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Remediation and monitoring of abandoned mines

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A B S T R A C T

This paper describes a recent study on using fly ash for backfilling abandoned room and pillar mines. Detailed investigations on fly ash properties such as the strength and stiffness of settled fly ash, flowability of fly ash grout, as well as chemistry and environmental aspects of fly ash backfill have been undertaken in the laboratory. Numerical modelling was also conducted to quantify the effects of fly ash backfill on the stability of underground pillars. The laboratory tests showed that with a solid concentration of approximate 50%, fly ash grout has an excellent flowability and very low viscosity. It is capable of penetrating and filling almost any voids underground if designed properly and settling as a reasonably stiff solid to provide support to the pillars. Several different types of strength tests proved that a consolidated fly ash should exhibit a friction angle above 42°. 3D numerical modelling on interaction between fly ash backfill and underground pillars has shown that fly ash backfill to 90% roadway height can raise the factor of safety (FoS) of a marginally stable area to above 1.6, which is the number often used in rock engineering design for long term stability. Chemistry and leachate analysis of representative fly ash samples from a local power station showed that the elemental concentrations in the fly ash solid sample are lower than the allowed contaminant threshold and specific contaminant concentration levels. Geotechnical monitoring in the high risk areas of an abandoned mine has been carried out as part of the risk management and control for potential subsidence. The monitoring has been very helpful in understanding the ground behaviour around the abandoned mine which can provide timely information to the parties concerned in order to make correct decisions to control the subsidence risk.

1. Introduction

During the 19th and 20th Century, the "bord and pillar" method of underground mining was implemented in a number of mines throughout large areas of Newcastle (NSW) and Ipswich (QLD) in Australia. With rapid urban development in recent years, many of the old mines have been abandoned and the mined areas have become densely populated residential areas. These abandoned mines impose serious threat to the local residents and infrastructure due to the potential for mine collapse and subsidence. At least two large subsidence events at Ipswich occurred during the last 20 years which resulted in the damage to roads and more than 20 houses [1]. Numerous sinkholes have also developed in the mining districts, causing serious economic, social and political concerns to the local resident as well as local and state governments.

Remediation of the old underground mines is often required to reduce or eliminate the potential risk of mine subsidence and sinkholes. However, several technical challenges exist for abandoned mine remediation.

Knowing the exact location of mined space and layout of the abandoned mines is essential but may not be easily achieved due to the age of the mine and the lack of mining records. In many cases the mining records may not be accurate for various reasons.

Accessibility and costs for remediation are other key challenges. In densely populated areas the accessibility for surface operations such as drilling and backfilling is very much confined. Using the traditional cement/concrete backfill will not only be difficult due to its requirement of closely spaced boreholes but also add significant costs to the operation, making it economically unviable.

Environmental impact is also a major factor of consideration for any remediation method used. Material used for backfilling the underground mine voids will interact with groundwater in the medium to long term, potentially causing chemical leaching from the backfill material to the ground water system. The effects of chemical leaching have to be assessed carefully to ensure the ground water quality in the residential areas.

In high risk areas of abandoned mines, particularly where mine failures and subsidence have occurred nearby in the past,

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geotechnical monitoring may be necessary. Monitoring ground deformation and fracturing activities will help to understand the change of ground conditions with time and hence be able to forecast potential mine instabilities. The geotechnical monitoring should be considered as an integrated part of the remediation plan for abandoned mines.

Many studies have been done in the past worldwide to investigate the overburden strata behaviour during mining, the effect of backfill on the stability of underground voids [2–5]. Different backfilling materials and technologies have also been thoroughly investigated [6,7]. However, each mine backfill operation is unique and it requires site-specific investigations to develop the most economic and effective backfill methods based on the site accessibility and material availability.

This paper describes a comprehensive study conducted recently by CSIRO on a fly ash backfill technology and a detailed geotechnical monitoring investigation of a high risk abandoned mine. The backfill technology uses simple fly ash and water mixes as the base material for backfill, without cement or other adhesive agents. As will be described below, this technology is low cost, easy to operate, capable of providing sufficient strength to support the pillars, and is environment friendly. The key aspects of this backfill technology, such as grout flowability, settled fly ash strength, improvement to pillar strength, and environmental impact from chemical leaching have all been investigated. The arrangement of geotechnical monitoring in an abandoned mine and its key results are discussed in the paper.

2. Physical and mechanical properties of fly ash

Fly ash samples from Swanbank Power Station, Queensland, were collected and tested for backfill purposes. Laboratory tests were conducted to characterise and assess physical and mechanical properties of the fly ash for back-filling of underground mining voids as a suitable and sustainable deposit. The average particle size of the samples is around 50 m and the average solid particle density, or specific gravity (SG) is 1.8.

Deformation characteristics and the load bearing strength of fly ash and their variation with time, space and surrounding environment depend on the fly ash's physical properties. An important property is density: the denser the fly ash, the stiffer and stronger it is against loading. Density of a fly ash sample depends on the mass and volume of its major components, i.e. solid particles, water and air (gas). The density of the fly ash slurry is normally in the range of 1.1–1.4 kg/cm^3 corresponding to a solid concentration range of 20%–60%, which can reach 1.6 kg/cm^3 and beyond depending on the compaction and consolidation loading history and time.

2.1. Fly ash strength

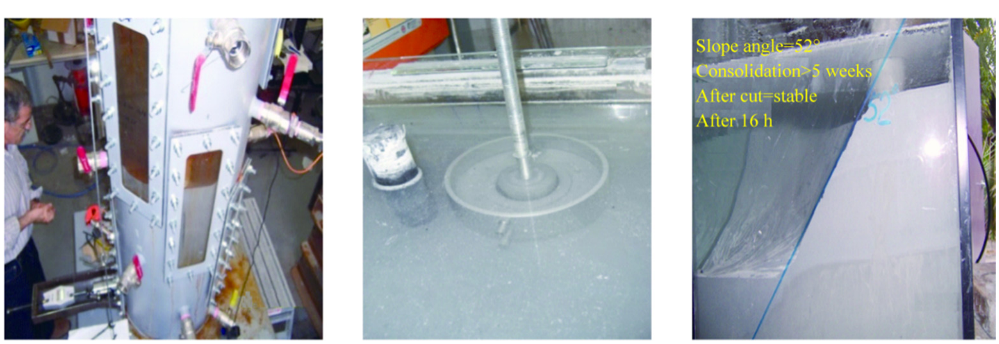
Deformation and load bearing capacity of the fly ash against any potential pillar failure are the two main concerns for the suitability of fly ash as a cohesionless backfill material. Therefore, two important questions arise: will the deposited fly ash have enough shear strength characterized by friction angle and stiffness to cater for any possible pillar volumetric expansion at any time (before or after any pillar failure). Various laboratory tests on settled fly ash were conducted to address both questions, including (Fig. 1):

(1) Horizontal passive strength test by a piston, where a mechanical piston of 50 mm diameter and 55 mm thickness was driven into a submerged fly ash sample inside a large cylinder. The cohesion and friction angle of the settled fly ash can be estimated from the resistance force measured.
(2) Vertical bearing strength test by a footing, where a small disc footing was loaded on top of settled and submerged fly ash. The ultimate bearing strength of the settled fly ash can be used to calculate its frictional and cohesive strength.
(3) Slope test, where a slope was excavated in the submerged fly ash and the maximum stable slope angle was measured which represents the apparent friction angle of the settled fly ash.

All these tests were conducted in the submerged condition to simulate the real conditions of backfill in the flooded underground mining voids. The results from all three types of tests suggest that the naturally settled fly ash after backfill has an internal friction angle greater than 42°. This high friction angle will be able to provide adequate support to the pillars in confined condition.

2.2. Fly ash stiffness

Lateral deformation of a backfilled coal pillar depends on the deformation characteristics or stiffness of the backfill; the stiffer the backfill, the less lateral movement of the pillar. However, the stiffness of a saturated confined fly ash depends on the rate of loading. Loading of a saturated fly ash transfers the load immediately to the water molecules of the mix causing generation of pore pressures equal to the loading pressures which requires time to dissipate. The time needed depends on the permeability of the mix. Consolidation tests were conducted to measure deformation behaviour and stiffness of non-cohesive fly ash slurries at different densities and loading histories–in a 50 mm diameter mould of 20 mm thickness. Two typical results are plotted in Fig. 2. In Fig. 2, *E* refers to the one-dimensional deformation or Young's modulus and the index *L* refers to loading and *UL* to unloading modulus. As indicated



(a) Horizontal piston tests (b) Footing test (c) Slope test

Fig. 1. Three different test methods to determine the strength of settled and submerged fly ash.