A Review on Use of Pozzolanic Materials and Geopolymers in Stabilizing Mine Tailings and Dredged Mud

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ABSTRACT: Mining and dredging are two major economic activities in Australia, and millions of tonnes of waste materials are produced every year by these activities. Mine tailings derived from crushed waste rock, and dredged mud removed from waterways during maintenance dredging, require effective means of disposal. While mine tailings are generally utilized as backfilling material to fill the underground voids created during mining operations, dredged mud is commonly used in land reclamation. In underground mining, accidents have resulted in severe economic damage and loss of lives, while in land reclamation, because of the very slow sedimentation and consolidation processes, future infrastructure development can be delayed. This paper summarizes an extensive literature review on the use of geopolymers and pozzolanic materials in stabilizing geomaterials. Generally, additives are used to enhance the engineering behaviour of soils and concrete. Cement is one of the most popular additives used to improve the properties of soils. Lately, there have been attempts to use pozzolanic materials such as fly ash and slag to partially replace cement. Excessive cement usage in soil may be reduced by using supplementary cementitious materials such as fly ash and slag, blended cement and geopolymers in some geotechnical applications, which should lead to environment sustainability and substantial cost savings.

1 INTRODUCTION

Mining and dredging are two major economic activities in Australia that produce millions of tonnes of waste material every year (Boger, 1998; Das & Choudhury, 2013). Mining and dredge spoils have previously been dumped on the ground surface and in the sea, respectively. However, strict regulations and guidelines that are currently in place to ensure environmental sustainability do not permit deep sea dumping of the dredged mud and also require that mine voids are backfilled properly. Mine tailings are produced from the crushed waste rock during mining processes and dredged mud is removed from waterways and the sea during maintenance or capital dredging. Mining and maintenance/capital dredging waste requires disposal in a responsible manner. While mine tailings are generally disposed by backfilling the underground voids created during mining operations or through tailing dams on the ground surface, dredged mud is used to reclaim land from the sea to overcome forthcoming land requirements due to the increasing population. To ease transportation through pipes, these materials are generally placed in the form of slurry, which is allowed to undergo sedimentation and followed by self-weight consolidation. In land reclamation, the sedimentation and consolidation process can be very slow and hence delay future infrastructure developments. Disposing these waste materials in the form of slurry poses many challenges. In underground mining, when the barricades fail while the slurry is placed into the mine stope, several accidents have been reported worldwide (Berndt et al., 2007; Kuganathan, 2001; Sivakugan, 2008), causing severe economic damage as well as fatalities. In an attempt to dispose of more tailings underground, the mines prefer increasing the solid content to the maximum possible limit. On the other hand, high solid content in the slurry increases viscosity and makes the flow difficult, causing blocks within the pipeline.

Use of additives to enhance the engineering behaviour of soils and concrete has been tried by many over the past decades(Larsson et al., 2005). Cement is one of the most popular additives tried in soils, but the cost can be prohibitive and cement production is one of the biggest sources of greenhouse gas emission. Recently, there have been attempts to use pozzolanic materials such as fly ash and slag in soil stabilization. However, there is no evidence that geopolymers have been used in soil improvement, still. Geopolymers can also partially replace cement in some geotechnical applications, resulting in substantial cost savings as well as environmental sustainability.

The objective of this paper is to summarize a broad literature on the use of pozzolanic materials and geopolymers in stabilizing geomaterials and the findings from previous laboratory studies carried out to assess their effectiveness in stabilizing mine fills and dredged mud. Soils, rocks and aggregates derived from the earth are called geomaterials. The optimum dosage with the right geopolymer is expected to enhance strength and consolidation characteristics in the long term, while ensuring that slurry has the desired rheological characteristics in the short-term, for smooth flow through pipes.

2 POZZOLANIC MATERIALS

Pozzolans are siliceous or aluminosiliceous materials that are generally added to enhance properties of soil and concrete. Waste glass (WG), lime, fly ash (FA), granulated blast furnace slag (GBFS) and silica fume (SF) are the examples of pozzolanic material. Among these, FA and GBFS are the waste and byproducts of coal power plants and metal furnaces, respectively. These two pozzolanic materials containing a certain percentage of cement are also used to produce building materials as well as to stabilize soil in a cost effective manner. Cement is used to improve the properties of backfilling material. Cement can be partially replaced with pozzolanic mineral admixtures in Cemented Paste Backfill (CPB). Furthermore, the utilization of pozzolanic admixtures can reduce binder costs substantially (which may constitute 40–70% of the operating costs in a CPB plant) since many industrial wastes with pozzolanic characteristics are available in large quantities and at low cost.

3 GEOPOLYMER

The term ‘‘geopolymers’’ was introduced by Davidovits in the mid-1970s. Geopolymer binder is used to produce building materials in a cost effective manner. Geopolymerization could convert a wide range of waste alumina silicate materials into building materials with excellent physical, chemical and mechanical properties as well as long-term durability (Davidovits, 1991).

The geopolymer can be synthesized from pozzolanic material under activation using alkaline solution. The ratio between alkaline activator and FA is found to have a great influence on the compressive strength of the geopolymer. Al-Bakari et al. (2012) concluded that the alkaline activator/FA ratio of 0.4 has the optimum amount of alkaline liquid, which could activate the FA in highest rate of geopolymerization. NaOH 10 M and slurry of $NaAlO_2$ in NaOH 10 M solution are generally used as alkaline solutions. The specimens were cured at 25°C and 100% RH for different ageing times. The weight ratio NaOH 10 M and $NaAlO_2$ solid was equal to 3.5. Verdolotti et al. (2008) found that pozzolanic material treated with 10 M NaOH and $NaAlO_2$ slurry was more effective than material treated with 10 M NaOH alone.

Compressive strength of geopolymeric specimens prepared with certain percentages of class C FA (containing more than 20% lime), GBFS, sodium silicate (or WG) solution and NaOH, were tested by (Bagheri & Nazari, 2014). In these tests, a specimen with 30 wt% GBFS and NaOH concentration of 12M after being cured at 90°C for 16h showed the highest compressive strength, which is over about 65MPa.

4 DREDGED MUD STABILIZATION

Dredged mud is removed from waterways and the sea during maintenance and capital dredging. It may contain sandy or silty materials, which speeds up the consolidation process significantly. Some literature reviews on dredged mud stabilization using some pozzolans are listed below.

High water content dredged material stabilized using 20 combinations of pozzolanic agents□(lime, cement kiln dust, high alkali and slag cements, and FA) was studied by Grubb et al. (2010). This study suggested that most of the stabilized dredged material blends can have considerable strength (up to 828 kPa) at 28 days.

The use of Dredged Materials (DM) blended with steel slag fines (SSF) was demonstrated by Malasavage et al. (2012) using laboratory and field test results. Different combinations of blends of steel slag fine concentration were used for testing. Friction angle, hydraulic conductivity and average cone penetration test tip resistance were found to be slightly increased by adding steel slag fines to the dredged materials.

The effect of lime on the dredged mud sediment and its consolidation behavior were investigated by Salehi and Sivakugan (2009). The investigation suggested that addition of lime to dredged mud slurry induces flocculation that results in increased porosity of sediment with increasing percentage of lime. The compression index increases with increasing lime content whereas the recompression index gradually decreases. When the percentage of lime is increased, the magnitude of primary consolidation in the normally consolidated state increases while in the over consolidated state it decreases. The secondary compression index, in both the compression and recompression range, decreases with increasing percentage of lime.

5 MINE TAILING STABILIZATION

Paste fill, hydraulic fill, rock fill and aggregate fill are the most common types of backfills in mining (Cowling et al., 1983). These can be divided into two broad groups, namely cemented or uncemented backfills. Cemented backfills commonly include a small dosage of pozzolanic binder such as cement, slag or FA to improve strength. Specific gravity and permeability of hydraulic fill range from 2.8 to 4.4, and 7 to 35 mm/h, respectively (Sivakugan et al., 2006). Hydraulic fills and paste fills are the two most popular examples of uncemented and cemented backfills, respectively, being used world-wide. Paste fill is a relatively new type of underground mine backfill. They contain a significant clay fraction. Hydraulic fills are generally deslimed, where the clay fraction is removed by hydrocyclones.

Paste fills are currently being used to fill the voids created by mining activities at Cannington mine and Mt Isa mine, which are two large mines in North Queensland, Australia. Paste fill consists at least 15% of grains finer than 20 µm with the effective grain size (D_{10}) in the order of 5 µm, water and probably 3% to 6% of binding agents (Sivakugan et al., 2006), which contain mainly Portland Cement (PC). Mines have been trying for a long time to reduce the cost of cement, by partially replacing it with geopolymers and blended cements.

Ahmari and Zhang (2013) studied the feasibility of enhancing the physical and mechanical properties and the durability of geopolymer bricks made of copper mine tailings (CMT) and cement kiln dust (CKD). The effects of CKD content (0–10%), sodium hydroxide (NaOH) concentration (10M and 15M) and initial water content (12–20%) on unconfined compressive strength (UCS), water absorption, and weight and strength losses after immersion in water were studied. Addition of CKD results in significant improvement in the physical and mechanical properties and the durability of CMT-based geopolymer bricks. Furthermore, addition of CKD decreases the loss of weight while increasing water absorption slightly.

Binding agents comprising 100% PC, 75% PC with 25% FA and 30% PC with 70% slag were used for the optimization exercise carried out by Pirapakaran et al. (2007). In this test, by adding 3%, 3.5% and 4% of binding agents by total dry mass of Cannington paste fill tailings having solids contents of 79%, 80% and 81%, specimens were prepared. These specimens were subjected to uniaxial compressive strength tests after curing periods of 7, 14, 28 and 56 days. The 3.5% binding agent (25% FA blended with 75% PC) mixture with 80% tailings solids content was identified as the optimal alternative mix, considering strength, rheology and binder cost. Summary of uniaxial compressive strength (UCS) after 28 days of curing is shown in Table 1.

Table 1. Summary of UCS results after 28 days of curing (after Pirapakaran et al. 2007

Paste fill mixtures	% of binder	79% of Solids content	80% of Solids content	81% of Solids content
		UCS (kPa)	UCS (kPa)	UCS (kPa)
Tailing & Binder (100% PC)	3.0	392	505	622
	3.5	500	531	675
	4.0	523	618	750
Tailing & Binder (75% PC & 25% Fly ash)	3.0	406	471	544
	3.5	531	608	760
	4.0	571	683	801
Tailing & Binder (30% PC & 70% slag)	3.0	595	745	826
	3.5	713	798	959
	4.0	739	895	1174

Use of pozzolanic additives, such as WG, FA, GBFS and SF, for the partial replacement of ordinary PC (OPC) in CPB of Sulphide-rich mill tailings was investigated by Ercikdi et al. (2009). The pozzolanic wastes in the binder phase decreased the rate of strength development in the CPB samples. The strength of CPB samples produced from exclusively OPC dropped after an initial curing period of 56 days (see Figure 1).

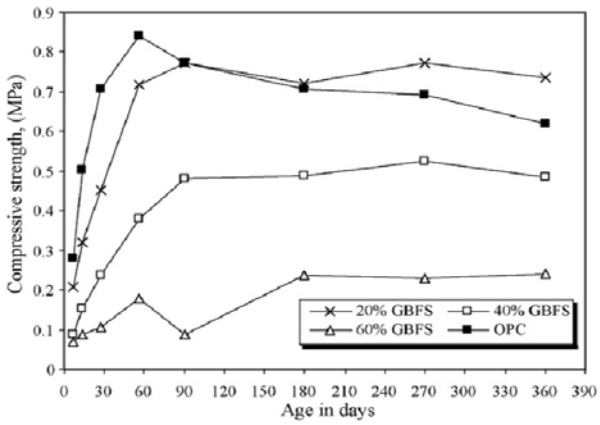

Fig. 1 Effect of GBFS addition on the strength of CBP samples (Extracted from Ercikdi et al. (2009)).

Although GBFS, FA and SF appear to improve the long term performance of CPB samples, only up to 20 wt% GBFS and 15 wt% SF should be allowed into the CBP sample to maintain consistently higher strength.

Waste rock dumps offer high strength and permeability and low compressibility characteristics while tailing deposits typically have low permeability, slow time rate consolidation properties and long term stability concerns associated with shear strength. Wickland and Wilson (2005) found that mixtures with approximately 5:1 waste rock to tailings by dry mass were found to have a hydraulic conductivity similar to tailings alone and total settlements similar to waste rock alone.

6 CONCLUSIONS

Mine tailings and dredge mud are two different waste materials that are produced worldwide in large quantities. Increasingly stringent regulations and guidelines mean that finding better ways of disposing of these materials in a responsible manner is necessary. Both materials are generally placed on the ground in a slurry form because this allows for ease of transport through pipelines. While it is necessary to dispose of large quantities of these waste materials, attempts are being made world-wide to utilize them as engineered fill materials by adding binders to enhance their engineering characteristics. Geopolymers in the form of fly ash and slag are already waste products that have to be disposed of, and using them sensibly in enhancing the properties of the dredge mud and mine tailings paves the way to environmental sustainability, and significant cost savings.

A slight reduction in the cement content by replacing alternative binder leads to a substantial cost saving and environment sustainability by reducing greenhouse gas emissions. By including binders, the properties of soils in general and the tailings and dredge mud in particular, can be improved significantly. Therefore, it is necessary to carry out further research using a series of laboratory tests on paste fill and dredge mud mixes with different types of binders, to study the effects of these binders and solids content on the strength and consolidation characteristics in the long term, while ensuring the slurry has desired rheological characteristics in short term, for smooth flow through the pipes.

Addition of binders in different dosages can alter strength, consolidation, and secondary compression characteristics in different ways. A thorough and systematic investigation is warranted to identify their effects.

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