

Structural use of site cast alkali-activated slag concrete in a building- Chongqing Jianke

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Abstract

This paper reports the first structural application of cast-on-site alkali-activated slag concrete in an office building, Chongqing Jianke, China. Special attention is given with respect to quality control of raw materials and concrete, construction procedure, and assessment. On the basis of the experiences obtained, the quality and cost involved could be controlled with a detailed feasible working plan including a careful control of raw materials, a suitable selection of admixtures, a proper mix proportions, and an efficient construction team. It is also found that the alkali-activated slag concrete has a potential to be used in cold-weather concrete construction, as the ambient temperature during construction was quite low, sometimes below 5 °C, and no specific procedures to maintain the temperature or provide additional heat were applied. The obtained experiences would be helpful to yield relevant knowledge of structural use of alkali-activated slag concrete.

Keywords: alkali-activated slag concrete, demonstration project, cast-on-site concrete, assessment of structural performance

1. Introduction

The impact of climate change on human society is no longer in question. In China, the frequency of extreme weather conditions has increased, causing more than 2,000 deaths and around 200 billion Yuan (£20 billion) of direct economic loss per year since the 1990s. In facing this urgency, “*China will speed up a green and low-carbon economy through reform and innovation in order to follow a sustainable development.*” Keqiang Li, Chinese Premier, said (Fu, 2013).

To achieve this target, controlling the increase of CO₂ levels in the atmosphere has been the major impetus, which is closely linked with global temperature fluctuations (Un et al., 2015, Shi et al., 2011, Bernal et al., 2014). The cement industry, representing around 5% of the global CO₂ emissions plays an important role in this process. According to the plan proposed by the International Energy Agency (IEA), CO₂ emissions from the cement industry need to be reduced from its current 2 Gtpa to 1.55 Gtpa in 2050. By comparison, over the same period, cement production is projected to increase by about 50 % (Xu et al., 2015a, Un et al., 2015, Karstensen, 2008). The cement industry has traditionally relied on three main approaches to reducing CO₂ emissions (Karstensen, 2008, Conesa et al., 2008, Barker et al., 2009): energy efficiency, alternative fuels and/or biomass, and clinker substitution. It is estimated that these existing technologies can meet half of this goal, so new approaches must be developed.

Emerging technologies, *e.g.* the carbon capture and storage technologies, could offer potential solutions, but these methods still need to be proven and currently are not ready to be used in a large scale. Another creative and constructive area is the development of more efficient and more economical materials (Xu et al., 2015b, Rakhimova and Rakhimov, 2015a). Designing new clinkers that require less (or no) limestone is one means to significantly reduce the CO₂ emissions, as most of the CO₂ footprint of cement is due to its decarbonation during clinker manufacture (Xu et al., 2015a, Taylor, 1997, Bernal et al., 2014). Alkali-activated materials (AAM) are among these choices, whose performance is comparable with Portland cement (Siriwardena and Peethamparan, 2015, Provis et al., 2015). Moreover, AAM is also regarded as a class of the green building materials, since many components are industrial by-products or wastes such as fly ash, slag, metakaolin and some combustion ashes.

Despite the bright future for AAM, its industrial application is limited and most developments are mainly restricted to the research laboratory. Three factors weigh heavily against its practical use. The first one is the general lack of efficient communication between material scientists, design engineers, construction engineers, government officers and developers. This is understandable, for example a design engineer is used to thinking in terms of strength, deformation, stability, modulus of elasticity and the cost per unit of volume, whereas the energy or environmental aspects are not of greatest concern (Neville, 1995, Provis et al., 2015). Secondly, some technical barriers remain to be solved prior to a large-scale on-site use. More specifically, some new admixtures (*e.g.* water reducer) need to be developed to reduce high viscosity of AAM, more researches are needed to understand the mechanisms

of relatively high shrinkage comparing with concrete mixed with Portland cement, the in-service durability performances have to be clarified, and optimisation of mix proportions should be carried out to achieve pre-specified properties (Provis et al., 2015, Un et al., 2015). Lastly, there remains the problem of conservatism in the construction industry. Few companies wish to undertake what they see as a 'risk' of using new materials, preferring to pay the costs (environmental and financial) associated with using conventional cement. This naturally leaves the research communities with the major problem of making the jump from the laboratory to the construction site. Now some demonstration projects using AAM are needed eagerly to help to overcome the aforementioned barriers.

On the basis of more than 30-year research in alkali-activated slag cement and concretes (Pu et al., 1992, Chen and Pu, 1997, Yang et al., 2006), the research team at Chongqing University (CQU) and the Chongqing Research Institute of Construction Science (CRICS) decided to apply some alkali-activated concrete in the new CRICS office building to explore the potential of structural application of AAM. It is hoped that the technologies and experiences established would serve as an example of the use of AAM as structural concrete that may be valuable for further applications. This paper summarises the construction process, the quality assessment and structural performance monitoring.

2. The demonstration project of alkali-activated slag concrete

Chongqing Jianke, the CRICS office building, designed by the Chongqing Architectural Design Institute, locates Yuzhong District, Chongqing, as shown in **Figure 1**. The building was constructed by Chongqing Construction Engineering Group Corporation (CCEGC). It has an area of 413033 m², among which 4500 m², 3 floors (12 meters high) were built by alkali-activated slag concrete (AASC) and 550 m³ concrete was used. The main structure frame manufactured using AASC has various types of elements, including slab, column, slabs and walls. Its construction began in November 2013 and the final component of the building's spire installed four months later in 2014, making it the first AASC structural application in China. Since very few experiences are available, the basic properties of AASC were strictly specified by research team members, site engineers, supervisors, designers and owners in order to ensure the quality of the structure, which are summarised in **Table 1**.

2.1 Raw materials and alkali-activated slag concrete mix proportion

The total amount of granulated blast furnace slag (GGBS), the main binder of AASC, used in this demonstration project was 10 tone which was from the same batch supplied by Chongqing Iron and Steel Group. The chemical compositions of GGBS are given in **Table 2**. To prepare GGBS, the slag was grounded for 40 mins in a ball mill, after which the specific area was determined by the Blaine method that varied from 420 to 450 m²/kg. Inorganic mineral admixture (YP-3) was added based on 4% mass of slag content to adjust the setting time (Yang and Pu, 1996). This admixture is a composite of clinker and chemicals and it was developed in Chongqing University as the third generation retarder to

control the setting time of AASC. It was patented by the authors with the NO: CN1071401A (Yang and Pu, 1993).

The fine aggregate was a combination of a natural sand (fineness modulus: 0.65) and an artificial sand (fineness modulus: 3.70) to achieve a medium graded sand (fineness modulus: 2.60), while the coarse aggregate was 10 mm and 20 mm crushed basalt in equal proportions, conformed to Chinese national norms GB/T-14684 (2011) and GB/T-14685 (2011).

Sodium silicate was used as the activator in this study. The activator was a mixture of a liquid sodium silicate solution with a pre-specified modulus of $MS=1.2$ (defined as the mass ratio of SiO_2 to Na_2O). It was prepared by mixing a NaOH solution and liquid water glass (Na_2O : 29.03%, SiO_2 : 12.07% by mass) in a pre-calculated ratio. The Na_2O dosage was kept constant for preparing AASC, 5% of the GBFS content. The density (ρ) was estimated on the basis of alkali content that should be in the range of between 1.23 and 1.25 kg/m^3 . It has been noticed that no commercial product is available that can meet the specified parameters. As such, the condensed alkali solution ($Ms=1.2$, $\rho=1.31\text{ kg/m}^3$) was manufactured in the factory and it was mixed with tap water to achieve the desired density on site. **Figure 2** illustrates the manufacturing procedure and the homogenisation equipment used in this project.

Once the raw materials are ready, the trials were carried out to adjust the mix proportions in order to satisfy the pre-specified requirements. **Table 3** gives the mix proportion of alkali-activated slag concrete. Note that the AASC mix proportion was selected according to the laboratory study, in which the aggregates were dried before mixing, meaning that the moisture in aggregates was removed. It was difficult to dry the aggregates for site application and the moisture content was not constant. As such, the moisture content of aggregate was determined every day and necessary adjustments were made on site according to the actual moisture content in the aggregates, which was determined before casting concrete.

2.2 Environmental conditions during the construction process

The construction of AASC started on 2nd December 2014 and ended on 10th February 2015, during which AASC was cast for 23 times. Ambient temperature and relative humidity were recorded to describe climate conditions during the construction period, as environmental conditions are the key influencing factors for field application of AASC.

Figure 3 plots the records of ambient temperature and relative humidity against the AASC casting number. Broadly speaking, the construction temperature was relatively low and the relative humidity was in the middle range during the construction period. The daily temperature changed by 10 °C that was generally in values between 5 to 15 °C. The trend of relative humidity is displayed in **Figure 3-b**. The RH range is quite large, approximately 35% and 80% respectively. This means that moisture

evaporation rates could be high in a certain period. Note that no specific activities (thermal insulation enclosures or supplementary heat) were carried out during the whole process even when the temperature was below 4 °C. It indicates that the AASC can be cast under a low temperature, but special attention needs to be given for crystallisation of the alkali solution under the low temperature, which could affect the construction process. This is because the activator was a super-saturated sodium silicate liquid at 20 °C and has a tendency to crystallise even in the laboratory. During the site application, the temperature was lower and hence the problem of crystallization was even worse. To avoid this, three actions were taken: 1) the manufacture process of AASC was carefully controlled using an auto-production line similar to the precast concrete; 2) two large containers with a capacity of 90 m³ were used to maintain the temperature; 3) the temperature of the sodium silicate liquid was monitored continuously, in most cases, the temperature above 28 °C, to ensure no crystallisation. On the basis of experiences obtained, the problem of crystallisation was effectively solved by taking care of above three aspects.

2.3 Construction process of alkali-activated slag concrete

After consulting the government officers and the owner, it was decided to cast alkali-activated slag concrete on site. **Figure 4** shows the construction process flowchart. The site supervisors checked and confirmed the qualities of moulds, supports and reinforcements according to the national standard “GB-50204: Code for acceptance of constructional quality of concrete structures” (2002) before casting AASC. The treatments of the construction joint between AASC and Portland cement concrete was carried out by cutting the top part of old concrete, cleaning the joint surface, wetting the surface by the alkali solution, and then casting the alkali-activated slag concrete.

On the basis of the local area and the arrangements of the concrete manufacture line, two C50 forced continuous mixers with a capacity of 0.5 m³ were selected. AASC mixing took 3 mins and the workability was checked after each batch. Once the fresh properties of AASC satisfied the requirements, the concrete was poured into a feeding hopper and was transported to the construction site by a crane. Then, the site workers started casting the concrete. To ensure the quality of concrete and control the plastic shrinkage cracking, the concrete was covered by plastic sheets immediately after compaction. Once the final setting reached, the sheets were thrown open and the water was sprayed on the concrete surface. After this, the concrete was covered by the sheets again and the moisture curing was maintained for 14 days. **Figure 5** shows the construction procedures. Due to differences between normal concrete and AASC, different colour at the connection was seen at the early age (for the first two weeks), while the appearance of two concretes was nearly the same at the age of 28 days, as shown in Figure 5-d and -e. Therefore, it is recommended that use of AASC would not significantly affect the final appearance in the demonstration structure.

3. Quality control of site cast alkali-activated slag concrete

3.1 Assessments of fresh properties of site cast alkali-activated slag concrete

Except for visually checking the workability for every batch of concrete, the slump and setting time of alkali-activated slag concrete were assessed according to Chinese norm (GB/T50080, 2002). **Figure 6** represents the control charts that summarise the behaviour of the slump. Evidently, most slumps appear approximately homoscedastic, staying within the upper and lower control limits. With respect to the moving range (MR) chart, the values of moving range randomly locate in the range from 0 mm to 30 mm and no outlier can be found. This indicates that the slumps were under control in the construction process and its value should be in the range of 220 ± 20 mm.

The setting time of AASC cannot be controlled by traditional Portland cement concrete admixtures due to the basic differences between two binders. To solve this technical problem, the research team at Chongqing University has developed an inorganic mineral admixture (YP-3, Chinese patent) which has been used since 1990s (Pu et al., 1992). In this demonstration project, the admixture was also added and the results of setting time are given in **Figure 7**. It is found that the initial setting varied from 6 hours to 9 hours, while the final setting time was generally before 12 hours. Since the environmental conditions, especially for ambient temperature, have a strong impact on the setting behaviour of AASC (Taylor, 1997, Neville, 1995, Pu et al., 1992), the setting time is plotted against corresponding average temperature on the day of casting in **Figure 8**. Clearly, the setting time increases with decreasing average temperature that is similar to the Portland cement concrete.

3.2 Assessments of compressive strength of site cast alkali-activated slag concrete

The compressive strength of AASC was assessed by 100×100×100mm cubes. During each casting, ten groups of samples (30 cubes) were randomly taken after mixing and were cured under the site condition for one day (GB-50204, 2002). The samples were removed from the moulds after one day. Five groups were placed in the laboratory and cured under the standard condition (temperature: 20 °C, relative humidity: >95%) (GB-50010, 2010), while the other five groups were left on site and exposed to the similar condition as the structure. After 28 days, all samples were transported to Chongqing Bureau of Quality and Technology Supervision (Yuzhong station) for compressive strength testing.

Figure 9 shows the results of compressive strength of two curing regimes. As indicated in **Figure 9**, all compressive strength results satisfy the requirements of C40 agreed by all members, as indicated in **Table 1**. Furthermore, the samples cured under the standard condition have a higher strength, but a lower standard deviation than that cured under the site condition. This observation is believed to be linked with two facts. The first one is the differences in temperature and relative humidity between two curing conditions. It clearly indicated in **Figure 3** that the samples were exposed to low temperature and humidity conditions, which naturally lead to a slower hydration and lower compressive strength development (Provis et al., 2015, Pu et al., 1992). The other reason associates with the fact that during the construction, the mix proportion was adjusted according to variations of raw materials, including

the density of the alkali solution, moisture contents of aggregates and the lot of aggregates (Neville, 1995, Rakhimova and Rakhimov, 2015b). This would also affect the compressive strength results.

3.3 Monitoring structural performance of site cast alkali-activated slag concrete

In order to reflect the performance changes of AASC in the structure, the electric and temperature sensors were embedded to monitor electrical resistance and temperature, which are measured by an LCR meter. Detailed information about the sensors and the installation can be found in the previous papers (Yang et al., 2013, Rajabipour and Weiss, 2006). The measurements were taken after casting at 15:30 every day for 6 weeks.

The electrical resistance data are shown in **Figure 10**. It can be found that the resistance increased over the whole period. The increasing rate was high for the first 15 days, growing from 100 Ω to 2400 Ω , while a fairly 'slow' increase was observed after this. This observation can be attributed to the microstructural changes resulting from the hydration of AASC, the influence of which is to reduce the porosity and the proportion of the liquid phase. Similar observations were also reported for Portland cement concrete (Neville, 1995, McCarter and Vennesland, 2004), although no direct evidences are given for AASC used in structures. Another reason for this observation is the decrease of ion concentration in the pore solution of AASC during hydration of GGBS. This is because the liquid sodium silicate was used to activate the slag and the concentration of ions in the liquid, especially for Na^+ and OH^- , was quite high. While sodium was consumed by hydration and thus, the ion concentration decreased. All these factors lead to the increase of electrical resistance (McCarter et al., 2005, Rakhimova and Rakhimov, 2015a). **Figure 10** also shows the variation of temperature throughout the exposure period. Generally, the overall variation of temperature fluctuated from 7 to 17 $^{\circ}\text{C}$, which agrees with the data of **Figure 3** with some extreme values. It is not surprising to see this phenomenon, because the results in **Figure 3** are information of the environmental condition, while the data presented in **Figure 10** are temperature inside the concrete.

The data of electrical resistance and temperature inside alkali-activated slag concrete indicate that both parameters are useful indicators to reflect the property changes in concrete, while a further quantitative investigation would be very helpful to establish a solid link between these responses and fundamental characteristics of alkali-activated slag concrete.

4. Conclusion

The demonstration project, Chongqing Jianke, is the first structural application of cast-on-site AASC in China. On the basis of experiences obtained in this project, the following conclusions could be drawn:

- 1) The performance characteristics of cast-on-site AASC, e.g. workability, setting time, compressive strength, are similar to the normal Portland cement concrete, provided that the quality of the alkali solution is carefully controlled, the suitable admixtures are used, and the mix proportion is cautiously selected.
- 2) There is no significant difference in construction procedures between AASC and Portland cement concrete, while the only difference is the use of the alkali solution instead of water. It suggests that the construction cost would be similar to Portland cement concrete.
- 3) It is recommended that additional water should be added to keep the surface wet for 14 days to the surface quality of AASC. Furthermore, the performance of AASC, including compressive strength and hydration process, is very sensitive to environmental conditions.
- 4) The results from the practical application indicate that no specific procedures were applied even at a low temperature (around 5°C), but the strength development was significantly affected, which means that the AASC has a very promising potential for projects under construction at a low temperature.

It is intended to show that for AASC, the quality and the cost involved could be controlled. The results also reveal that its performance could be further improved by optimising the mix proportions and the construction procedures without increasing the cost. As such, further work on these aspects would explore the potential of this material.

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Table 1 The requirements of the properties of alkali-activate slag concrete

Property of concrete		Controlling target
Workability	Slump	220±20 mm
	1h slump loss	Less than 100 mm
	Other	No bleeding, no segregation
Setting time	Initial setting	6-8 hours
	Final setting	Less than 12 hours
Compressive strength grade		Greater than C40

Table 2 Chemical compositions of slag used (%)

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SO ₃	Loss
34.67	13.86	1.18	8.37	37.7	0.16	0.64	0.2	0.73

Table 3 Mix proportion of alkali-activated slag concrete (kg/m³)

Binding material		Alkali solution	Aggregate	
Slag	Inorganic admixture		Coarse aggregate	Fine aggregate
400	16	220±10	1145±30	610±15



Effect drawing of Jianke Chongqing

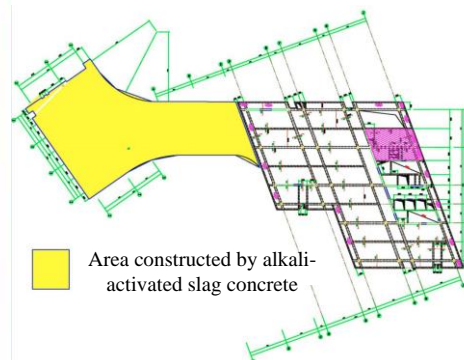


Illustration of the construction section



Side view of the structure made by alkali-activated slag concrete

Figure 1 Illustration of the alkali-activated slag demonstration project

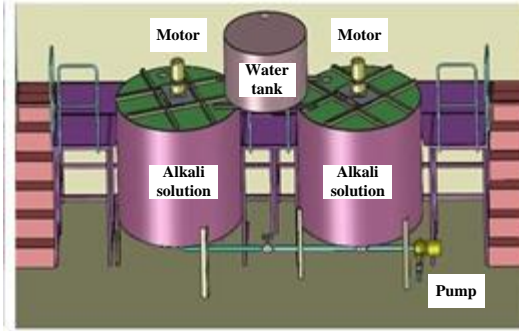


Figure 2-a Alkali solution manufacturing factory Figure 2-b Field storing and homogenisation set-up

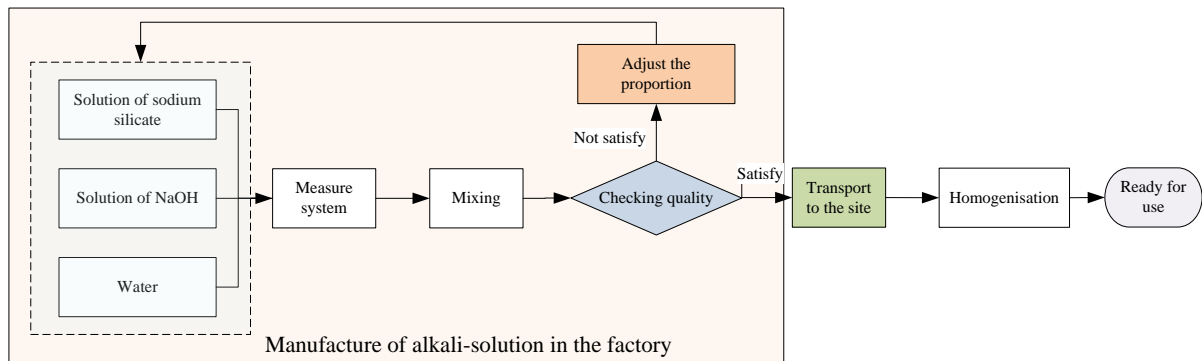


Figure 2-c Flowchart of alkali solution manufacturing process
Figure 2 Alkali solution manufacture process and the field storing set-up

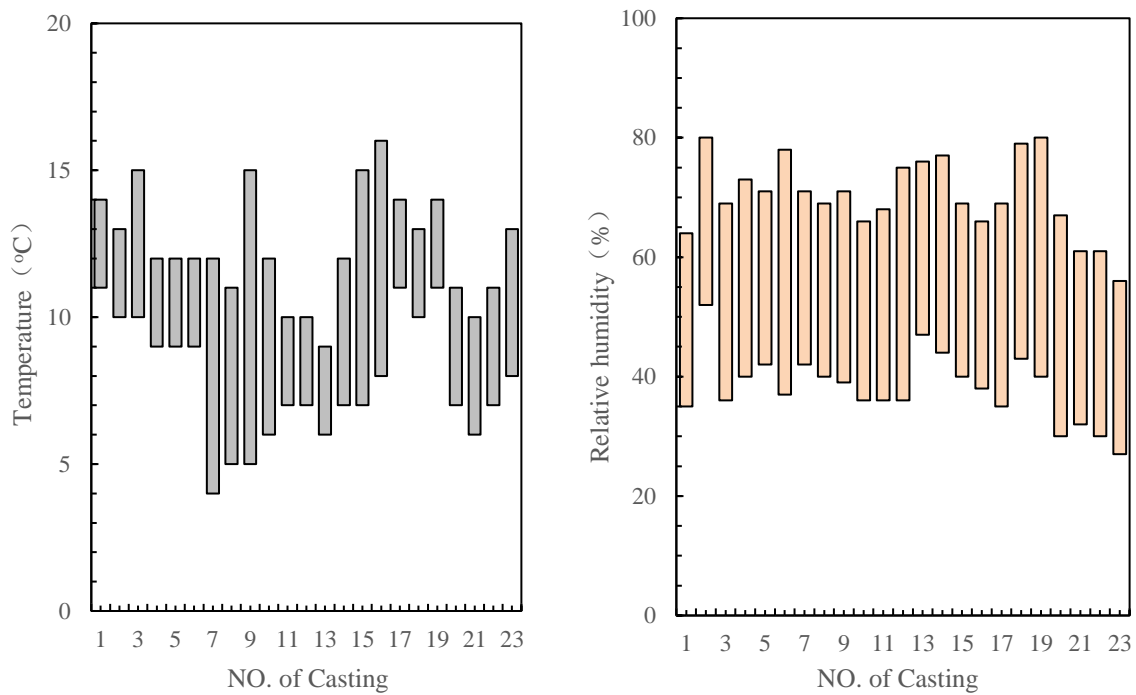


Figure 3 Environmental conditions (variations of temperature and relative humidity) during the whole construction process

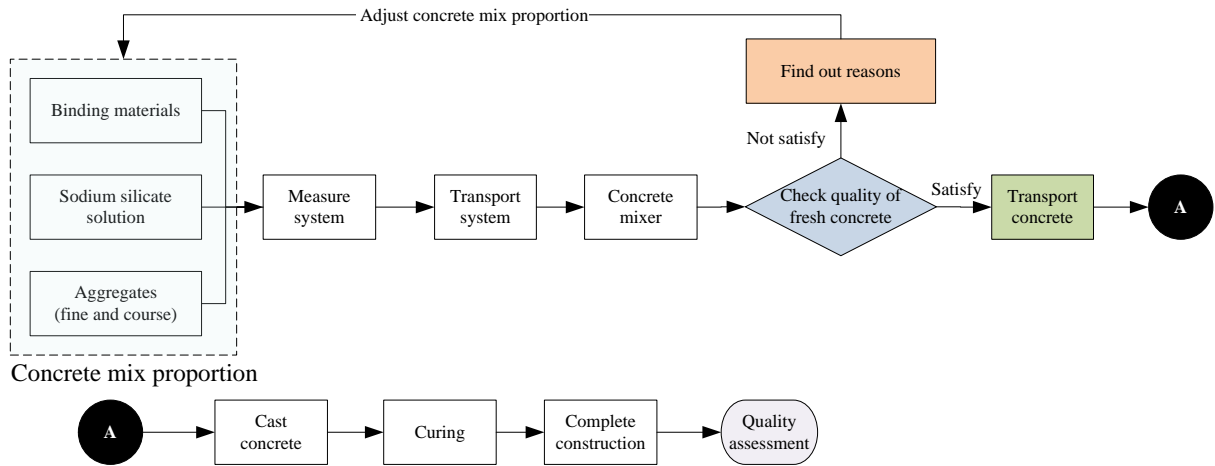


Figure 4 The flowchart for construction process and quality control



(a) AASC transport



(b) AASC cast



(c) AASC curing after placing



(d) Overall view of the connection between AASC and NC



(e) Large view of the connection

Figure 5 The construction procedures of alkali-activated slag concrete and illustration of connection between normal concrete and alkali-activated slag concrete

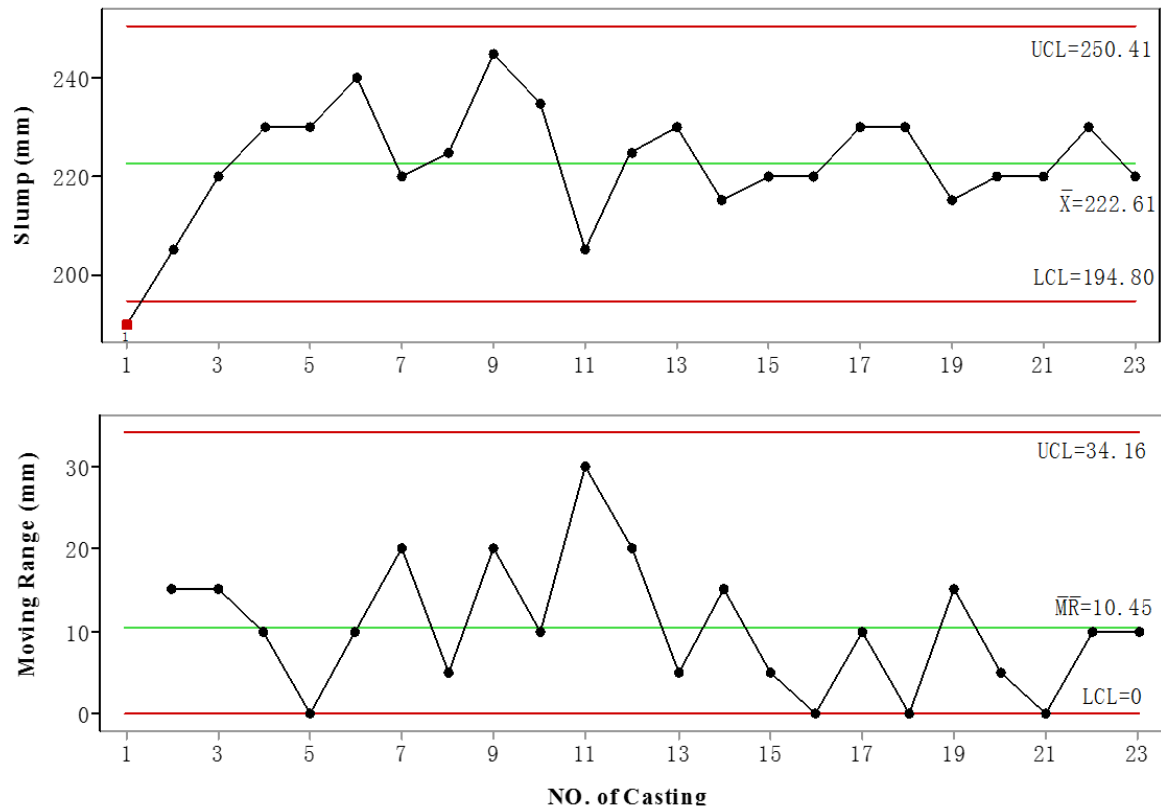
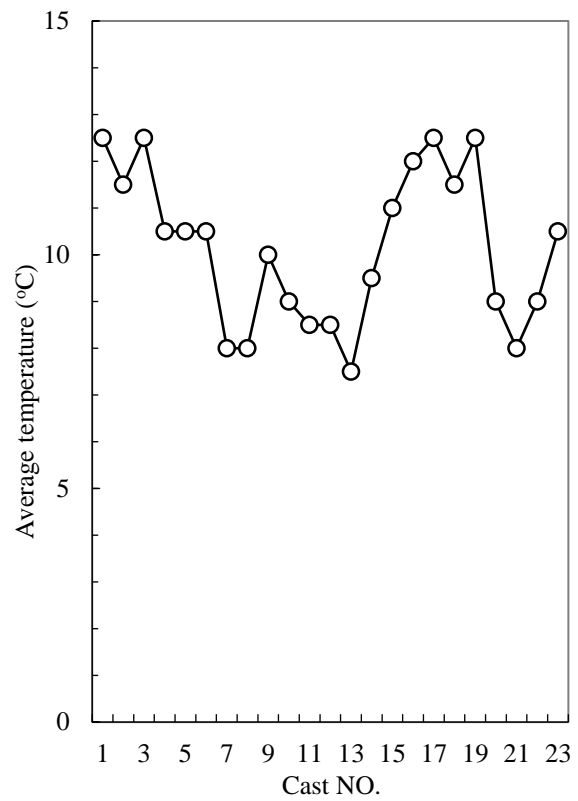
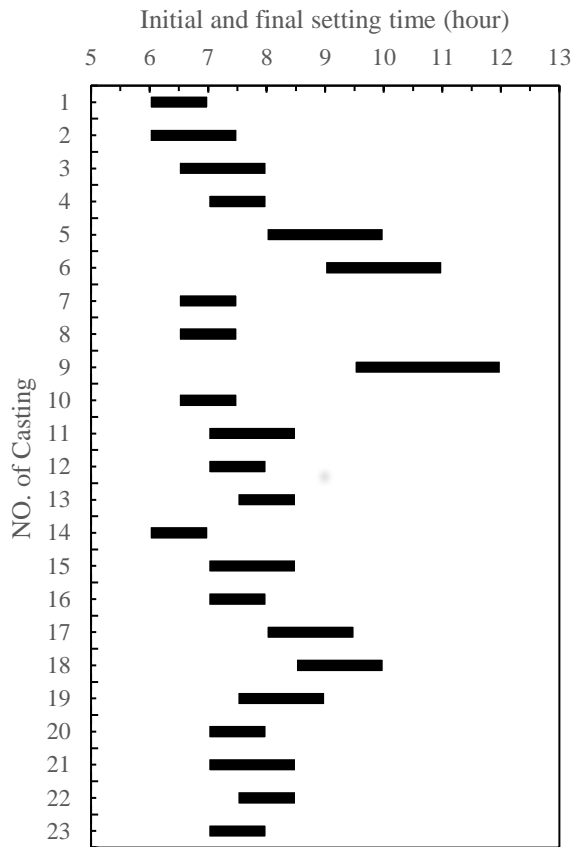


Figure 6 Control chart of alkali-activated slag concrete slump



(a) The record of setting time of AASC (b) The average temperature in the cast

Figure 7 Initial and final setting time for alkali-activated slag concrete

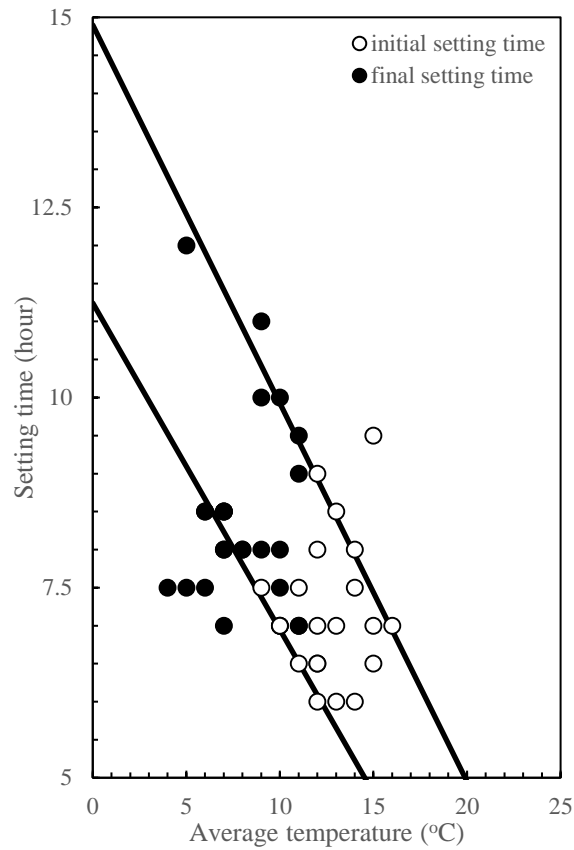


Figure 8 Relationship between the setting time and the average temperature

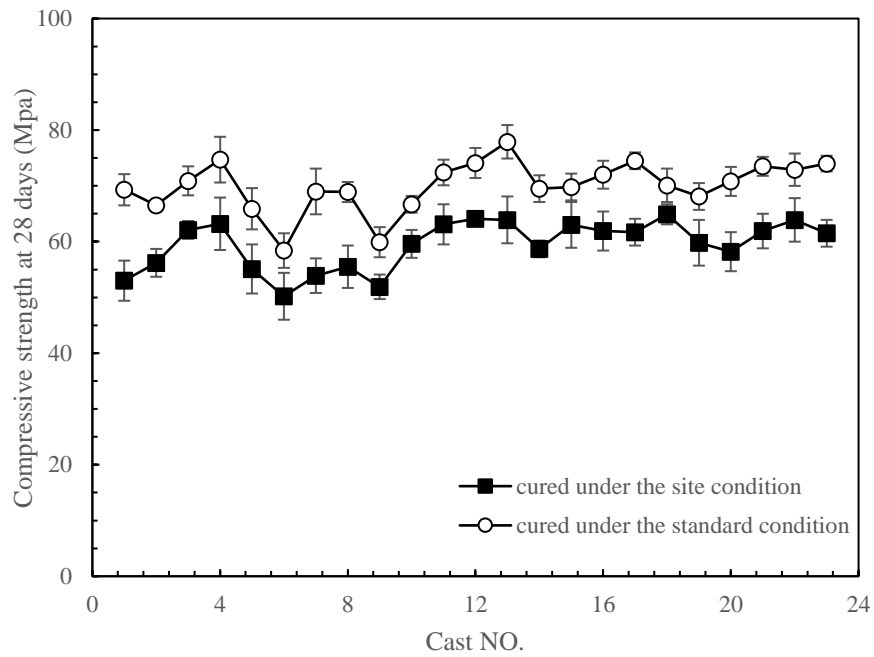


Figure 9 Compressive strength of alkali-activated slag concrete at age of 28 day under the standard condition and the similar condition

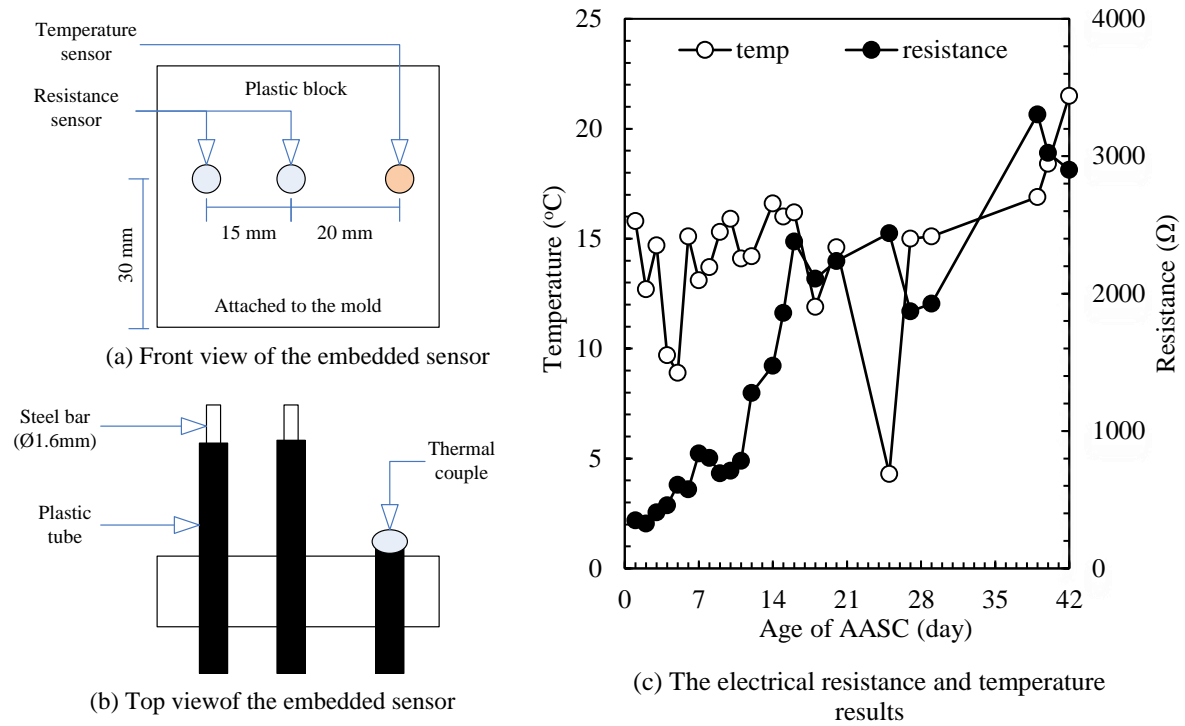


Figure 10 Temperature and electrical resistance data obtained from the embedded sensors in the structural elements

Note: Figure 10-a and -b illustrates the configuration of the embedded resistance and temperature sensor which were installed on the mold before placing AASC. The electrical resistance of AASC was determined by a manual LCR bridge (Tonghui LCR bridge-TH2822: the working frequency: 100 Hz).