International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 4 ǁ April 2023 ǁ PP. 497-502

Effect of Curing Methods on the Shrinkage of Alkali Activated Concrete

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Abstract
Construction is now one of the main emitters of greenhouse gases in the world as a result of the extensive urbanisation and population growth. Due to greenhouse gas emissions from the production of concrete, which are a major factor in global warming, the industry has a significant influence on the environment. One of the fundamental components of concrete is Portland Cement (PC), which accounts for 10-12% of the total volume. Nevertheless, the PC is regarded as the major source of gas emissions during the manufacture of concrete. This calls for researchers to create an environmentally acceptable substitute, and Alkali-Activated Concrete (AAC) is a viable, long-lasting replacement for regular Portland Cement Concrete (PCC). AAC is made up of water, fine and coarse aggregates, one or more alumino-silicate sources (such as Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA), or Silica Fume (SF), and one or more alkali activators (such as silicates, hydroxides, or carbonates). However, the issue with AAC is that it experiences greater shrinkage than regular concrete. Curing is a crucial component in ensuring the effectiveness and quality of concrete, particularly for AAC. In order to find the ideal curing condition, this study focuses on the impact of various curing conditions on the mechanical characteristics and shrinkage of alkali activated concrete.

Keywords: *Alkali activated concrete, Curing condition, Fly Ash, Shrinkage, Slag, Strength.*

Date of Submission: 08-04-2023 Date of acceptance: 22-04-2023

I. INTRODUCTION

The most common type of construction material is Ordinary Portland Cement Concrete. As one of the essential components of concrete, Portland Cement (PC) accounts for 10-12% of the total volume of concrete. The production of PC has recently increased due to its rising demand; currently, the world produces more than 3 billion tonnes of PC annually. In the next forty years, it is predicted that this need would rise to 6 billion tonnes annually.

Due to the greenhouse gas emissions from the concrete manufacture, which are a major factor in global warming, the industry has a significant influence on the environment. The fundamental elements of concrete are cement, water, fine particles, and coarse aggregates. However, the PC is still regarded as the primary source of gas emissions in the manufacturing of concrete, accounting for 74% to 81% of the CO_2 emissions from conventional concrete mixes.

In addition to the environmental issues the cement industry creates and the substantial energy utilised during the cement manufacturing process, PCC also faces a number of durability issues such sulphate attack, alkali-aggregate reaction, and poor fire resistance. So, one of the key goals of the researchers is to provide environmentally acceptable building materials as a replacement for OPC concrete.

Alkali Activated Concrete (AAC) is considered as a potential alternative by utilizing industry by-products such as Fly ash, GGBFS, Silica Fume etc. AAC can be manufactured without PC, so it can be considered green concrete. AAC has been confirmed to have good mechanical characteristics in addition to reducing CO_2 emissions.

Additionally, AAC emits fewer CO_2 emissions than PCC. It uses a lot of industrial waste, such as slag and fly ash, in addition to lowering CO_2 emissions. AAC is made up of water, fine and coarse aggregates; one or more alumino-silicate sources (such as ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA), or Silica Fume (SF), one or more alkali activators (such as silicates, hydroxides, or carbonates). An environment with a high pH value is created by the activator solutions (e.g. hydroxides, silicates, carbonates or sulfates).

1.1 CONSTITUENTS OF AAC

1.1.1 Alkaline Activators

One of the main differences between OPC binder and the alkali activated binder is that cement uses water which is having a neutral pH initially, and turns alkaline as the hydration process goes on; whereas in alkali-activated systems, it needs a strong alkaline solution to start the dissolution process. So, in order to produce cementitious materials, the alumino-silicate sources needs to be activated by an alkaline solution. Usually, sodium hydroxide and Sodium silicate are the most commonly used alkaline activators. Sodium hydroxide is available as solids, flakes and beads. The required concentration of NaOH solution can be prepared by dissolving anhydrous NaOH. In some cases, Potassium hydroxide and Potassium silicate solutions are also used.

1.1.2 Cementitious Components

Most commonly used cementitious materials for AAC is GGBS and FA either as combination or individually. In addition to these, Silica Fume, Metakaolin, Rice Husk Ash etc can also be used. GGBS is obtained as the by-product from iron manufacture and Fly Ash is obtained from the coal industry or thermal power plants.

1.1.3 Aggregates

The irregularity of aggregate shape, aggregate saturation level, and the amount of aggregate used in the mixture are the primary factors of aggregates determining the hardened state properties of alkali activated materials, much like how aggregates are utilised in OPC concrete. Due to the absorption of free liquid solution and a reduction in polymerization, dry and unsaturated aggregate content is linked to a significant loss in strength while also increasing the likelihood of drying shrinkage at later stages of curing. On the other hand, pre-saturated porous aggregate adds extra water through internal curing to the mixture to replace moisture lost during curing and prevent self-desiccation.

1.2 REACTION MECHANISM OF AAC

Alkaline cements are cementitious materials formed as a result of an alkaline attack on the amorphous or vitreous aluminosilicates. When mixed with alkaline activators, these materials set and harden, yielding a material with good binding properties. Destruction, coagulation, condensation and crystallization are the connected reactions which represents the components of the mechanism model. The first step is the breaking of Si-O-Si and Al-O-Si bonds that occurs when increasing the pH value of the alkaline solution, so that these bonds are converted to a colloid phase. Consequently, the disjointed products are combined, that reacts with each other to form a coagulated structure, resulting in generating a condensed and crystallized structure in third phase.

II. EFFECT OF CURING ON COMPRESSIVE STRENGTH OF AAC

2.1. AMBIENT CURING

Ambient curing condition is considered to resemble in-situ curing conditions. The high calcium based alkali activated systems can be better cured in ambient conditions and it does not require any high temperature curing. This curing condition produces lesser carbon dioxide and is cost effective [6]. The compressive strength of ambient cured alkali activated concrete depends on type and ratio of binder materials as well as the activator solution [28].

When alkali activated slag and slag – fly ash based mortar specimens are placed at room temperature of about 25ºC, higher compressive strength is observed and is higher in case of sodium based activator for all molarities [1]. More than 70 and 95% of the 28 day strength will be attained in 1 and 7 days of ambient cured alkali activated slag concrete specimens [2]. Under standard curing conditions of temperature 20±5ºC for 24h, there is a faster development of early age strength in case of slag based and metakaolin based alkali activated mortars, which continued to increase with time.

Standard curing is not suitable for alkali activated fly ash based mortars and is more beneficial for slag based mortars [27]. The strength development of ambient cured fly ash based geopolymer specimens is comparable to that of heat curing at 60ºC [9]. Even though there is a decrease in initial strength and increase in final strength with increase in fly ash content, samples with higher fly ash content are able to be cured in ambient conditions since fly ash contributes to strength gain with time [10].

The compressive strength of medium calcium fly ash and slag pastes is seen to be increased with increase in CaO content when cured under ambient conditions of 20ºC [18]. Ambient cured metakaolin based geopolymer concrete developed strength with time and is comparable with OPC [7].

2.2. HEAT CURING

When cured at elevated temperature of 50ºC for about 48 h, the compressive strength of alkali activated fly ash concrete was increased but the rate of strength gain is not accelerated as that of PCC [17]. By placing the specimens in oven at 65±5ºC for 24h, it increases the compressive strength of fly ash based specimens but adversely affected the strength of slag based specimens [1]. The compressive strength of alkali activated high-

MgO Swedish slag concrete is higher for non heat-treated sealed cured samples than heat-treated sealed curing [3].

The strength of high calcium based and low calcium based alkali activated mortars can be improved by curing in a temperature range of 60 to 80ºC for first 6h and first 24h respectively [6]. The 28 day compressive strength of alkali activated slag concrete cured in a curing room at a temperature of 60ºC and 80% relative humidity is seen to be higher than air curing and saturated lime water curing, which again confirms that elevated temperature curing is more beneficial for the development of compressive strength [29].

When specimens were first cured under steam curing of 80ºC for 6h, then demoulded and placed in oven at 60ºC and 80ºC; it is seen that there is no negative impact on the compressive strength development of fly ash based alkali activated mortar, but will affect slag and metakaolin based mortar specimens [27]. Metakaolin based geopolymer concrete when heat cured at 75ºC for 26h after a delay time of 2 to 3 days accelerated the strength development and the corresponding 28 day compressive strength is higher than that of OPC [7].

There will be strength reduction in geopolymer fly ash concrete when exposed to elevated temperatures like 400ºC, 600ºC and 800ºC after heat curing in oven at 70ºC for 24h and the reduction increases with increase in exposed temperature [4]. Similar results were also obtained when geopolymer fly ash concrete was exposed to fire at 800, 1000 and 1200ºC after heat curing by increasing the temperature to 80ºC and 100ºC for 24h. Strength degradation started at 1000ºC [31]. Compressive strength development will get accelerated by providing heat treatment but the later age strength will be reduced as compared to those cured at room temperature [25].

2.3. STEAM CURING

Steam curing is more favorable for the strength development in alkali activated fly ash based mortars which is more predominant especially when the temperature is increased from 60 to 80ºC. So, steam curing at 80ºC is beneficial for fly ash based mortars. Even though steam curing can accelerate the rate of strength gain of slag based mortars, it cannot increase the strength to a much higher value as that of fly ash based mortars. For metakaolin based mortars also, steam curing can increase the compressive strength [27]. Compressive strength of 15-90 MPa was attained in slag based alkali activated concrete by steam curing at 100ºC for 8h.

For Hybrid Alkali Activated Cement (HAAC) mortars; where high proportion of mineral admixture and low proportion of Portland cement is mixed with small dosage of alkaline activator solution; steam curing done at 85ºC for 2h can increase the compressive strength but it is inferior to that of OPC mortars [23].

2.4. WATER CURING

Water curing is done by immersing the specimens in water having ambient temperature of about 20 to 25ºC or in hot water of about 65 to 95ºC. This can improve the compressive strength [6]. Compressive strength of water cured alkali activated slag mortar specimens increased when demoluded specimens are immersed in water tank at 25ºC for 28 days even when samples are exposed to elevated temperature heating regimes, when heated to a temperature range of 25-600ºC [8].

Water curing can be conducted either as continuous water curing during the entire curing period or as intermittent curing by placing the specimens in water for initial few days and then followed by ambient curing. The intermittent curing is adopted to resemble the conditions in site. It is seen that water curing has better performance after 7 days but after 28 days, intermittent curing is seen to be more effective [2]. Curing in high temperature water increases the early age compressive strength very rapidly which increases with the temperature, but slows down in the later age [13].

2.5 LOW TEMPERATURE CURING

The low temperature preparation technology of alkali activated concrete provides new idea for its commercial application where the raw materials can be stored and stirred at low temperature and fresh concrete can be transported at room temperature. But it is seen that the low temperature preparation technology has slight influence on the mechanical properties of Alkali Activated Concrete [24]. Lowering the curing temperature to about 7-15ºC may reduce the compressive strength in short term, but the long term strength will not be adversely affected [19, 30].

2.6. CO_2 CURING

Carbon dioxide curing is done by placing the alkali activated mortar samples in an accelerated carbonation chamber with 5% CO_2 level at 20ºC and 60% relative humidity and is compared by curing in an environment chamber whose CO_2 level is equivalent to atmospheric conditions. Reactive magnesium oxide is used as a partial substitute for fly ash. It is observed that curing in carbon dioxide rich environment improved the compressive strength as compared to normal curing methods. The compressive strength increased as a result of the carbonation of mixtures with MgO [15]. For slag based alkali activated concrete, carbon dioxide curing does not affect much on the compressive strength [13].

2.7. CURING AGENTS

Covering the concrete specimens with an envelope or any membrane is more desirable for on-site applications, so that it prevent the loss of moisture from the surface. Curing compounds can also be added [6]. Addition of internal curing agents like Superabsorbent Polymer (SAPs) reduced the compressive strength of alkali activated systems. Increasing the dosage of SAPs increased the volume of voids; thereby reducing the compressive strength [14, 16].

Sodium hydroxide solution, deionized water and zeolite sand were used as internal curing agents to produce sustainable alkali activated concrete. The compressive strength of alkali activated slag mortars increased with increase in zeolite sand content when sodium hydroxide solution is used as the internal curing liquid. There is a decrease in compressive strength when water is used as internal curing liquid [22].

Since the compressive strength is decreased when SAPs are added, it can be improved by using perforated cenospheres. Even though the early age compressive strength is reduced; the later age compressive strength is increased when perforated cenospheres is used as internal curing agent in alkali activated mortars [26].

2.8 OTHER CURING METHODS

Other curing methods such as solar curing, microwave curing, immersion in saline water, curing under natural atmospheric conditions are also adopted for alkali activated materials. All these are seen to increase the compressive strength of alkali activated concrete [6]. For conducting hydrothermal curing, specimens were kept in hydrothermal chamber before demoulding at a temperature of 135±5ºC and pressure of 2.3±0.2 bar for 2h and then cooled down and demoulded. Slag based alkali activated specimens after hydrothermal curing is heated to attain a temperature of 200, 400, 600 and 800ºC and it is seen that the highest compressive strength is seen for hydrothermal cured samples in 25-800ºC compared to ambient and water cured samples [8]. Autoclave curing is done at 210ºC, but it develops compressive strength lower than that of steam curing [11].

III. EFFECT OF CURING ON SHRINKAGE OF AAC

3.1. PLASTIC SHRINKAGE

There are only limited studies regarding the plastic shrinkage of alkali activated concrete and its mitigation. The addition of calcium hydroxide mitigated autogenous and drying shrinkage but increased the plastic shrinkage. Plastic shrinkage is determined by recording the time required for the appearance of the first crack in concrete.

As an internal curing agent, Super Absorbent Polymers (SAP) is seen to effectively mitigate the plastic shrinkage of alkali activated systems. The reduction of plastic shrinkage depends on the dosage of SAPs. It is seen that SAPs reduced the chances of cracking due to shrinkage; even small dosage can reduce the severity of cracking before final setting time especially in sodium hydroxide based alkali activated system [16].

3.2. DRYING SHRINKAGE

The main limitation of alkali activated concrete for its in situ application is its high early age drying shrinkage which needs to be effectively mitigated. This can be done either curing for longer curing period or by curing at elevated temperatures. But these curing methods are not practically possible in site which makes alkali activated concrete suited for precast applications [17].

After 56 day ambient curing of metakaolin based geopolymer concrete at 22±3ºC temperature, the samples were subjected to drying procedure. It can be seen that the structural water required to prevent shrinkage increases when the ratio of Si:Al was increased. Also, increasing the Na content also increased the structural water requirement [5]. It is seen that shrinkage of OPC concrete is stabilized when it was less than 1000 micro strain after 45 days, whereas in case of alkali activated concrete specimens cured at room temperature, shrinkage stabilized after 60 days when it reached about 2000 micro strain [20].

Steam curing of hybrid alkali activated cement mortars reduced its drying shrinkage and is intermediate to corresponding OPC and alkali activated mortars [23]. Compared to steam curing; autoclave curing is more effective in reducing the drying shrinkage. Heat treatment with autoclaving can reduce the drying shrinkage in case of sodium silicate activators [11].

Mixing the slag based alkali activated concrete at low temperature of -5, 0, 5ºC for 10 to 50 min and subsequent curing at 20±2ºC reduced the drying shrinkage. The drying shrinkage decreased with increase in mixing time at -5ºC [12, 24]. Curing the alkali activated mortar at below normal temperature can reduce the shrinkage which is desirable for its practical applications [19].

Heat curing can considerably reduce the drying shrinkage of alkali activated slag concrete. Elevated temperature cured specimens have shrinkage lesser than those cured at room temperature and it makes the concrete more stable [25]. Pretreatment can further reduce the magnitude of drying shrinkage. Heat treatment and sealing of concrete can also reduce the drying shrinkage of alkali activated concrete by 30 to 50% than non heat treated and unsealed specimens which exhibited higher drying shrinkage [3]. Rate of drying shrinkage in high temperature water curing condition decreased with increase in temperature. When this temperature increases from 20 to 60ºC, drying shrinkage is seen to be decreased. Water curing resulted in lesser drying shrinkage than air curing.

Even though elongated heat curing can develop higher shrinkage, the drying shrinkage is lesser in case of thermal cured specimens than lime water curing and is more effective than ambient and high humidity curing [6]. When cured in temperature of 60ºC, it is observed that the drying shrinkage was reduced than lime water curing and air curing [29].

Relative humidity is very important for drying shrinkage in case of carbon dioxide curing, since increase in relative humidity decreased the drying shrinkage of alkali activated slag concrete. Overall, carbon dioxide curing reduced the drying shrinkage of alkali activated concrete [13, 15]. Specimens cured in natural atmospheric conditions; where they are exposed to a temperature of about 36ºC; have shown lesser drying shrinkage at the end of 28 days [1].

3.3. AUTOGENOUS SHRINKAGE

Slag and fly ash based alkali activated concrete can exhibit higher autogenous shrinkage, which can be measured using corrugated pipe method. It is seen that slag-fly ash based paste experience lower autogenous shrinkage than fly ash based pastes. Also, alkali activated pastes show larger shrinkage than OPC pastes. It is concluded that self-desiccation is not only the reason, but also the reduction of steric-hydration force induces autogenous shrinkage [21].

For normal concrete, autogenous shrinkage occurs during first 24 hours, whereas in alkali activated concrete, it is seen that autogenous shrinkage continuous for a long time of about 90 days. Replacing GGBFS with silica fume of about 15% can reduce autogenous shrinkage [30]. Super Absorbent Polymers can reduce the autogenous shrinkage of alkali activated concrete also [14]. Also, it is seen that when sodium hydroxide solution is used as the internal curing liquid, autogenous shrinkage is being reduced than using water as internal curing liquid [22].

By using perforated cenospheres, the autogenous shrinkage of alkali activated mortar can be can be successfully mitigated. Since autogenous shrinkage has been reduced, total shrinkage was also reduced subsequently. Perforated cenospheres hence acts as a reservoir for internal curing water as well as an aluminosilicate source for alkali activated mortars [26].

IV. CONCLUSION

Alkali-activated concrete has developed significantly in recent years, as a result of the main research focus on increasing the sustainability of the concrete industry through the use of durable concrete with low energy intensity. Since AAMs were first discovered, the curing regime has been a significant obstacle to their on-site application. Studies prove that there is a direct relationship between the curing regimes adopted and the behaviour of alkali activated concrete.

Alkali activated concrete has been subjected to a variety of curing processes, which can be water curing, thermal curing, ambient curing, oven curing, hydrothermal curing, limewater curing, etc. Water curing leads to higher porosity in low calcium based alkali activated mortars, whereas in high calcium systems, it may leads to the dilution of activator solutions and thereby reducing the reactivity. For laboratory conditions, sealing or wrapping type curing is found to be more effective since it develops lower porosity. Oven curing is effective in developing high early strength but can contribute to higher magnitude of drying shrinkage. Certain studies prove that delaying the oven curing can also provide better performance.

The successful development of compressive strength in alkali activated binders made with waste-derived materials shows that municipal solid waste can be better recycled or utilized as building and construction materials.

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