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GROUT FOR TWO-STAGE ALKALI ACTIVATED CONCRETE

Nada Zod[1] and Ahmed M. Soliman[2]

[1,2] Concordia University, Canada
[2] ahmed.soliman@concordia.ca

Abstract: Production of ordinary Portland cement (OPC) has several negative ecological and environmental impacts. This includes rapid depletion of natural sources and high carbon dioxide (CO_2) emissions. Many attempts have been made to find an alternative binder for OPC. Among differently proposed binders, alkali-activated material showed promising performance. It is characterized by very low carbon footprint along with low strain on natural resources as it mainly composes of industrial by-products. Therefore, this paper highlights the potential of using AAM as a replacement for OPC in producing grout for two-stage concrete (TSC). A review for the uses of Two stage concrete and alkali activated materials in repair along with their advantages were provided. Different advantages of combing two-stage concrete and alkali-activated material were explored. It is clear that this new type of grout will enhance the sustainability for two stage concrete making it a green material for repair/ rehabilitations for infrastructure.

INTRODUCTION

Concrete production emitting high amount of carbon dioxide (CO_2) to the environment. Cement and concrete production contributes about 7% of the total worldwide CO_2 emissions, and thus finding a practical way to reduce the greenhouse gas emission is essential. Alkali-activated materials are emerging as alternative cementitious materials. These binding materials are synthesized through combining source materials rich in silica and alumina such as fly ash, ground granulated blast furnace slags with strong alkali solutions namely sodium hydroxide and sodium silicate. Upon mixing, a reaction takes place resulting in the formation of a three-dimensional amorphous aluminosilicate network with strength similar or higher than that of ordinary cement. (Part, Ramli, Cheah, & Materials, 2015).

Alkali-activated binders are rapidly drawing attention not only because they reduce the carbon footprint and use by-products but also because they are durable. They possess several interesting features such as high strength, corrosion resistance, water resistance, high temperature resistance, enclosed metal ions etc. (Zhang, Gong, & Lu, 2004). These features promote alkali-activated binders as ideal materials for sustainable construction and rehabilitation.

On the other hand, Two-stage concrete (TSC) is a type of concrete first realized as a repair technique. Two-stage concrete is obtained by preplacing the coarse aggregates in a form then injecting with a cementitious flowable grout. The grout fills the voids leaving a high aggregate/cement ratio with point-to-point aggregate contact (McLeish, 1994). This type of concrete has several applications as a repair material.

Using alkali-activated grout to replace the traditional cementitious grout of two-stage concrete gives a new material, two-stage alkali-activated concrete(TSAAC). This new material if utilized in repairs promises an eco-friendly durable repair that lasts. This merge promises a much-sought green material that will give a repair that requires little/no maintenance while decreasing the negative effect on the environment.

Applications of two-stage concrete as a repair material

The first ever use and discovery of two-stage concrete is during the repair of the Santa Fe railroad tunnel, California. While concreting, Louis S. Wertz and Lee Turzillo start to add coarse aggregates to fill large spaces in order to reduce grout consumption. This way, two-stage concrete emerges as an infrastructure rehabilitation technique especially used in bridges and tunnels (Bayer, 2004). The second major use of TSC is in the rehabilitation of the spillway tunnel of Hoover dam (Keener, 1943). This technique is used to backfill the eroded area in the tunnel.

Later, further studies are carried out on two stage concrete. New uses where brought to light among which is underwater concreting. The cost of dewatering is quite high, thus two-stage concrete offers a technique for repair which is feasible and more durable (Woodson, 2009). Two-stage concrete is ideal for where access is limited or where the concrete might wash away by fast flowing water (Allen, Edwards, & Shaw, 1992). Moreover, concrete used in underwater repairs should be free-flowing, cohesive, self compacting and not prone to plastic shrinkage; all of which are characteristics demonstrated by two stage concrete (McLeish, 1994).

Two-stage concrete is also used in the repair of vertical and horizontal concrete members (Watson). In areas heavily congested with reinforcement, two-stage concrete is utilized for repair (Bayer, 2004).

Furthermore, two stage concrete has been used for the repairs of lock walls. Damage in lock walls mainly occurs in the form of concrete spalling. Since it is common to remove from 1 to 3 feet (30 to 90 centimeters) of the spalling concrete, two-stage concrete poses as a suitable rehabilitation technique (Woodson, 2009). The repair is done by forcing the grout into the voids of clean, graded coarse aggregates pre-placed in formwork (Mishra, 2017).

Advantages of Two-Stage Concrete as a repair material

Two-stage concrete was initially widely known as a repair method and this can be attributed to its many advantages. In two-stage concrete the washed aggregates are placed in the formwork then injected with the flowable grout which maximizes the aggregate-to-cement ratio. Thus, shrinkage is reduced leading to less cracks (Schmitz, 2012). According to the ACI-journal, drying shrinkage in two-stage concrete is less than half of that in ordinary concrete (Bayer, 2004). Moreover, two-stage concrete is also advantageous due to its no segregation and low settlement (McLeish, 1994).

On the other hand, one of the important factors that determine the strength of a repair material is its ability to adhere to the existing material. In structures that are not anchored or tied back by encapsulating existing or new reinforcing steel or anchors, bond compatibility is of utmost importance for the long-term success of the repair (Morgan, 1996). Two-stage concrete has an excellent ability to bind to roughened existing surfaces. This advantage is linked to the fact that the added grout can penetrate through the surface irregularities and pores creating an initial bond with the substrate material ("Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications," 2005). Also the low drying shrinkage of two-stage concrete leads to less interfacial stresses upon drying which strengthens the bond (Bayer, 2004).

The homogeneity of the repair material is strongly linked to the strength of the repair. In two stage concrete especially in formwork partially or fully submerged in water, the aggregates are placed and then the injection of grout begins at the bottom and progresses upwards through separate injection inlets (Schmitz, 2012). Water in the form is gradually displaced thus giving way to the grout to fill the voids and form a homogeneous solid (Woodson, 2009).

Furthermore, two-stage concrete used in repair exhibited excellent durability when exposed to severe weathering conditions. For instance, a column in 6^{th} the West Street Viaduct (Erie, Pennsylvania) repaired using two-stage concrete still looks in great condition after 26 years of being repaired (Figure 4) (Bayer, 2004).

Applications of Alkali-Activated Concrete in repair

Cement-free alkali-activated mortars prepared from alumino-silicate waste materials and alkaline activators are emerging as prominent sustainable repair materials. Greenhouse gas emissions from the production of alkali-activated binders are 70-80% less than those due to ordinary cement, which highly promotes alkali-activated materials as eco-friendly materials (Huseien et al., 2017).

Alkali-activated materials have been used as concrete surface treatments (F Pacheco-Torgal et al., 2012). They have also been utilized in the repair of deteriorated infrastructures i.e. manholes, pipes and chambers especially because they can be applied using the same equipment and techniques as OPC (Huseien et al., 2017).

In marine construction, concrete exposed to continuous wet/dry cycles in the presence of salt deteriorates fast. To repair the damage epoxies and other organic matrices have been used as a coating to avoid deterioration. However, the used materials do not release the vapor pressure buildup which is a serious draw back as a repair material (Balaguru, Nazier, Arafa, & Sasor, 2008). Geopolymer coatings are permeable to vapor pressure and thus do not delaminate from the parent surface (F Pacheco-Torgal et al., 2012). This feature makes geopolymers ideal for the coating and strengthening of marine structures.

The presence of stagnant or ponded water in cold weather environments will lead to the eventual decay of concrete surfaces. The recurring cycles of freeze and thaw in concrete lead to scaling. Scaling occurs when the expansion pressure of the ice exceeds the tensile strength of the concrete causing localized fracture at the surface (Balaguru et al., 2008). Alkali-activated materials have been used to repair scaling which widely occurs in dams and retaining walls.

In brief, whether used as a form of slurry for crack injection, mortar for section restoration, jacketing, filling or as concrete for section restoration and jacketing, alkali-activated materials demonstrate a great potential in the rehabilitation field (Wazien et al., 2016).

Advantages of Alkali-Activated Concrete as a repair material

Alkali-activated concretes exhibit good bond capabilities. The bond strength between alkali-activated materials and the substrate is much higher than that of Portland cement based repair material (Wazien et al., 2016). A study reports that the bond strength of metakaolin/slag based alkali-activated repair materials is 55.9% higher than that demonstrated by cement-based repair materials (Hu, Wang, Zhang, Ding, & composites, 2008). This strength is even higher than that provided by other repair materials such as epoxies (F Pacheco-Torgal et al., 2012). A study states that metakaolin/fly ash-based alkali-activated materials cured at room temperature reveal slightly lower bond strength than epoxy resin at ambient temperature. However, they possess much higher bond strength within 100 – 300°C (212 - 572℉) temperature range suitable for several applications (Huseien et al., 2017).

Another advantage for repairs is the compatibility between alkali-activated concrete and ordinary concrete. This compatibility is clearly evident through their similar properties namely modulus of elasticity, Poisson's ratio and tensile strength (Huseien et al., 2017). The conformity between the repair material and the substrate is crucial to assure that the repair will not delaminate.

On another note, it is necessary to point out that the bond strength does not rely on the repair material solely, but also on the surface roughness of the substrate material. Hence, roughening the surface is essential to assure the success of the repair (Wazien et al., 2016).

Moreover, being impermeable is very crucial for the success of a repair material. Alkali-activated concretes with slag as a binder demonstrated low permeability and convincingly assured that these materials have excellent anticorrosion property (Zuhua Zhang, 2010).

The interface zones between substrate and alkali-activated materials are homogenous at contact zones which is a critical factor for the success of the repair (Wazien et al., 2016).

Alkali-activated mortars demonstrate better durability for acid sulfate attack, abrasion and fire resistance than commercial and cement repair materials (Huseien et al., 2017). A test performed on fly ash-based alkali-activated materials by exposing it to sulphuric acid, shows that these materials are more resistant than corresponding ordinary cement based (Singh et al., 2013). On a different note, AAMs are by far the most cost-effective repair materials (Huseien et al., 2017) (Wazien et al., 2016).

Alkali activated materials are sulfate, acid and sea water resistant. A test carried out on slag immersed in sea water confirms that AAMs are more chemically resistant than sulfate resistant cements (SRC). AAM's strength keeps on increasing even after 12 months of immersion and that is due to the continuous activation by seawater giving calcium silicate hydrate (CSH); whereas, SRC's strength increases up to 6 months then decreases afterwards (El-Didamony, Amer, & Ela-ziz, 2012). Thus, AAMs exhibit a great potential as repair materials for marine and underwater construction.

A study done confirms that alkali-activated materials can be used as coatings to resist corrosion. These materials can reduce the corrosion rate compared to concrete without coating (Aguirre-Guerrero, Robayo-Salazar, & de Gutiérrez, 2017).

A study on the abrasion resistance of alkali-activated metakaolin shows that these materials are more abrasion resistant than cement-based repair materials (Hu et al., 2008). Upon the addition of steel slag to the alkali-activated metakaolin, the abrasion resistance increased significantly (Hu et al., 2008).

Several prominent attributes of alkali-activated concrete including reduced pollution, cost-effectiveness, eco-friendliness, and high-performance durability in aggressive environment make them prospective sustainable materials in the construction rehabilitation industry (Huseien et al., 2017).

Combining AAC and TSC (TSAAC)

Two-stage alkali-activated concrete (TSAAC) is a novel material which utilizes alkali-activated materials as a grout for two-stage concrete. Two-stage concrete is a concreting technique that has been successfully used as a repair material. On the other hand, alkali-activated concrete has proved its potential as a good repair material. Combining those two concepts has the potential of creating a much-needed durable-green repair material.

Advantages of TSAAC as a repair material

The main and best advantage of TSAAC is the fact that it is a green material. In the face of the paramount number of concrete infrastructures that require rehabilitation and immediate intervention on one hand, and the deteriorated state of the atmosphere due to the huge amount of CO_2 emissions on the other hand, arose the need for a green repair material. TSAAC promises a huge reduction in CO_2 emissions while aiding in the conservation of natural resources. Alkali-activated grout, the grout used in TSAAC, is reported to have 70 to 80% less carbon dioxide with remarkable lesser green house gas emissions compared to ordinary cement (Huseien et al., 2017). Moreover, this grout utilizes industrial by-products (waste material) as a precursor.

Even though conventional cement is the most used material in infrastructure, the deteriorated state of these structures dictates the need for a more durable material. When the structure under construction or repair is exposed to extreme conditions (i.e. chemical attacks from acids or chemicals) or is subjected to aggressive erosion or abrasion, then the use of a durable material is of grave importance (Morgan, 1996). Using TSAAC as a repair material promises more durable results since the alkali-activated grout used is reported to deliver a repair that lasts lifetime (Wazien et al., 2016) when compared to the other existing repair materials.

The merge between alkali-activated materials and two-stage concrete, both of which exhibited impressive durability results, will yield a repair material that requires little/no maintenance. The idea of a repair that lasts is a very important feature of TSAAC. Thus, it is essential to choose a precursor and an activator for alkali-activated grout that will give the best durability results.

On another note, both two-stage concrete and alkali-activated materials have been proven to be cheaper than other available repair materials. Hence, TSAAC warrants a cost-effective repair material.

Major Challenges and limitations of TSAAC

This paper proposes the use of a green grout, alkali-activated grout, to replace the traditional cement grout when using the two-stage concrete technique in repairs. However, selecting the right mix design is crucial since the obtained grout should meet the expectations of TSC as well as the specifications of repair materials. For the green grout to be suitable for use in TSC, it should be flowable and exhibit low shrinkage and bleeding (M. F. Najjar, 2016). On the other hand, this grout should be corrosive resistant, freeze thawing resistant, shrinkage resistant and consistent to qualify as a good repair material (Watson).

The success of a repair material is strongly linked to its ability to adhere to the substrate material. Thus, obtaining a grout that is capable of meeting the qualities of the existing concrete substrate is a major challenge in TSAAC (Morgan, 1996). Identifying the compressive strength of the substrate material is the first step in selecting the target efflux time of the grout. For low strength concrete an efflux time between 15 to 20 seconds is the target; however, in high strength concrete the target is between 35 and 40 seconds (M. F. Najjar, 2016).

Alkali-activated materials have shrinkage problems. This defect should be compensated for the TSAAC to succeed as a repair material. Great effort should be put forward in selecting the alumino-silicate, activator and needed additives to obtain a green grout with minimum shrinkage values. On the other hand, TSC is known for its volume stability which is attributed to the high volume of coarse aggregates present in the product. Drying shrinkage of two-stage concrete is reported to be about 50% less than that of ordinary concrete (M. Najjar & Abdelgader, 2009). Thus, this merge could limit the shrinkage in the alkali-activated grout to a certain extent. To further limit the shrinkage, many mitigation techniques could be employed such as adding shrinkage reducing admixtures to the mix.

Alkali-activated materials are prepared by mixing a precursor rich in aluminum and silicates with an alkaline solution. The most common studied alumino-silicates include metakaolin, fly ash, ground granulated blast furnace slag (GGBFS), palm-fuel ash due to their easy availability and favorable properties (Zarina, Al Bakri, Kamarudin, Nizar, & Rafiza, 2013) (Huseien et al., 2017). Based on the literature review, fly ash, slag and metakaolin based alkali-activated repair materials demonstrate great results. Metakaolin requires calcining kaolin at 750 ℃ for 6 hours (Hu et al., 2008). This calcination at high temperature increases the embodied energy. Thus, using metakaolin contradicts the aim of this study which is using a sustainable material. On the other hand, using fly ash as a precursor requires curing at elevated temperatures for 6 hours to be able to achieve strengths comparable to that of ordinary cement (Turner, Collins, & Materials, 2013). Curing is a major limitation especially when applied for repairs. In the pursuit of a green repair material, the use of metakaolin and fly ash as sole precursors for TSAAC will be ruled out. The study will be based on slag (GGBFS) as a precursor for the grout or on a combination between slag and fly ash. Studies have shown that alkali-activated slag (AAS) demonstrates mechanical strength comparable or higher to that of ordinary cement. Moreover, AAS is seawater, acid and sulfate resistant which is attributed to the main hydration product C-S-H gel which is less basic and more polymerized than the hydration product of ordinary cement (El-Didamony et al., 2012). AAS has good bond strength and is wear resistant due to the Fe phase existing in it (Hu et al., 2008). However, AASs set fast when activated with certain types of activators. This problem should be mitigated so that slag can perform well in TSAAC.

Potential green repair applications for TSAAC

Replacing the traditional cement grout with alkali-activated slag grout yields a green grout to be used in the traditional TSC repair applications. Based on the literature review, the properties displayed by alkali-activated grouts make this material suitable to be used in all the repair applications of TSC. For example, AAMs have great bond-ability and have properties similar to those of ordinary Portland cement. Hence, they can be used as grout for TSC in repairing horizontal and vertical elements, lockwalls, dams etc.

Most concrete infrastructures have their foundations in water, thus they are in continuous need of repairs. Underwater concrete repairs are very difficult and expensive. Two-stage concrete is the cheapest technique for underwater applications since the cost of water-tight forms and dewatering is removed (M. Najjar & Abdelgader, 2009). According to studies done on alkali-activated materials, these materials demonstrate great resistivity to seawater and salt-attacks. Therefore, using TSAAC in marine repairs will provide a cost-effective, durable and green repair.

On the other hand, a possible application of TSAAC would be in the repairs of sidewalks. Both asphalt and Portland cement concrete contribute to the depletion of natural resources. These structures are in continuous need of rehabilitation since they are subjected to surface scaling and cracking induced by freezing and thawing cycles. It is reported that premature failure of concrete sidewalks due to extreme weathers can occur only after five years of construction. A study reports that 28% of the total sidewalks in Canada need replacement. Both asphalt and Portland cement concrete take a toll on the environment due to depletion of natural resources and greenhouse gas emissions. (M. F. Najjar, 2016) Thus, rehabilitation should be done by means of a green material namely TSAAC. Aside from TSAAC being an eco-friendly material, it is also a cost-efficient material since 60% of the material (i.e. coarse aggregate particles) is directly preplaced into the formwork and only 40% (i.e. grout) goes through mixing and pumping procedures.

CONCLUSION

In conclusion, based on the applications and advantages of alkali-activated grouts and two-stage concrete, it can be concluded that these two materials complement each other. Using alkali-activated grout as a binder for two-stage concrete will mitigate the shortages in each of these materials yielding a durable green material that an be used in various applications. However, various studies must be carried out to find suitable precursor and activator that can meet the requirements of TSC grout while satisfying the requirements of repair materials. Successful innovation of this material will help in achieving the following;

- Reducing the embodied energy and carbon emissions of repair materials along with decreasing the strain on natural resources.
- Cost-effective repair material with shorter application time and made with locally available materials/waste and does not require heavy machinery.
- Durable repair with little to no maintenance that can be used in different applications.

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