Durability of concrete with alkali-activated materials, a short literature review

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ABSTRACT: Alkali-activated materials are considered the most promising alternative to Portland cement in making the concrete industry more environmentally friendly by reducing CO2 emissions. However, these alternative binders face challenges, particularly related to durability. This work presents a brief literature review on the durability of concrete produced using alkali-activated binders. The mechanisms of degradation are discussed, namely steel corrosion, carbonation, acid attack, permeability, porosity, and capillarity. Comparison to typical concrete that uses Portland cement as a binder is common.

1 INTRODUCTION

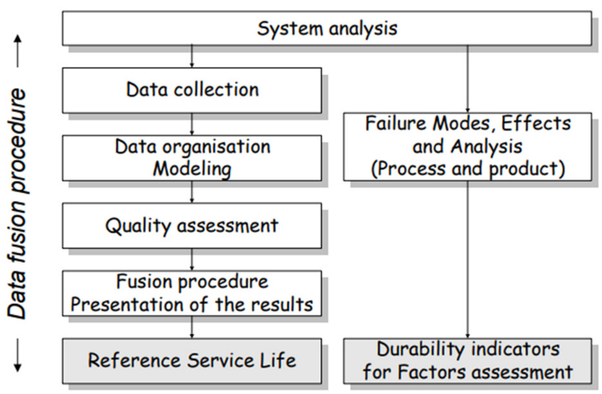
The production and consumption of ordinary Portland cement are responsible for 5 to 8% of total anthropogenic CO_2 emissions, of which 95% is generated during cement production (C. Ouellet-Plamondon 2014). Furthermore, this production has been contributing to the degradation of terrestrial ecosystems for decades by exploiting calcareous and clayey materials. To address environmental concerns, alternative materials are being considered to replace Portland cement, such as supplementary cementitious materials. To achieve carbon neutrality by 2050, the use of binders obtained from alkaline activation (also known as alkali-activated materials or alkaline cement) appears to be the most reliable alternative. This is because it is expected to significantly reduce CO_2 emissions (Habert G 2010). However, there are no standards for concrete made of alkali-activated materials. Subsequently, there are concerns regarding the durability of products, knowledge of useful life-cycle planning methodologies, analysis of applicable standardization, approach to determining estimated lifetime, and implementation of measures to promote durability.

2 DURABILITY OF ALKALI-ACTIVATED MATERIALS

According to (Jannie S.J. VAN DEVENTER 2011), raised an important question regarding the durability of geopolymer concrete and alkali-activated materials, which remains a significant obstacle to their widespread commercial adoption. That means the obstacle lies in the question, not the answer. Some argue that alkali-activated materials lack decades of durability data to prove their long-term stability due to recent research, but this is not accurate (C. Shi 2006). It can also be asked what evidence existing binding systems have, in addition to structures that have been in service for long periods of time, to prove their fundamental durability? The answer is that there is very little doubt about the durability of Portland cement. However, recent analytical studies have shown significant changes in hydrated Portland cement binder and cement-slag mixtures over a 20-year period (R. Taylor 2010).

According to (Jannie S.J. VAN DEVENTER 2011) alkali-activated systems face the challenging task of proving their durability. Ultimately, the only accepted verification tool is the presence of decades-old structures. Most conventional methods for testing the durability of cement and concrete involve subjecting small samples to extremely harsh conditions, such as exposure to highly concentrated acid or saline solutions, for brief periods of time. These results are used to predict how the material will perform under typical environmental conditions for several decades or longer. (Jannie S.J. VAN DEVENTER 2011) explains that predictive models rely on concepts such as mass transport through porous media, reaction kinetics, and particle packing. One limitation of this approach to demonstrate durability is that it can only offer estimations of anticipated performance under real environmental conditions, rather than providing conclusive evidence. Furthermore, the research community's structure is fundamentally based on the time frame of graduate research projects, which typically span 3 to 6 years. This leads to the inherent problem that what is typically considered a "long-term" test is significantly shorter than the expected service life of most concrete structures. When projects are conducted over extended periods, it is crucial to have effective management and maintain focus on the project, which is often lacking. So, the reality is that durability tests hold little significance without real-world validation (Jannie S.J. VAN DEVENTER 2011).

Today, society is increasingly focused on achieving "sustainable development" in civil construction. This involves considering social, environmental, and economic aspects to avoid quality problems. In this context, two complementary tools were developed by (Lair 2000), being 1-Data fusion procedure , on left part of Figure 1; and 2-Analysis of Failure Modes and Effects , on right part of Figure 1. On the same plane, Figure 2. by (J. LAIR 2001).



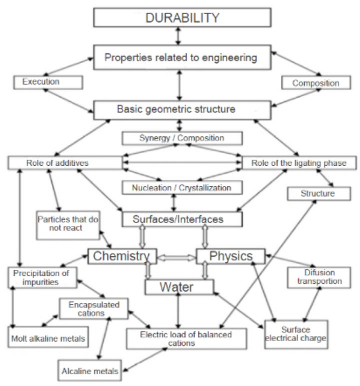


Figure 1; and Figure 2. Durability evaluation methods and tools for geopolymeric binders were discussed by (J. LAIR 2001). A schematic diagram illustrating the relationships between different areas of geopolymeric technology was adapted from (Duxson P 2007) and cited by (F. Pacheco Torgal.; Said Jalali. 2010).

In terms of durability, materials that undergo alkaline activation are known to reduce both permeability and porosity. This is because a porous material allows for the entry of liquid and gaseous agents that can cause chemical changes within the concrete . (Amândio Teixeira Pinto 2006). Alkaline cements and alkaline hybrid cements have been found to exhibit similar durability to Portland Cement in most cases, as demonstrated by studies conducted by (Wang 2020). However, these cements are particularly notable for their exceptional resistance to acid attack and their remarkable fire resistance, as evidenced by research conducted by (Donatello 2014) .

These indicators contribute significantly to the performance of materials associated with the results, although there are only a limited number of life cycle analyses of alkaline activation technology available (van Deventer JSJ 2010) . A comprehensive research program conducted in Germany (Weil 2009) has yielded valuable information on the selection of precursors and mixing designs for various materials, typically utilizing geopolymers. Geographical specificity plays a significant role in conducting a comprehensive life cycle analysis. Therefore, further studies are necessary in various locations, along with a diverse range of mixing projects that cover a broader spectrum of alkali-activated materials. (van Deventer JSJ 2010).

For (Duxson P 2007), the durability of alkali-activated materials is the key factor that sets them apart from Portland cement (Duxon 2007). In addition to these advantages, it should be noted that these binders enable the reuse of certain materials, such as waste from mines and quarries. Furthermore, they possess a high capacity for immobilizing toxic and radioactive waste, which makes them highly valuable from an environmental standpoint (van Deventer 2010). There exists a direct relationship between durability and various comprehensive engineering properties, such as geopolymeric structure, surfaces and interfaces, chemistry, physics, aquatic environment, additives, binders, alkaline metals, cationic charge balance, surface electrical load, composition, execution, synergy, competition, the role of the ligating phase, diffusion transport, nucleation, crystallization, precipitation of impurities, alkaline-ground metals, non-reactive particles, encapsulation, and others. This broad relationship between durability and engineering properties is crucial to understanding the factors that contribute to the longevity of materials.

3 DEGRADATION PROCESSES

3.1 *Degradation due to steel corrosion*

Currently, our understanding of the chemistry of steel corrosion within alkali-activated binders is likely insufficient to develop specific testing methods for these materials (Susan A.Bernal 2014). This is particularly true for alkali-activated materials based on granulated blast furnace slag (GBFS) or other metallurgical slags containing sulfates. These materials generate a reducing environment within the linker, which leads to complexities in electrochemistry that are not yet well understood (Susan A.Bernal 2014).

The corrosion of steel can occur by the destruction of the reinforcements, when the pH value is lowered through the phenomenon of carbonation by CO_2 ingress, or through the ingress of chlorides. Generalized corrosion may occur when there is a general destruction of the passive layer or corrosion by bites, due to the localized dissolution of that layer, typical of chloride ions. (F.Pacheco Torgal ; Said Jalali. 2009).

In order to gain a deeper understanding of the influence of sulfate chemistry on the corrosion rates of steel, it is necessary to analyze and comprehend the mixtures of large-volume granulated blast furnace slag with Portland cement. Although the analysis of alkali-activated materials has reached a more advanced stage, with greater maturity in this research topic, the complexity of the issue requires further investigation (Susan A.Bernal 2014).

For alkaline activated binders little information is available on their ability to prevent corrosion of the steel of the reinforcements.(F.Pacheco Torgal ; Said Jalali. 2009).The presence of high concentrations of can have significant effects on steel corrosion, particularly when combined with carbonation and chlorides. Understanding, the interaction these factors chlorides their impact on between the transport properties the chemistry at the interface is an important area of research ground in the decades. Despite progress in this field, and much remains to be (Susan A.Bernal 2014) . Therefore, it is crucial to suggest that regardless of the chosen test methods for analyzing alkali-activated materials, a comprehensive report of the experimental conditions and details in each published study is necessary. This will enable the reader to comprehend and utilize the results of the research effectively (Susan A.Bernal 2014). This is universally important for implementing durability testing, but it is particularly critical in areas such as corrosion testing. There are many misunderstood parameters that can potentially influence the results obtained in all tests performed (Susan A.Bernal 2014). In most reinforced concrete applications, the primary modes of structural material failure are more closely related to the deterioration of the embedded steel reinforcement than to the concrete itself (Susan A.Bernal 2014).

3.2 *Carbonation*

There is limited knowledge about carbonation in alkali-activated materials, as noted by (Susan A.Bernal 2014), identified higher carbonation rates in concretes containing granulated blast furnace slag (GBFS) activated by sodium silicate when compared to common concretes in accelerated tests (Susan A.Bernal 2014). These results are in accordance with the observations of (Bakharev 2001) , who also reported greater susceptibility to carbonation in concrete prepared alkali-activated materials with sodium silicates and granulated blast furnace slag than in reference concretes to the common Portland cement base, when evaluated under accelerated carbonation conditions (Susan A.Bernal 2014). On On the other hand, (Deja 2002) identified that granulated blast furnace slag (GBFS) mortars and concretes activated with alkali showed carbonation depths comparable to those obtained for Portland cement reference samples, along with increased compression strengths and longer CO_2 exposure time (Susan A.Bernal 2014). This was associated with a refinement of the pore structure, as carbonates precipitated during the carbonation reaction. That effect was more noticeable in silicate-based activated samples than in sodium carbonate-activated samples (Susan A.Bernal 2014) .

It is important to note that accelerated carbonation of the specimens in this study was induced using a carbonation chamber at a relative humidity temperature of 90% and fully saturated with CO_2 (Susan A.Bernal 2014). These results should be interpreted very carefully because, in such high relative humidity, pore saturation in these specimens is such that even when exposing alkali-activated materials to extremely severe CO_2 concentrations, the carbonation reaction does not develop in the same way as it would be at lower relative humidity values (Susan A.Bernal 2014).

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3.3 *Acid attack*

Alkali-activated materials and alkaline hybrid cements have been studied for their durability (Wang 2020) have shown that in most cases, these materials exhibit behavior like Portland Cement. However, they are notable for their excellent resistance to acid attack and their extraordinary fire resistance, as demonstrated by .(Donatello 2014)

Although most concrete structures are not exposed to highly acidic conditions, there are certain situations where this can become problematic. In such circumstances, the lifespan of concrete structures can be significantly reduced. Acid rain (Xie 2004), acid sulfate soils (Floyd 2003), animal waste (de Belie 2000) ; (Bertron 2007), and industrial processes (Chaudhary 2009) are all potential sources of acid that can degrade concrete. However, the most economically significant industrial cause of acid-induced damage to infrastructure elements is corrosion by biogenic sulfuric acid, which typically occurs in sewage pipes (Davis 1998).

This issue is a crucial area of research in several long-standing studies worldwide, with various technical solutions developed and implemented. These solutions include the manipulation of concrete by the pipe itself or the use of coatings (Fourie 2009).

3.4 *Permeability, porosity and capillarity*

There is no universally applicable technique that can provide a comprehensive multiscale characterization of a complex material, such as alkali-activated materials or concrete. To obtain details on the length scales of interest, a more comprehensive toolkit of techniques is required. The BJH (Barrett-Joyner-Halenda) method for calculating pore size distribution has been standardized in several countries .

However, it is a general method for porous materials and not specifically designed for cements or building materials. Although this method has been unfavorably compared in recent years to more advanced techniques for converting gas sorption data into pore size distribution information (Metroke 2012), it is still the most widely used method for extracting gas pore size distribution information from sorption data for alkali-activated binders. (Lloyd 2009) and (Zheng 2010) utilized the BJH how technique to observe the pore refinement in alkali-activated materials derived from fly ash as the activator concentration increased. This finding aligns with the conceptual understanding of the formation of these materials.

Capillarity tests have shown that the pore networks of granulated blast furnace slag concrete, when activated with alkali, are sufficiently refined and tortuous. This refinement and tortuosity result in a low extent of capillary sorptivity in these materials (Bernal 2011). A study conducted by (Adam 2009), found that, in most cases, the porosity of alternative cements was similar to or higher than that of comparable Portland cements . The use of a higher module activator (Bernal 2010) or a lower water content (Collins 2008) in alkali-activated granulated blast furnace slag elements reduces the water absorption rate. Sorption decreases with increased curing time in humid conditions (Collins 2008) . The high capillary suction of highly porous alkali-activated metakaolin or natural pozzolan-based binders can pose potential problems in many applications. If alkali movement is not properly controlled, it can lead to efflorescence, as noted by (Najafi Kani 2012). However, this property also presents opportunities for thermal control and can provide a water source for evaporative cooling, as observed by (Okada 2009).

4 CONCLUSIONS

The question regarding the durability of the alkali-activated materials remains open. Therefore, it constitutes an obstacle to used widely the alkali-activated materials as the binder material in the concrete.

Regarding durability, alkali-activated materials are highlighted in the reduction of both permeability and porosity. Moreover, the alkali-activated materials present an excellent behavior against acid attack and have extraordinary fire resistance.

Currently, the understanding of the chemistry of steel corrosion inside binders of alkali-activated materials is still likely insufficient to allow the development of specific test methods for the chemistry of these materials. The effects of the presence of high concentrations of alkalis and, in particular, the interaction between carbonation, chlorides and alkalis, is not totally understood.

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