ABOVE AND FAR LEFT: Figure 1a – inside views of the structure using alkali-activated slag concrete.

INSET: Figure 1b – overall view of the structure using alkali-activated slag concrete.

Site application of alkali-activated slag concrete in a Chinese building

Kai Yang and **Muhammed Basheer** of the **University of Leeds**, **Changhui Yang** of **Chongqing University**, China, **Jingjie Zhang** and **Qun Pan** of **Chongqing Construction Science Research Institute**, China and **Yun Bai** of **University College London** report on the first cast-in-situ structural application of alkali-activated slag concrete in a building in China. Attention was given to quality control of raw materials and concrete, construction procedure and assessment of both the consistence and strength. This project has demonstrated that the quality and cost involved could be controlled with a detailed working plan. It has also been found that the alkali-activated slag concrete has the potential to be used in cold-weather construction, as the ambient temperature during the construction of the demonstration building was quite low, sometimes below 5°C.

The continuing urbanisation and growth of the world's population are estimated to add approximately 2.5 billion people to the urban population, which necessitates an urgent increase in urban infrastructure. It is anticipated that approximately 60% of the global construction for 2030 will be built new, which will definitely lead to an increase in the use of cement. Therefore, cement production is expected to grow from the current value of approximately 280 million metric tonnes per year to well over 600 million metric tonnes per year by 2025. The cement industry is currently responsible for approximately 5% of the global CO_2 emissions. According to a proposal by the International Energy Agency, CO_2 emissions from the cement industry need to be reduced from their current 2Gtpa to 1.55 Gtpa by 2050. By comparison, over the same period, cement production is projected to increase by approximately 50%. The cement industry has traditionally relied on three main approaches to reducing CO_2 emissions, *viz* energy efficiency, alternative fuels and/or biomass, and clinker substitution. It is estimated that these existing technologies can meet only half of the above goal, so new approaches must be developed.

Emerging technologies, eg, carbon capture and storage, could offer potential solutions, but these methods still need to be proven further and currently are not ready to be used on a large scale, particularly for ready-mixed concretes. Another creative and constructive area is the development of more efficient and more economical materials. Designing new clinkers that require less (or no) limestone is one means to reduce CO_2 emissions significantly, as most of the CO_2 footprint of cement is due to its decarbonation during clinker manufacture. Alkali-activated materials (AAMs) are among these choices, whose performance is comparable with Portland cement. Moreover, AAM is also regarded as a class of green building materials, because many components are industrial by-products, 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 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 the greatest concern. Second, some technical barriers remain to be solved prior to a large-scale use in practical applications. More specifically, some new admixtures (eg, water reducer) need to be developed to reduce the high viscosity of AAM, further research is needed to understand the mechanisms of relatively high shrinkage compared with conventional Portland cement concrete, the in-service durability performances have to be clarified and optimisation of mix proportions should be carried out to achieve pre-specified properties. Third, 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 the use of conventional cement. This naturally leaves the research communities with a major problem of transferring their research from the laboratory to the construction site. So, demonstration projects using AAM are needed urgently to help to overcome the aforementioned barriers.

On the basis of more than 30 years of research in alkali-activated slag cement and concretes, a decision was taken to use alkali-activated concrete in the new Chongqing Research Institute of Construction Science (CRICS) office building at Chongqing, China, in order to explore the potential for structural application of AAM. This article summarises the construction process and quality assessment of the building manufactured with alkali-activated slag concrete (AASC).

AASC DEMONSTRATION PROJECT

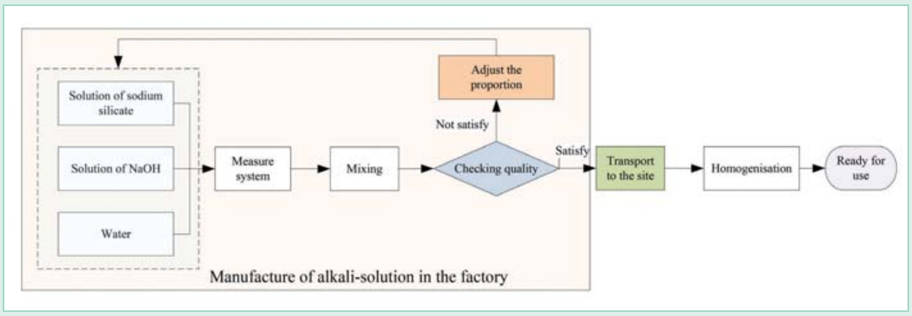
Chongqing Jianke, the CRICS office building (shown in Figure 1a–b), designed by the Chongqing Architectural Design Institute, is located Yuzhong District, Chongqing. The building was constructed by Chongqing

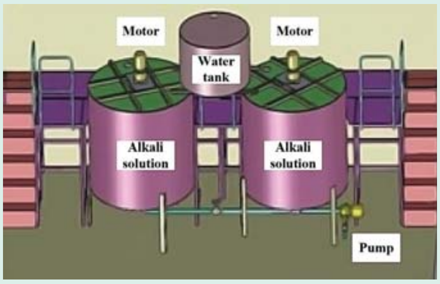
Properties of concrete	Target values
Consistence	
Slump	220± 20mm
1h slump loss	Less than 100mm
Other	No bleeding, no segregation
Setting time	
Initial setting	6–8 hours
Final setting	Less than 12 hours
Compressive strength class	Greater than C40

ABOVE:
Table 1 – the requirements of the properties of alkali-activated slag concrete.

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

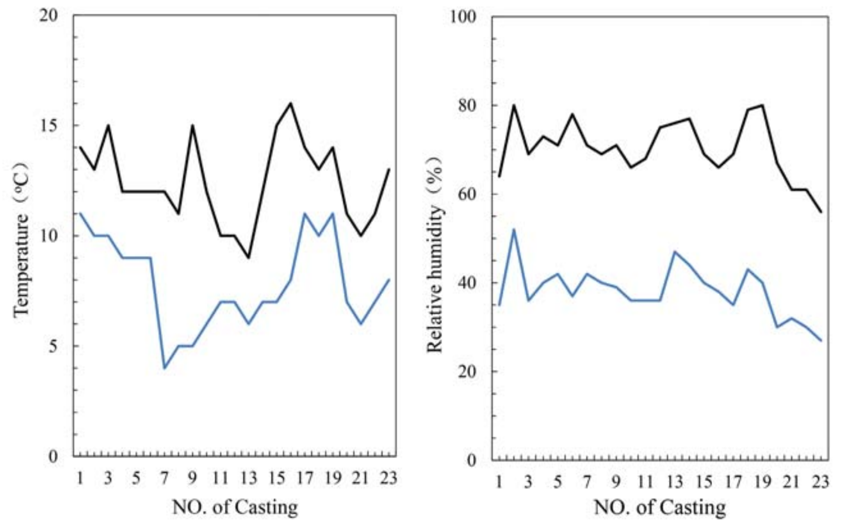
ABOVE:
Table 2 – mix proportions of alkali-activated slag concrete (kg/m^3).





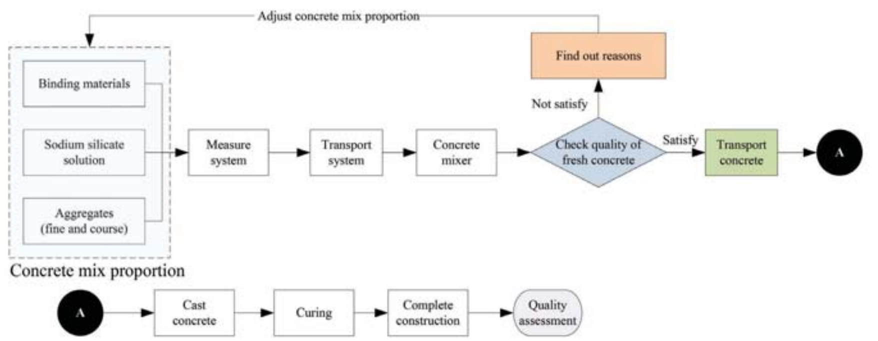
ABOVE:
Figure 2a – flowchart of alkali solution manufacturing process.

LEFT:
Figure 2b – field storage and homogenisation set-up.



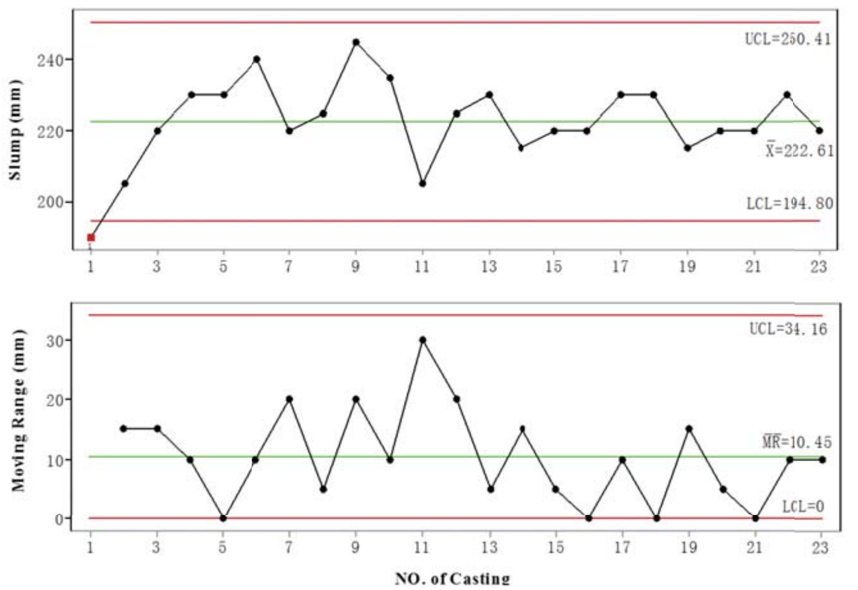
(a) Temperature (b) Relative humidity

ABOVE:
Figure 3 – environmental conditions (variations of temperature and relative humidity) during the construction process.



ABOVE:
Figure 4 – the flowchart for the construction process and quality control.

BELOW:
Figure 5 – control chart of alkali-activated slag concrete slump.



Construction Engineering Group Corporation (CCEGC). It has an area of 413,033m^2, among which 4500m^2, three floors (12m high) were built by AASC and 550m^3 of concrete was used. The main structural frame manufactured using AASC has various types of elements, including slab, column and walls. Its construction began in November 2013 and the final component of the building's spire was installed four months later in 2014, making it the first AASC structural application in China. Due to the lack of experience of using AASC for field applications, 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.

RAW MATERIALS AND AASC MIX PROPORTION

The total amount of GGBS, the main binder of AASC, used in this demonstration project was 10 tonnes, which was all from the same batch supplied by Chongqing Iron and Steel Group. An inorganic mineral admixture (YP-3) was added based on 4% mass of slag content to adjust the setting time. The fine aggregate was a combination of natural sand and an artificial sand to achieve a medium-graded sand, while the coarse aggregate was 10mm and 20mm crushed basalt in equal proportions.

The activator was a mixture of a liquid sodium silicate solution with a pre-specified modulus (Ms) of 1.2. It was prepared by mixing NaOH solution and liquid water glass in a pre-calculated ratio. As no commercial product was available that could meet the specified parameters, the condensed alkali solution (Ms=1.2, ρ=1.31kg/m^3) was manufactured in the factory and it was mixed with tap water to achieve the desired density on-site. Figure 2a illustrates the manufacturing procedure and Figure 2b demonstrates the homogenisation setup used in this project. Once the raw materials were ready, the trials were carried out to adjust the mix proportions in order to satisfy the pre-specified requirements. Table 2 gives the mix proportions of the alkali-activated slag concrete.

CONSTRUCTION PROCESS – ENVIRONMENTAL CONDITIONS

The construction of AASC started on 2 December 2014 and ended on 10 February 2015, during which AASC was cast 23 times. 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 and was generally between 5 and 15°C. The trend of relative humidity is displayed in Figure 3b. The relative humidity 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. This indicates that AASC can be cast at a low temperature, but special attention needs to be given to crystallisation of the alkali solution at the low temperature, which could affect the construction process.

AASC CONSTRUCTION PROCESS

After consulting the government officers and the owner, it was decided to cast AASC on-site. Figure 4 shows the construction process flowchart. The site supervisors checked and confirmed the qualities of moulds, supports and reinforcement according to the Chinese national Standard GB-50204[1] 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 with the alkali solution and then casting the alkali-activated slag concrete. To ensure the quality of concrete and to control the plastic shrinkage cracking, the concrete was covered with plastic sheets immediately after compaction. Once the final setting was reached, the sheets were removed and water was sprayed onto the concrete surface. After this, the concrete was covered with the sheets again and the moisture curing was maintained for 14 days.

ON-SITE AASC QUALITY CONTROL

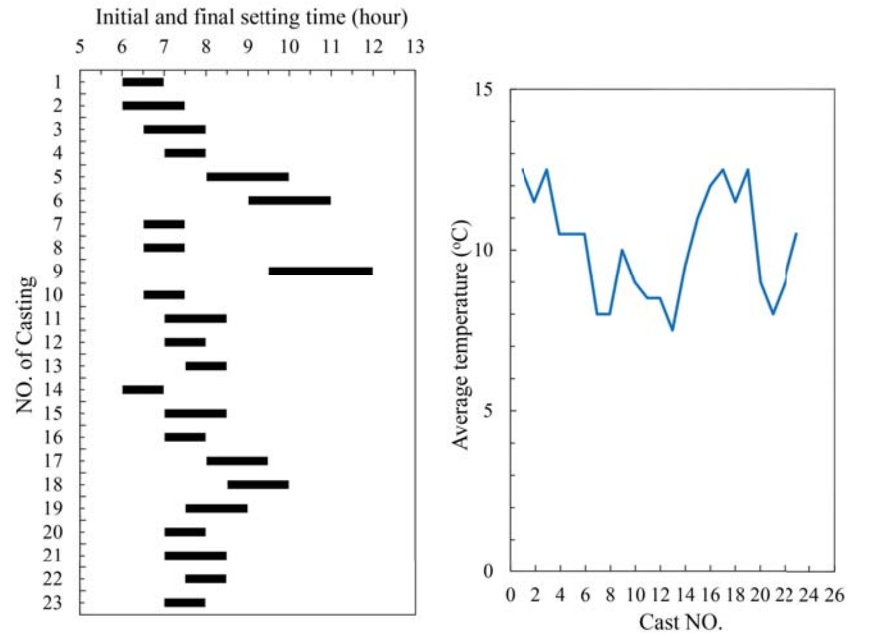
ASSESSMENT OF FRESH PROPERTIES

In addition to visually checking the consistence of every batch of concrete, the slump and setting time of the AASC were assessed according to standard protocols. Figure 5 represents the control charts that summarise the trend of the slump. Evidently, most slumps appear approximately homoscedastic, staying within the upper and lower control limits. With respect to the moving range chart, the values randomly locate in the range from 0 to 30mm and no outlier can be found.

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 developed an inorganic mineral admixture (YP-3, Chinese patent), which was also added. The results of the setting time are given in Figure 6. It was found that the initial setting time varied from six to nine hours, while the final setting time was generally before 12 hours.

ASSESSMENT OF THE COMPRESSIVE STRENGTH

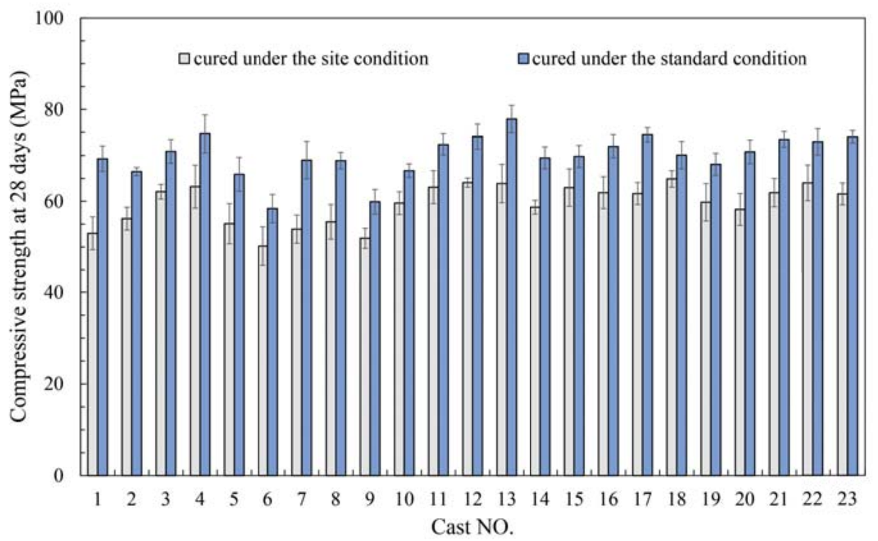
The compressive strength of AASC was assessed using standard cubes of 100mm size. During each casting, ten groups of samples (30 cubes) were randomly taken after mixing and were cured under



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

ABOVE:
Figure 6 – initial and final setting time for alkali-activated slag concrete.

BELOW:
Figure 7 – compressive strength of alkali-activated slag concrete at the age of 28 days under the standard curing condition and the site condition.



the site condition for one day. 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%), 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 7 shows the results of compressive strength of the two curing regimes. As indicated in Figure 7, all compressive strength results satisfy the requirements of strength class C40 agreed by all members. Furthermore, the samples cured under the standard condition have a higher strength but a lower standard deviation than those cured under the site condition. This is believed to be due to two reasons. One is the differences in temperature and relative humidity between the two curing conditions. It was 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. The other reason is associated 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 supply of aggregates.

CONCLUDING REMARKS

On the basis of experiences obtained in this project, the following concluding remarks can be made:

- The performance characteristics of cast-on-site AASC, eg, consistence, setting time and 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.
- There is no significant difference in construction procedures between the AASC and Portland cement concrete, while the only difference is the use of the alkali solution instead of water. It is recommended that additional water should be used to keep the surface wet for 14 days to ensure the surface quality of AASC. Furthermore, the performance of AASC, including compressive strength and hydration process, is very sensitive to environmental conditions.
- The results from the practical application indicate that no specific procedures are required even at a low temperature (approximately 5°C), but the strength development could be significantly affected, which means that AASC has much potential for projects under construction at a low temperature. C

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Reference:

1. NATIONAL STANDARD OF THE PEOPLE'S REPUBLIC OF CHINA, GB 50204. *Code for Quality Acceptance of Concrete Structure Construction*. Standardization Administration of China, Beijing, 2015.