Backfill analysis and parametric evaluation of the cement binder on cured strength and curing time

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ABSTRACT
This paper investigates the effects of binder dosage (6%,8% and 10% wt.), binder composition (Portland cement and fly ash), and curing time (7,14, and 28 days) on the unconfined compressive strength (UCS) of backfill materials. At each curing stage, density tests and UCS tests were conducted for each backfill specimens. In total, 72 backfill specimens were prepared by the cemented paste backfill (CPB) method. Consequently, the UCS and stiffness of backfill material increased with the increasing binder dosages. The addition of fly ash caused a notable increase in the compressive strength and stiffness of backfill materials. Also, the compressive strengths for all studied combination backfill materials increase with curing time.

RÉSUMÉ
Cet article étudie les effets du dosage du liant (6%, 8% et 10% en poids), de la composition du liant (ciment Portland et cendres volantes) et du temps de durcissement (7, 14 et 28 jours) sur la résistance à la compression non confinée (SCU) de matériaux de remblayage. À chaque étape de durcissement, des tests de densité et des tests UCS ont été effectués pour chaque échantillon de remblai. Au total, 72 échantillons de remblai ont été préparés par la méthode du remblai en pâte cimentée (CPB). Par conséquent, le SCU et la rigidité du matériau de remblayage ont augmenté avec l'augmentation des doses de liant. L'ajout de cendres volantes a provoqué une augmentation notable de la résistance à la compression et de la rigidité des matériaux de remblayage. De plus, les résistances à la compression de tous les matériaux de remblayage combinés étudiés augmentent avec le temps de durcissement.

1 INTRODUCTION

An innovative method named the Sustainable Mining by Drilling method (SMD) (Lopez-Pacheco, A. 2019) has been proposed and used for mining recently. The SMD method is based on a two-pass drilling procedure. Primary holes, drilled in the intact rock, need to be backfilled. With the expansion of the mining scale, the potential danger caused by the goafs has become a serious problem. Meanwhile, the tailings discharged from the mines increase annually. In traditional methods, the tailings were directly discharged in the nearby tailings pond by most mining operations. As reported by the United Nations Environment Programme (UNEP), Canada has more mine tailings than most other countries in the world. The capacity of the tailings pond had difficulty in meeting the requirements of expanding production in the future, and the discharged tailings caused many environmental issues, such as water pollution, landslides, leaching and dust. The mining industry has been under increasing pressure to develop waste management practices, which has resulted in a greater focus on the role of backfill in waste disposal. With the development of backfill technology, the tailings have become the main materials used as backfilling materials to fill the underground goafs. Mine backfilling has many environmental and operational benefits for the mining industry. It provides an environmentally friendly material for backfill and surface disposal by utilizing the tailings. Backfilling with tailings will reduce the tailings pond accumulation on land, and the costs associated with constructing and reclaiming tailings ponds during mining are also reduced. Therefore, backfilling can not only solve the safety and environmental issues caused by mine production and tailings discharge but also maximize the recovery of resources, which is of great significance for the development of sustainable mining by drilling.

Gradually, backfilling has attracted more attention, and the percentage of tailings being sent underground has increased. In order to extract a very small portion of ore, a huge amount of waste material needs to be removed from the ground. Also, a great fraction of tailings will be produced after ore processing. The three main types of backfill include hydraulic fill, paste fill, and rock fill. The difficulty of adapting to the environmental applications and the cost stresses of tailings management led to the paste fill method being created as an alternative to rock fill and hydraulic fill. Since the introduction of paste fill in the late 1970s, the use of paste filling has been limited. However, significant advances in paste technologies have been made in the past decades, resulting in further achievements of paste backfill systems. In order to meet the strength requirements for ground support, a small amount of binder (Portland cement) is generally added to the backfill material. Because of several environmental and operational advantages, paste fill has become increasingly popular in the past few years (Landriault, 1995; Brackebusch, 1994). The paste fills can obtain a similar strength of rock fills by using less cement than hydraulic fills. It utilizes different size distribution of tailings and consists of high solid contents, resulting in the reduction of surface tailings impoundment requirements. Whereas rock fills and hydraulic fills use less solid content or a larger size distribution of tailings. Furthermore, the decant water from paste fills can be virtually eliminated, which lowers costs and reduces associated problems with barricade set-up. The existing bore-hole delivery systems of slurry fills can also be applied to the paste fills delivery.

Currently, the technology of cemented paste backfill (CPB) is implemented in many modern mines around the world, especially in Canada (Grice, 1998). CPB is an engineered mixture of wet fine process tailings (75–85% solids by weight), a hydraulic binder (3–7% by dry total paste weight) and mixing water to set the paste solids density of 70–80% at the desired consistency. Binders used within paste backfill aim to produce mechanical strength (Kesimal et al. 2005). Typically, one or two types of cement, such as regular Portland cement, sulphate-resistant cement, ground granulated blast furnace slag (fine-grained smelter slag), and strong pulverized fly ash are mixed with the tailings as hydraulic binders, to bind the tailings particles and increase the strength of the CPB. If the mixture can give 18-25 cm of slump height, the CPB is ready to transport as a backfill to the underground voids (Helms, 1988; Brackebusch, 1994; Benzaazoua et al., 1999; Yilmaz et al., 2014). The tailings contain very fine, fine, and course proportion grains, some of which are acid generators (reactive), while the rest are non-reactive. Coarse grains are used by many companies for backfilling purposes, while the fine grains must be disposed of on the surface in a tailings pond. However, by utilizing the cemented paste fill method, fine grains (10–30% by weight finer than 45 microns) are used to make paste fill materials (Brummer and Moss, 1991).

Fly ash is a very fine powder composed of spherical particles of less than 50 microns in size and is one of the most widely used pozzolans in the construction industry. Fly ash can be used as a mixture of cement or concrete due to its pozzolanic activity. Under normal temperature, when Portland cement is mixed with water, most of the cement forms insoluble cementitious compounds, and CaOH is also formed in this reaction. After adding the fly ash, it will react with CaOH and produce hydrate with hydraulic cementitious ability. Fly ash can optimize many concrete properties, such as improving workability and stabilization, flexural and compressive strengths, pumpability, and decreasing permeability when a proper amount is adopted. (Thomas, M et al. 1999)

The main purpose of this study is to evaluate the influence of binder dosage, binder composition and curing time on the strength of backfill materials. This paper studied two recipes of backfill materials, including 100% Portland cement and a combination of 80% Portland cement with 20% fly ash. The curing time of the backfilling materials varied from 7 days, 14 days and 28 days after the specimens casting. The tests, including particle size distribution analysis (PSD), and UCS tests were conducted to measure the different parameters. All the performed tests in this study were based on the American Society for Testing and Materials (ASTM) standards.

2 METHOD

One of the essential tasks of the post-mining process is called mine backfilling. Backfill is made by soil, overburden, mine tailing or any kind of aggregate which can be imported as a filler and booster to emplace in the extracted area, which was excavated by mining operations.

There are multiple backfilling methods, and the two most popular types are hydraulic fill and paste fill. Backfill material is categorized as hydraulic fill, paste fill, and rock fill. In order to increase the strength of the backfill material, a small amount of binder (Portland cement) is usually added to the mixture. For designing backfill and barricades, there are strict rules applied within the procedure of the backfill process. Progressively, hydraulic backfill is being replaced by cemented paste backfill wherever strength is needed from backfill or a waste product contains a better quantity of very fine particles.

An extensive amount of tailings and waste rocks are produced in Canada annually. The tailings contain very fine, fine, and course proportion grains, some of which are acid generators (reactive), and the rest are non-reactive. Coarse grains are used by many companies for backfilling purposes, while the fine grains must be disposed of on the surface in a tailing pond. However, by utilizing the paste fill method, which is relatively recent, fine grains (10–30% by weight finer than 45 microns) are used to make paste fill materials.

Cemented paste backfill (CPB) is made by mixing waste tailings, cement, and water. It is a non-homogenous material that contains between 70% and 85% solids, and the utilized water can be either clean water or mine processed water. Usually, a hydraulic binder is added to the mixture to increase the strength of the CPB. The binder fraction is mostly between 3–7% of the total weight. In the mining industry, CPB is improved and expanded every day because it helps to manage the waste tailing in an economical method (Brackebusch, 1994). On the other hand, it provides safety and support for mine and mine workers in the underground. Additionally, CPB develops the technology to help solve environmental issues.

3 MATERIALS AND EQUIPMENT

3.1 Portland Cement and Fly Ash

Portland cement (PC) is the most common type of cement, which is used as a fundamental component of concrete, and it is used in the backfill mixture as a binder to increase the strength of the backfilling. Considering the high cement, and the transport cost to the mine site, cement adds high cost to the backfills, even in such small dosages in the order of 2–10 %. As a binder, a regular type GU Portland cement was used to make specimens in this study. The mines have been trying to replace cement with blended cement, which consists of cement mixed with fly ash and/or slag, with considerable success. A type C fly ash (FA) was used for binder composition with the proportion of 80% PC and 20% FA since the pozzolanic activity of this type FA is 91.3%. (Amaratunga, 1992)

3.2 Mill Tailings and the Grain Size Distribution

The Tailings characteristics can be identified by grain (particle) size distribution, which has a great influence on backfill porosity and delivery. The size distribution analysis is based on a cumulative function. According to the previous work, the sample tailings were classified by an electric shaker containing 2000, 630, 315, 250, 150, and 75 microns mesh. Figure 1 shows the tailings are well-graded with 90% of the tailings less than 560-micron, 50% of the tailings less than 350-micron, and 10% of the tailings less than 130-micron. (Someehneshin et al. 2020) The measured bulk density of the waste tailings is 2000 kg/m^3.

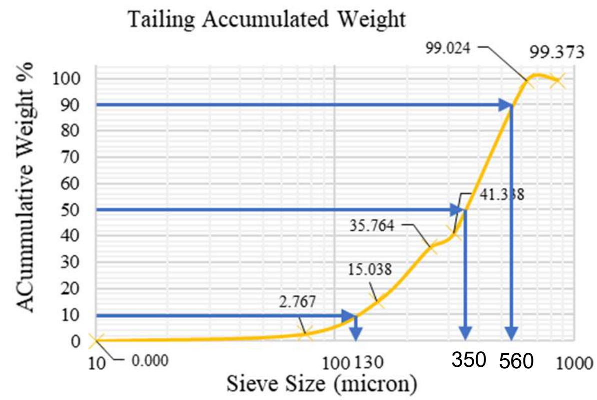

Figure 1. Tailings accumulated weight and grain size distribution

3.3 Moulds

According to the ASTM Standard C192/C192M-15 and C39/C39M-12, the mixture can be cast in a 2" by 4" (5.08 cm by 10.16 cm) moulds. The specimen length to diameter ratios is between 2.0:1 and 2.5:1. The moulds (kraft tubes) used in the backfill tests were obtained from the *Uline* company. The volume of each mould (2" * 4") is 0.00021 m^3, and the mass of each mould containing backfill is 0.378 kg.

3.4 Geomechanical Loading Frame

Figure 2 shows the Geomechanical Loading frame used for the Unconfined Compressive Strength (UCS) measurement. The frame is equipped with the Data Acquisition System (DAQ-Sys) that records the main parameters required for constructing the stress-strain relationship, including load in Kilo Newton and displacement in millimeters. The DAQ-Sys utilizes LabVIEW software that records at 100 Hz sampling rate for these tests. The compression hydraulic pump is manually operated; however, a fixed loading rate was maintained in all tests. The tests of the same sample types, percentage, parameters, and under the same conditions are repeated at least three times and the strength, then they were estimated based on the average.

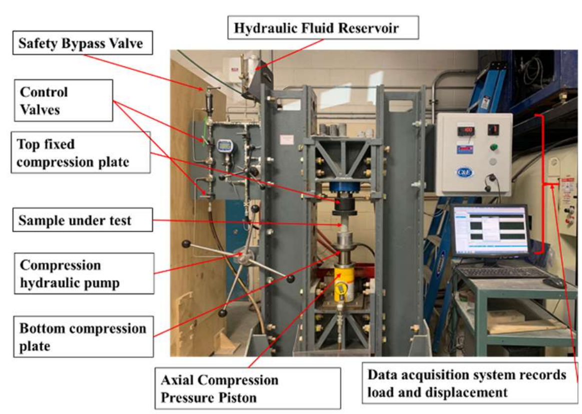

Figure 2. Geomechanical Loading Frame

4 EXPERIMENTAL DETAILS

4.1 Backfill Preparation

The tailings were mixed with Portland cement to give a homogeneous mixture before adding the water. After the addition of water, the mixture was stirred for about 5 minutes before preparing sample specimens. After blending, the mixture was removed to the casting moulds. By using a tamping rod, moulds would be tamped to reduce the bubbles in the backfill specimens and covered by plastic bags to prevent the evaporation of water. According to ASTM standard C192/C192M-15, the curing temperature is 23±2℃. After 24 hours, the specimens were removed from the moulds and were kept in the moisture room until the test dates. In order to investigate the influence of binder composition on the strength development of backfill, another group of backfill specimens, which contained Portland cement and fly ash as a binder, were cast following the same procedures. Typically, according to ASTM standard C 1157, three standard samples should be used to do the UCS test after curing periods of 7, 14, and 28 days. In order to observe the development of backfill compressive strength, additional UCS tests were conducted on 21 days with all binder compositions consisting of Portland cement with fly ash. A total of 72 backfill specimens were produced for the tests.

The binder dosages were expressed as a percentage of the total mass of feed materials. Extra 10% of total weight was added to the calculated amount of the backfilling. Table 1 gives the dosages of all components without fly ash. Table 2 shows the dosages of all components with fly ash.

Table 1. Cement, tailings, and water percentage

Binder (%)	6%	8%	10%
Mass of tailings (%)	75.2%	73.6%	72%
Mass of cement (%)	4.8%	6.4%	8%
Mass of water (%)	20%	20%	20%

Table 2. Cement, fly ash, tailings, and water percentage

Binder (%)	6%	8%	10%
Mass of tailings (%)	75.2%	73.6%	72%
Mass of cement (%)	3.8%	5.1%	6.4%
Mass of fly ash (%)	1%	1.3%	1.6%
Mass of water (%)	20%	20%	20%

4.2 Backfill Testing

One of the most important backfill properties is the Unconfined Compressive Strength (UCS). UCS can evaluate the structural stability of the backfill and concretes against static loads. The UCS is the maximum axial compressive stress that a backfill or a concrete specimen can tolerate under zero confining stress. UCS value represents the uniaxial loading capacity of a material.

After keeping specimens in the moisture room for scheduled periods, both surfaces of each specimen were grinded using a grinding machine to have a smooth and flat surface. Then, a caliper was used to measure the length and the diameter of the specimens. All specimens had the same length and were broken under a constant axial load by a loading frame. The displacement and the load were measured through a LabVIEW software connected to the loading frame (Figure 2). The UCS tests of all backfill specimens, based on ASTM C39/C39M-12, were conducted. The UCS of the backfill samples at different binder dosages, binder compositions and curing time (7, 14 and 28 days) were evaluated.

During the UCS tests, the backfill specimens started failure with small vertical cracks and gradually extended their lengths through the samples. The failure of samples was slow to progress, and most of the fractures on the specimens had a well-formed cone on both ends. Figure 3 (A, B, and C) shows a portion of samples while in the moisture room, one set of samples containing 8% and 10% of cerment before and after testing, repectively. This procedure of testing was performed for all samples of cement and flyash content following the order in Table 1 and 2.

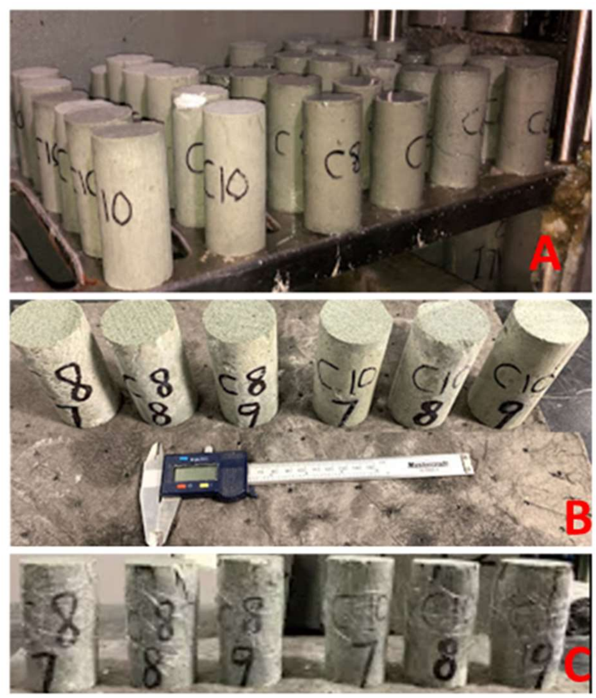

Figure 3. A) Samples while in the moisture room, B) and C) one set of samples before testing and after, respectively.

5 RESULTS AND DISCUSSION

This section analyzes the recorded data, and the stress-strain graph for each specimen was plotted. Each compressive strength value presents an average value obtained from three UCS tests. The maximum peak of the stress-strain graph before failure shows the UCS of the specimen and the slope of the linear part of the graph is the Young's Modulus.

5.1 Effect of Binder Dosage on UCS

Figure 4 shows that the strength of backfill developed with the increasing curing time under all binder combinations. Expediting the mining process is one of the key benefits of achieving high backfill strength over a short curing time. The strengths of the backfill are relatively low when the dosage of Portland cement is 6%-8%. However, the strengths of backfill perform a notable increase when the dosage of Portland cement reaches 8%.

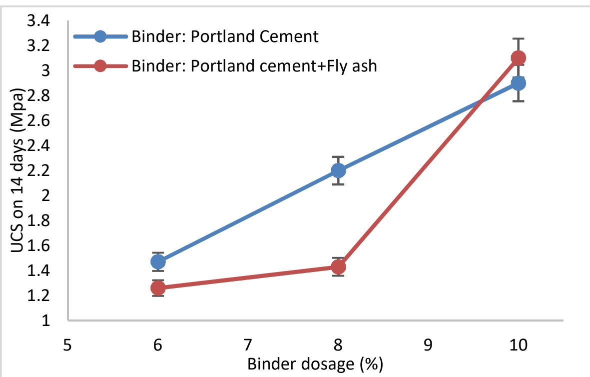

Figure 4. UCS on 14 days versus binder dosage

5.2 Effect of Binder Composition on UCS

Adding a quantity of fly ash into Portland cement instead of pure Portland cement to evaluate the influence of binder composition on UCS is one of the major aims in this paper. Binder composition gives a significant performance on the backfill compressive strength development. Figures 5 and 6 illustrate the short-term strength development of backfill specimens with the addition of fly ash (20% wt. of binder). The sample specimens with the two binder compositions (Portland cement 6%+fly ash and Portland cement 8%+fly ash) show a corresponding 14.8% and 7.7% drop respectively in UCS over the first 7 days. However, after 28 days of curing, an increasing trend in the strength development of the specimens can be noted obviously. The specimens have obtained about 37.5% and 16.1% strength increase compared with the specimens consisting of pure Portland cement, which illustrates the pozzolanic reaction from the hydration of fly ash and Portland cement.

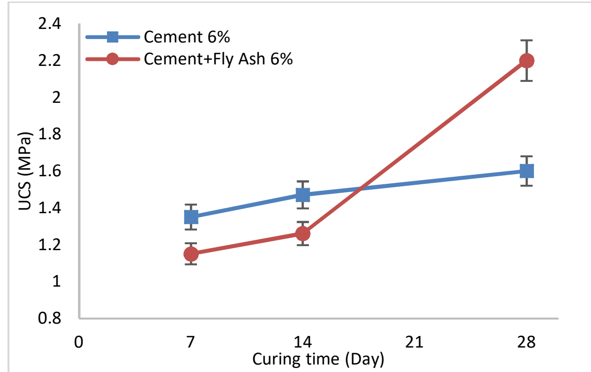

Figure 5. UCS of Cement 6% vs. Cement 6%+ Fly Ash

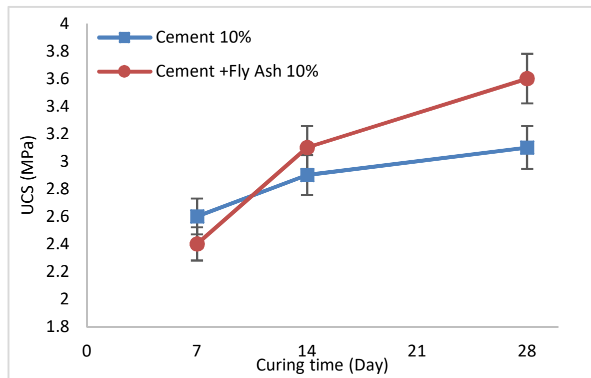

Figure 6. UCS of Cement 10% vs. Cement 10%+ Fly Ash

5.3 Effect of curing time on UCS

The effect of curing time with different binder dosages and binder compositions are shown in Figure 7 and 8. From 7 days to 28 days, the strengths for all specimens increase with curing time. It can be observed that the increasing rate from 7days to 14 days is higher than the rate from 14 days to 28 days. The nearly completed hydration of cement around 28 days may account for this performance. Klein and Simon (2006) reported that the shear velocity of 5% CPB increases with curing time up to 600 h, which means that the 5% cement completed hydration after 600h (25 days) of curing. Ercikdi (2009) states that the UCS of CPB with low cement dosage (5%) keeps constant after 30 days, while the strength of CPB with high cement dosage (7%) keeps increasing till 60 days. Therefore, the strength does not increase notably after the 28-day curing time.

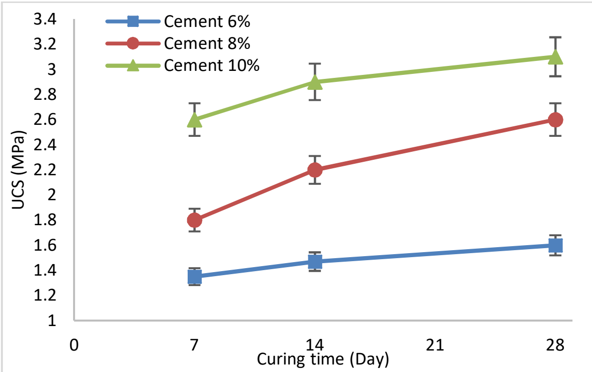

Figure 7. UCS development of Portland cement specimens versus curing time

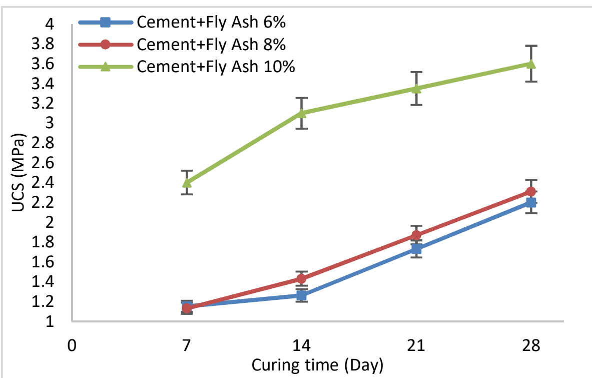

Figure 8. UCS development of binder composition versus curing time

5.4 The Stiffness of Backfilling Materials

Young's modulus *E* is obtained from an initial linear portion of the stress-strain graphs of backfill specimens and is the sample's resistance against being compressed by uniaxial stress. Young's modulus is the ratio of stress to strain within the elastic region of the stress strain curve. It is a measure of the stiffness of a material and is also known as the elastic modulus. The stiffness of the specimens can be measured by Young's Modulus:

$$E = \frac{\sigma_e}{\varepsilon_e} \quad [1]$$

where σ_e is the axial stress and ε_e is the axial strain.

Figures 9 and 10 show the increasing trend of Young's modulus for the backfill specimens with different cement dosages and compositions. It can be found that Young's modulus values of these specimens also follow the same trend as the development of compressive strength.

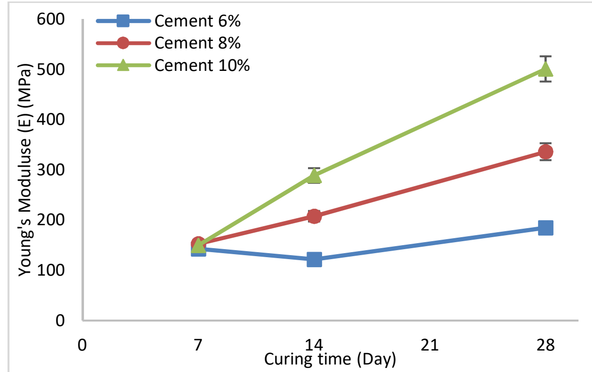

Figure 9. Young's modulus of specimens with only cement

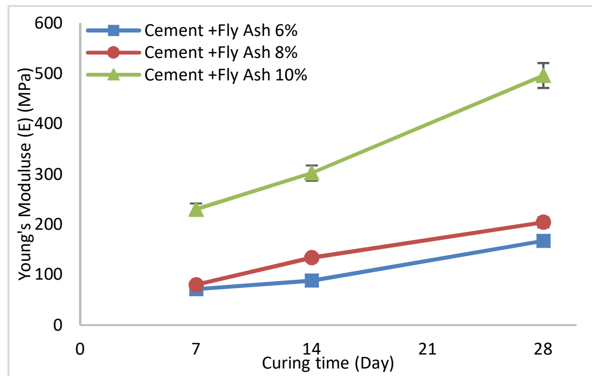

Figure 10. Young's modulus of specimens with cement and fly ash

6 CONCLUSIONS

In this study, the CPB method was used to prepare the backfill materials based on three main components (tailings, binder and water). Backfill materials with three different binder dosages and two different binder compositions were prepared to investigate the unconfined compressive strength of the backfilling during the curing time on 7 days, 14 days, and 28 days. From the results, the UCS and the stiffness of backfill material increase with the increasing binder dosages. Mixing with fly ash, the backfill material performs a notable increase in the compressive strength and stiffness. For the short-term curing time, the compressive strengths for all studied combination backfill materials increase with curing time. While increasing the rate of compressive strength decreases with the finished hydration of cement. There is no typical recipe for all backfill materials. Each type of backfill material is based on laboratory optimization. The characteristics of three main components play a significant part in the compressive strength development and must be carefully considered in the backfill design.

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