studies and verifications.

3.1.3 Time-dependent behavior of reinforced AAC beams

Un et al. [31] verified that previous estimation methods of long-term deflection applied for CC beams (such as effective modulus method (EMM) and age-adjusted effective modulus method (AEMM)) could also be applied for the tested AAC beams. However, the input parameters of these prediction models mainly relied on the material properties of concrete and only one kind of AAC was taken into account. The feasibility of such methods for other types of AAC needs to be further studied. Moreover, the cracking characteristics under long-term load were not studied in this research. Moreover, a series of experiments were carried out on reinforced AAC beams with different curing ages till 91 days in order to clarify their time-dependent flexural behavior, considering the change of material properties over time [14]. But it was found that the decrease of material properties had no significant effects on the flexural capacity of AAC beams. Also, a reduced tension stiffening effect in the stabilized cracking stage was observed, but no explanation was given for this phenomenon. A longer time test was advised.

3.1.4 Structural behavior of prestressed AAC beams

Few researchers gave insight into prestressed AAC beams in the past years. The feasibility of applying AAC to prestressed beams was first proposed by Liu et al. [32] and calculation methods for prestress loss due to anchorage slip and prestress tendon retraction were then put forward. The flexural performance of prestressed fly-ash/slag-based AAC beams was investigated and compared with CC counterparts of the same strength class in [33]. The experimental results indicated that prestressed AAC beams had better cracking resistance and could undergo slightly higher ultimate load and deflection. However, in the above research, the long-term deflection, cracking characteristics, as well as the effects of creep and shrinkage on the long-term behavior of prestressed AAC beams, were not yet reported.

3.2 Composite AAC beams

Apart from monolithic reinforced AAC beams, researchers have begun to introduce AAC into composite beams and verify its feasibility. Steel-concrete composite beams composed of precast AAC panels connected by tensioned friction-grip bolts were proposed to achieve the target of low-carbon design, illustrating good load-carrying capacity and desirable system deconstructability [34], [35]. The influence of the depth of AAC layers on the structural behavior of reinforced multi-layered concrete beams consisting of AAC and Normal Concrete was investigated through traditional and non-destructive testing methods [36]. The multi-layered concrete beams were found to have higher ductility compared to beams with a single layer. Similar results were reported on AAC-High Performance Concrete (HPC) beams with shear reinforcement [37]. However, debonding between AAC and HPC resulted in a lower carrying capacity when no shear reinforcement was applied. AAC-filled pultruded composite beams introduced by Ferdous et al. [38] illustrated satisfactory stiffness and strength under flexure through experimental and numerical investigations. As such, the elements could be used as railway sleepers.

4 Modelling methods of AAC beams

4.1 Numerical simulation

Apart from experimental studies, numerical simulations are used to evaluate and predict the structural behavior of AAC beams. Since only limited experimental studies are available, numerical studies based on such experiments are even more scarce.

Finite element modelling is mainly conducted by ANSYS [39] and ABAQUS [40] following similar procedures for simulation of CC beams. The widely used constitutive models of CC are also chosen for characterization of AAC. The definition in the elastic stage is similar while different models are chosen for the characterization of nonlinear behavior. Hammad et al. [41] adopted a multilinear elastic model with no consideration of post-peak behavior. Few researchers chose the “concrete damage plasticity model” (CDP) to simulate the fracture propagation of AAC by introducing damage variables [28], [42], [43]. Such a model is comparatively precise but parameters regarding the post-peak performance need to be calibrated. The choice of these parameters would significantly affect the prediction of crack propagation. The stress-strain curves of AAC adopted in most research are determined by the simplified equation for CC while few of them refer to relevant experimental results of AAC specimens. Perfect bond assumption is justified to model the concrete-reinforcement interaction since higher short-term bond strength between AAC and reinforcement is reported by Mo et al. [44].

In general, it can be concluded that the flexural and shear behavior of AAC beams in terms of load-deflection relationship and crack propagation obtained by the numerical approach are in good agreement with the experimental results. Thus, the numerical methods for CC are confirmed applicable for AAC beams based on the available literature. Nevertheless, the reliable analytical stress-strain curve of AAC and bond-slip relationship needs to be developed to simulate the structural behavior of AAC beams under more realistic situation.

4.2 Analytical prediction

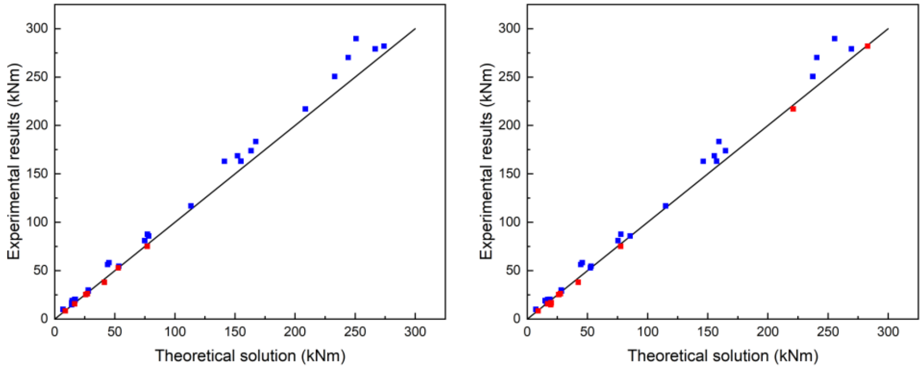
Existing codes for the design of reinforced CC beams were applied to reinforced AAC beams. The feasibility of code equation for ultimate capacity calculation is only discussed within the scope of steel-reinforced AAC specimens.

As mentioned in Section 2, owing to the relatively large number of collected data, a small dataset is established, in which 38 specimens subjected to flexure varying in AAC mixtures, geometry and reinforcement configuration are included (see Table 2).

Table 2 Specimens used for the dataset.

Literature	[11]	[14]	[18]	[19]	[21]	[45]	[46]
Number of specimens	6	4	12	1	7	2	6

Fig. 1 demonstrates the comparison of ultimate bending moment (M_u) between experimental results and theoretical values obtained from ACI 318-19 [47] and EN 1992-1-1:2004 [48], respectively. The situations of "underestimate" ($M_{u,exp} > M_{u,theo}$) and "overestimate" ($M_{u,exp} < M_{u,theo}$) are classified in blue and red dots. As shown in Fig. 1, the ultimate bending capacity is underestimated in most cases. For ACI 318-19, the average $M_{u,exp} / M_{u,theo}$ ratio is 1.09 with standard deviation of 0.11. Slightly overestimated capacity with a $M_{u,exp} / M_{u,theo}$ ratio in a range of 0.92-0.99 is reported for 7 specimens. Regarding EN 1992-1-1:2004, the average $M_{u,exp} / M_{u,theo}$ ratio is 1.05 with standard deviation of 0.13. 12 specimens exhibit a lower ultimate bending moment than the theoretical value, in which beams produced with high strength AAC (> 70MPa) show a low $M_{u,exp} / M_{u,theo}$ ratio up to 0.75. Generally, current codes for CC can be applied to conservatively calculate the ultimate bending moment of reinforced AAC beams.



(a) ACI 318-19 (b) EN 1992-1-1:2004

Fig. 1 Theoretical solution vs experimental results of ultimate bending moment of steel-reinforced AAC beams.

Shear tests conducted in the previous years are not sufficient, which restrict the establishment of a dataset. Yost et al. [16] and Madheswaran et al. [29] compared the ultimate shear load of steel-reinforced AAC beams with stirrups that failed in shear obtained from experiments and code provisions. In [16], ACI 318-08 [49] is selected for comparison and the average V_{exp} / V_{theo} ratio of 1.52 with standard deviation of 0.03 is reported for 3 specimens with the same configuration. In [29], an average V_{exp} / V_{theo} ratio of 1.42 with standard deviation of 0.28 and 1.40 with standard deviation of 0.29 are recorded for 6 samples with different stirrup spacing based on ACI 318-08 [49] and IS 456 [50], respectively. It can be seen that both codes give conservative results in comparison with measured test values. Further studies on shear behavior are necessary to provide a sufficient database for assessing current codes as well as proposing guidelines, specifically for AAC elements.

5 Discussion and recommendation for future work

Existing reviews generally conclude the performance of AAC structural members including beams, columns and slabs [44], [51], [52] while this review only targets AAC beams, which allows specific insight into the discussion of their structural behavior. Despite the difference in research scope, the applicability of AAC as a replacement for OPC has been confirmed. However, current results from the literature on the mechanical behavior of reinforced AAC beams are still insufficient for the development of common analytical and design methods. Besides, Ma et al. [53] pointed out that most investigations focused on fly-ash-based AAC members. But, considerable attention to fly-ash/slag-based AAC beams is paid in this review because of the narrow research scope and the increasing awareness of the utilization of combined precursor systems after 2018.

Reinforced AAC beams show comparable load-carrying capacity and cracking behavior to CC beams under flexure while the underlying reason for the inconsistent results regarding ductility needs further investigation. Besides, shear behavior, as well as the governing factors, are recommended to be clarified. In addition, the focus of research on structural behavior of AAC beams is mainly on the reinforced AAC elements. It is promising to apply the prestressed technology, which could lead to the effective utilization of AAC on a larger scale. The application of prestressed AAC elements and their working mechanism are meaningful to involve in future research topics. Apart from short-term behavior, long-term behavior is also of great importance to investigate with regard to long-term deflection, cracking behavior and prestress loss. Such studies will be beneficial for a safe design regarding the long-term serviceability of AAC beams. Furthermore, it turns out that AAC is more sensitive to curing regimes than CC and the mechanical properties of AAC under certain curing conditions may decrease over time. The role of curing regimes and the effects of time-dependent material properties are still unclear for both short-term and long-term structural behavior.

As a powerful tool for prediction of structural behavior without performing a large number of experiments, numerical methods need to be further developed and promoted. The bond-slip relationship between AAC and reinforcement is suggested to be considered for more precise simulation. Finally, simply relying on existing codes of CC beams could lead to an unsafe design with inaccurate prediction because of the difference in terms of chemical reaction and matrix formation of AAC. Thus, it is an important task to provide recommendations for the prediction of the structural response and develop specific codes for AAC elements.

6 Conclusion

This paper provides a state-of-art review on the structural behavior of AAC beams. The main findings are concluded as follows:

(1) Reinforced AAC beams exhibit comparable ultimate capacity and crack pattern to reinforced CC counterparts under flexural and shear conditions. Similar to CC, the ultimate flexural strength is improved by the increase of compressive strength, tensile reinforcement ratio and addition of fiber within a reasonable range. The methods used in the numerical simulations of CC beams are applicable for AAC beams, which is confirmed by the good agreement between experimental and numerical results in terms of load-deflection response and crack development.

(2) Related to the applicability of existing codes and methods, ACI 318-19 and EN 1992-1-1:2004 can be conservatively applied for the prediction of ultimate bending moment of steel-reinforced AAC beams in general, with average $M_{u,exp}$ / $M_{u,theo}$ ratio of 1.09 and 1.05. The prediction of shear strength of steel-reinforced AAC beams is underestimated according to ACI 318-08 and IS 456 based on the available dataset. The feasibility of prediction methods for long-term deflection of CC beams was confirmed by AAC beams cast in one mixture.

(3) Few researchers gave insight into the time-dependent behavior of reinforced AAC beams. Though decrease of long-term material properties of AAC was measured, the relevant consequence for long-term structural behavior of AAC beams is still unknown. Besides, ambient-cured reinforced AAC beams with high content of slag illustrate lower post-crack stiffness compared to CC due to severe drying shrinkage, which indicates the importance of research on the impacts of curing conditions.

(4) In general, current studies regarding the structural behavior of AAC beams are still limited. More experimental and numerical studies on AAC beams need to be conducted, allowing the establishment of a large dataset. Thus, the development of design guidelines specifically for AAC beams can be facilitated.

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