Chapter 4
Properties of Cemented Paste Backfill

A. Ghirian and M. Fall

1 Introduction

Knowledge on the properties of cemented paste backfill (CPB) material is essential for the design of cost-effective, safe and durable cemented backfill structures. The primary properties and characteristics of CPB are categorised by their physical, mechanical, hydraulic, thermal, chemical and microstructural aspects. Each property can be affected by different parameters that are mainly classified as (1) internal factors, which include all the intrinsic and multi-physics properties, such as parameters related to the main components of CPB (e.g. binder, tailings and water) and their changes with curing time. They also include other processes, such as self-desiccation, cement reaction and heat generated by binder hydration, and (2) external factors or processes, which include all phenomena that take place in relation to environmental aspects. For example, the effects of thermal loads (e.g. temperature of the rock mass, self-heating of the rocks) on the strength development of CPB, or the effects of the pressure of the self-weight of backfill and the filling rate on its consolidation behaviour, are external factors. These processes and their interactions affect the behaviour and performance of CPB. Thus, an understanding of the properties of CPB and the factors that affect them is critical for the safe and cost-effective design of CPB structures. In this chapter, a comprehensive review of the current knowledge on the physical, thermal (T), hydraulic (H), mechanical (M), microstructural and chemical properties (C) of CPB as well as the factors that affect them and their interactions is provided. However, the properties for assessing the transportability of CPB (e.g. yield stress, viscosity) are not addressed in this chapter.

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2 Physical Properties of CPB and Influential Factors

The behaviour and performance of CPB are influenced by its physical properties, such as porosity (or void ratio), density (or unit weight), water content and degree of saturation. The physical properties of CPB have been investigated by several previous studies (e.g. le Roux et al. 2002; Fall et al. 2005, 2008; Belem et al. 2006; Yilmaz et al. 2009). However, most of these studies are laboratory investigations and the in situ physical properties of CPB have been only occasionally reported in the literature. This is mainly due to the difficulties associated with in situ sampling and testing, such as lack of access to backfilled stopes, mining activity interruptions, costs of the procedure and safety issues.

The field results obtained by le Roux et al. (2005) (which include a summary of the results obtained by Pierce (1997)) showed that there are variations in the physical properties of mine backfill due to numerous reasons, such as preparation and placement techniques, stress regime, and tailings and cement properties. They reported that at 90 days of curing, the void ratio ranges between 1.10 and 1.40, unit weight from 18.40 to 20.10 kN/m^2 and degree of saturation between 79 and 100% for the studied mine and CPB. Also, they compared the field and laboratory results obtained from tests conducted on the same CPB mix. They found that the in situ void ratios and degree of saturation are approximately 20 and 10% higher and lower, respectively, than the laboratory values.

Laboratory experiments carried out by Belem et al. (2006) on an undrained column that was 3.0 m in height showed that 91-day CPB samples have a void ratio that ranges between 0.85 and 0.97 and degree of saturation between 83 and 94%. In the drained column, however, the void ratio ranges from 0.77 to 0.91 and degree of saturation varies between 75 and 93%, thus generally lower values compared to those of the undrained column. They showed that the variations of the studied physical parameters depend on the location of the column and are not uniform with height.

Experimental studies carried out by Ghirian and Fall (2013) on the physical properties of CPB with the use of column experiments (Fig. 4.1) showed that three important mechanisms can influence the void ratio variation of the studied CPB with time and height: (1) decrease of the void ratio due to the progression of binder hydration. More hydration products fill the empty pores in the CPB matrix and therefore pore refinement takes place as curing time advances (Fig. 4.1a); (2) decrease of the void ratio as a result of drainage (Fig. 4.3a). CPB cured with a lower water-to-cement ratio (*w*/*c*) produces lower void ratios as less water fills the pores (Fig. 4.2). Moreover, water drainage results in an increase of the effective stress and consolidation of CPB; and (3) shrinkage of the CPB matrix because of evaporation. As can be seen from Fig. 4.1a, a high evaporation rate at the surface results in the development of shrinkage, which is associated with volume changes. A low void ratio (0.86–0.89) at the shrinkage limit can be observed in the 90- to 150-day samples, as shown in Fig. 4.1d.

Moreover, Fig. 4.1b shows that as an overall trend, the wet density (γ_{wet}) decreases and dry density (γ_{dry}) increases as the curing time proceeds. The reduction in the wet density with time is attributed to the water consumption by the binder hydration reaction as well as desaturation due to evaporation. However, due to the pore refine-

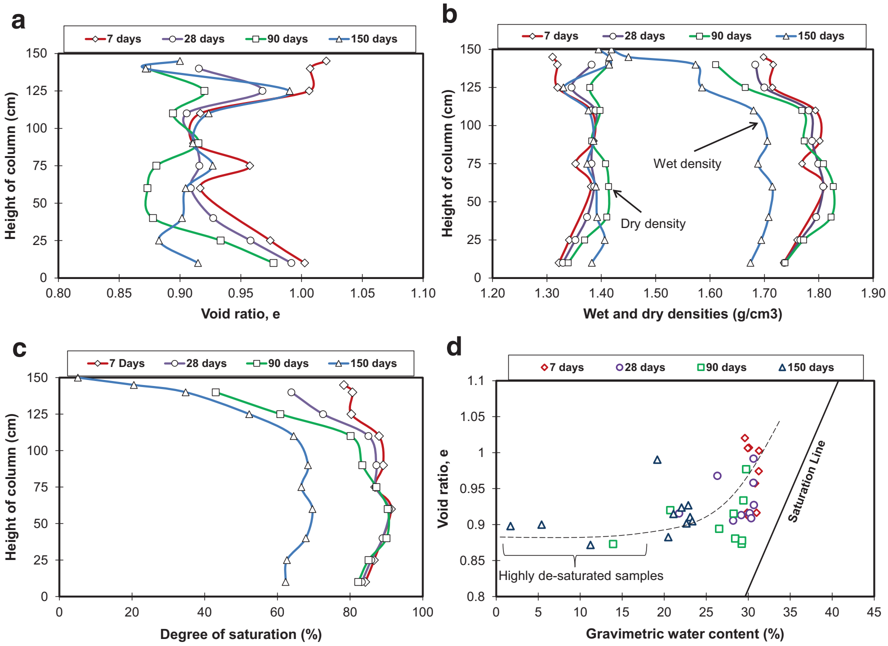


Fig. 4.1 Changes in physical properties in columns with different curing times: (**a**) void ratio, (**b**) wet and dry densities, (**c**) degree of saturation and (**d**) gravimetric water content (shrinkage curve) (Ghirian and Fall 2013)

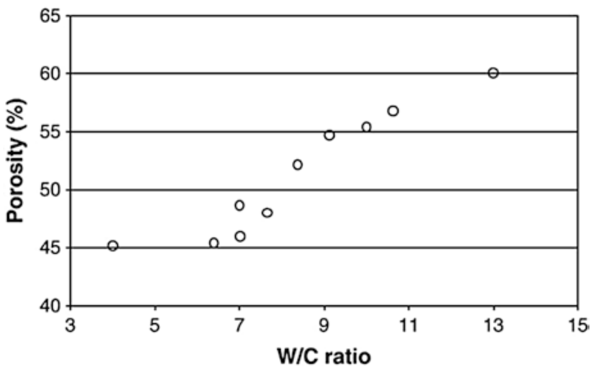


Fig. 4.2 Effects of water-to-cement ratio on porosity of CPB (Fall et al. 2010)

ment and filling of the voids with cement hydration products, an increase in the dry density can be observed as the curing time proceeds. A high rate of surface evaporation results in the lowest wet density value of 1.42 g/cm^3 at 150 days. The wet density shows an almost uniform behaviour in the column. It should also be emphasised that in underground mine environments, evaporation is limited.

In CPB material, the variation of the degree of saturation with time and height can be a function of the binder hydration and evaporation, respectively. As illustrated in Fig. 4.1c, the degree of saturation is reduced as curing time is increased as the result of self-desiccation due to cement hydration. However, the variations within the column are significantly influenced by the effects of evaporation. There is a slight increase of the degree of saturation in the middle layer and then a significant reduction towards the surface. For example, the degree of saturation is 85% in the middle of the column and then reduced to approximately less than 40% when closer to the surface of the column at 90 days.

Figure 4.1d presents the changes in the void ratio with respect to the gravimetric water content (shrinkage curve). A direct relationship between the water content and void ratio can be observed for a degree of saturation that is almost greater than 80%. The excessive desaturation resulted in further reductions of the void ratio until the shrinkage limit is reached, mainly due to cement hydration induced self-desiccation and evaporation, as can be observed in Fig. 4.1d.

Yilmaz et al. (2009) investigated the variations in the physical properties of CPB with respect to binder content (3, 4.5, 7 and 10%), for unconsolidated and consolidated 28-day samples. They reported that for the unconsolidated samples prepared with Portland cement (PC), the porosity ranges between 0.42 and 0.47, degree of saturation between 90 and 97% and gravimetric water content between 38 and 46%. For consolidated samples (cured under pressure), the porosity ranges between 0.41 and 0.45, degree of saturation between 80 and 94% and gravimetric water content between 33 and 42%. This study showed that the values of the physical properties (porosity, void ratio, degree of saturation, bulk density) of CPB decrease as the cement content increases due to the formation of hydration products and the effects of desaturation from cement hydration (in the unconsolidated samples). Also, a comparison between the unconsolidated and consolidated tests showed that drainage due to consolidation reduces the values of the physical properties. Yilmaz et al. (2014) studied the physical properties of CPB samples prepared with a blend of slag-Portland cement (3, 4.5 and 7%) that were cured for 7, 14 and 28 days under different drainage conditions [undrained, gravity drained and consolidated drained (CD)]. They reported that the gravimetric water content varies between 13 and 25%, degree of saturation between 67 and 98% and void ratio between 0.59 and 0.8. They found that the CD samples have a lower void ratio, water content and degree of saturation compared to the undrained samples, regardless of the cement content.

Ghirian and Fall (2015, 2016) investigated the physical properties of CPB samples in laboratory tests with regard to curing stress, curing time, filling rate and drainage conditions. The CPB samples were cured under zero stress (control sample, C–U) and under stress (up to 600 kPa) by using a curing cell system developed at the University of Ottawa, and considering both drained and undrained conditions. Also, three different backfilling rates of 0.155, 0.31 and 0.62 m/h, as well as three curing ages of 1, 3 and 7 days, were adopted in their studies (Fig. 4.3). The results showed that in all of the samples, the porosity (or void ratio) decreases as the curing time is increased. This is due to the ongoing cement hydration process, which produces more hydration products and thus causes the refinement of the pore structure with time (Fall and Samb 2008). Moreover, the samples cured under stress (both drained and undrained conditions, and cured under different filling rates) showed lower porosity compared to the control sample (C–U). This is mainly due to the pore refinement because of the application of pressure. Applied pressure can

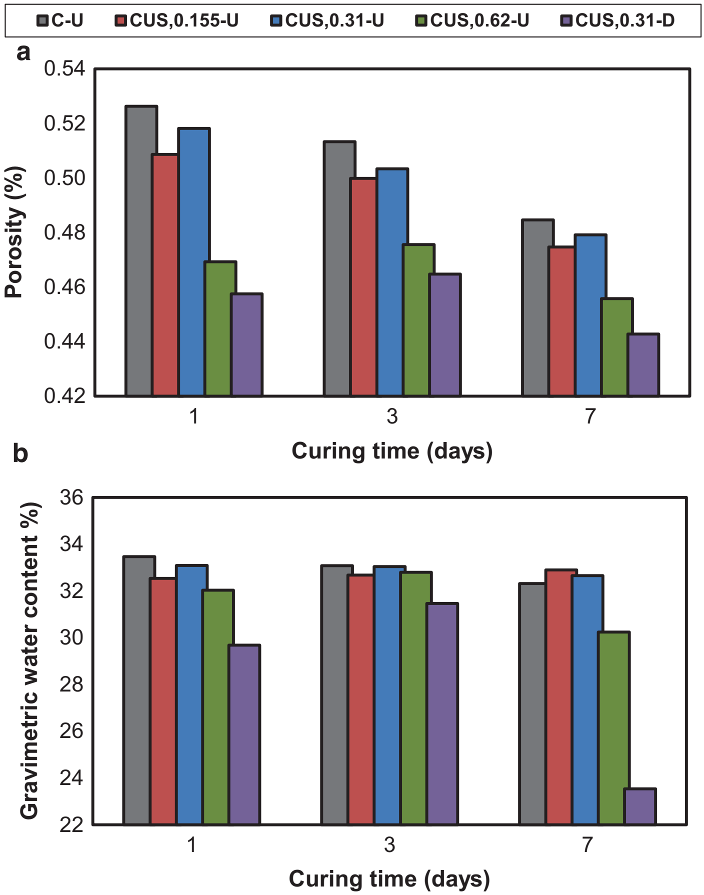


Fig. 4.3 Changes in physical properties: (**a**) porosity, and (**b**) gravimetric water content in load cell experiments (Ghirian and Fall 2016)

increase the packing density of CPB, which decreases the porosity. In the drained condition, however, the CPB samples showed considerable porosity reduction due to the applied pressure and effects of consolidation. Consolidation initially expels unbound water from the CPB pores due to volume changes until setting takes place at a later time of curing, when cementation in CPB and its water retention capacity are more developed.

Figure 4.3b shows that the gravimetric water content of all of the samples decreases with curing time. This is mainly due to the consumption of water by self-desiccation. The water content variation of the control sample and samples cured under stress is similar in the undrained condition, which suggests that the effect of pressure application on the water content is minimal in undrained loading conditions. However, the water content of the samples cured under stress (drained condition) shows a significant reduction as the curing time is increased due to consolidation-induced drainage.

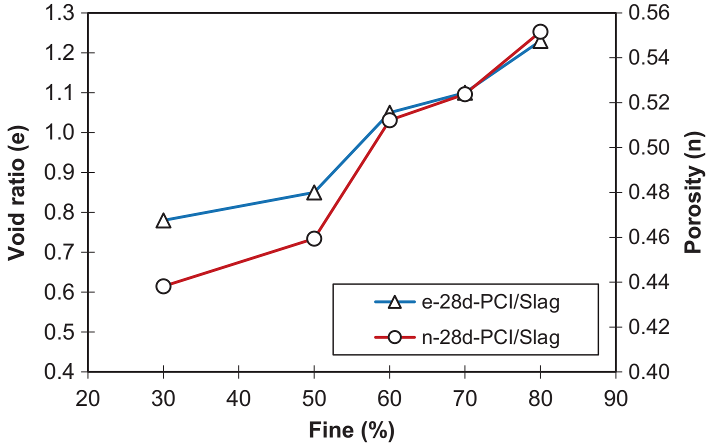


Fig. 4.4 Effects of fine content of tailings on void ratio and porosity of CPB (Modified from Fall et al. 2004)

The physical properties of CPB are also affected by the physical characteristics of the tailings, such as the particle size and fine content. The proportion of fine tailings (<20 μm) significantly influences the porosity (or void ratio) and pore size distribution of CPB, as illustrated in Fig. 4.4 (Fall et al. 2004). A higher proportion of fine particle tailings results in a higher void ratio (Fall et al. 2004). Also, there is a greater reduction in porosity with a decrease in the fines content in CPB samples made with fine (fines <60%) or medium (fines = 35–60%) fine tailings, compared to samples made with coarse tailings (Fall et al. 2004).

In summary, the above findings show that various factors, such as CPB mix components, curing time, curing stress, drainage and consolidation, affect the physical properties of CPB at the laboratory scale. Environmental factors such as evaporation, backfilling rate and stress can also influence the physical properties, but to a certain extent. The obtained results from both field and laboratory tests show that the physical properties of CPB widely differ from one backfill or mine to another. Also, they vary with respect to the height of the backfill. These variations are due to the tailings type, field conditions and placement, as well as the thermo-hydro-mechanical chemical (THMC) processes to which the CPB is subjected in field curing conditions.

3 Mechanical Properties of CPB and Influential Factors

Mechanical stability is one of the most important design criteria of CPB (Fall et al. 2007). The mechanical properties of CPB are usually related to the uniaxial compressive strength (UCS), shear strength properties or parameters, stress–strain behaviour and modulus of elasticity. A good understanding of the mechanical properties is key to assessing the mechanical stability and performance of any CPB structure.

The most common, economical and direct method to determine the mechanical strength and stress–strain behaviour of backfill materials is UCS testing (Fall et al. 2007). Other methods, such as direct shear and triaxial testing, can also be used to determine the shear strength properties and failure criteria of CPB (e.g. le Roux et al. 2005; Rankine and Sivakugan 2007; Fall et al. 2007; Ghirian and Fall 2014). In addition to these conventional testing methods, different indirect techniques have been recently used to assess the mechanical strength of CPB, such as through ultrasonic wave measurements, thermal profiling (maturity index) and measuring the shear wave velocity (e.g. Klein and Simon 2006; Mozaffaridana 2011; Ercikdi et al. 2014).

3.1 Shear Strength Properties or Parameters of CPB

There is limited available information on the shear strength properties or parameters (cohesion and internal friction angle) of CPB in the literature. Triaxial tests have been carried out in previous studies (e.g. le Roux et al. 2005; Fall et al. 2007; Rankine and Sivakugan 2007; Veenstra 2013) to determine the shear strength properties of backfill which showed different values of the internal friction angle (φ) with respect to curing time, binder type and content, and tailings type. For example, Belem et al. (2000) performed triaxial CD compression tests on CPB samples and reported that the friction angle of the 112-day samples varies from 5 to 28°, depending on the binder type and content (3, 4.5 and 6%). They showed that the friction angle decreases as cohesion of the backfill increases. Also, they found that at a certain curing time, the friction angle decreases when the percentage of the cement content is increased. Rankine and Sivakugan (2007) conducted triaxial CD tests on CPB samples and reported that the friction angle is slightly reduced from 38° at 14 days to 37.9° at 28 days, and from 35.7° at 14 days to 32.7° at 28 days for samples with a binder content of 2 and 6%, respectively. Pierce (1997) reported that the cohesion significantly increases when the binder content and curing time are increased. On the other hand, the friction angle decreases when the curing time is increased. le Roux et al. (2005) conducted triaxial tests and reported that the friction angle ranges between 32 and 37° for an undisturbed unsaturated CPB sample at 90 days (field-cured sample), while laboratory-prepared samples from the same CPB mix showed a friction angle of 37°, thus suggesting that there is no significant change in the friction angle due to in situ curing conditions. Direct shear tests conducted by Veenstra (2013) showed that the friction angle is reduced when curing time is increased. Different tailings grain size (from clayey silt to fine sand) and different binder contents were used to prepare the CPB samples. The typical values obtained ranged on average from 38° to 43° at day 1 and from 23° to 36° after 7 days of curing.

A review of the previous work shows that there is a slight decrease in the friction angle with curing time, mostly taking place in the long term. This reason is not well understood, but most likely attributed to different mechanisms, such as the chemical processes related to cement hydration reactions, oxidation of mine backfill (weathering), self-desiccation, drainage, in situ stress and presence of air voids in the backfill (Rankine 2004; Rankine and Sivakugan 2007). The changes in the friction angle

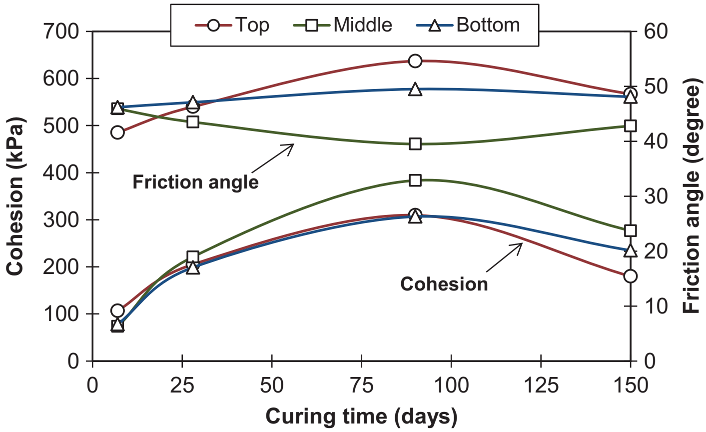


Fig. 4.5 Changes in shear strength parameters in column experiments (Ghirian and Fall 2014)

with increased curing time in the column experiments conducted by Ghirian and Fall (2014) showed that the friction angle of the CPB samples taken from the middle of the column decreases from 46° at 7 days to 39° at 90 days (Fig. 4.5). However, the samples taken from the top and bottom of the column showed different behaviours due to the effects of drying shrinkage and drainage. In these samples, the friction angle is increased with curing time from approximately 42° at 7 days to approximately 52–55° at 90 days followed by a reduction to 48° at 150 days. Ghirian and Fall (2015) also found changes in the friction angle in the short term in their load cell experiments, as illustrated in Fig. 4.6. The friction angle of the undrained CPB samples cured under stress (CUS-U) is slightly decreased as the curing time is increased, while the friction angle of the control sample (cured under zero stress) remains almost constant. It can also be observed that the curing stress does not have a significant influence on the changes in the friction angle.

Cohesion in cemented backfill materials is normally developed through cementation by the bonding that takes place between the tailings particles and cement hydration products. Other sources of cohesion development in CPB can result from desaturation induced by self-desiccation and/or evaporation. Cohesion is a time-dependent property and can develop up to 1.5 MPa, depending on the binder type and content, solid content and curing time (Rankine and Sivakugan 2007; Fall et al. 2007; Veenstra 2013; Ghirian and Fall 2013, 2014). The majority of the previous studies that have examined cohesion development in backfill reported an increase with curing time. For example, Veenstra (2013) reported that cohesion values obtained from direct shear tests increase from 40–130 kPa at 7 days to 240–680 kPa at 21 days for the studied materials. Rankine and Sivakugan (2007) performed a series of undrained unconsolidated (UU) tests and reported that the changes in undrained cohesion with longer curing time for a cement content of 6% in CPB range from 158 to 384 kPa for 1 to 9 months of curing. The reported results in Ghirian and Fall (2013) (Fig. 4.5) for column experiments showed that cohesion increases as curing time is increased from 83 kPa at 7 days up to 400 kPa at 90 days. It should be noted that the cohesion at 90

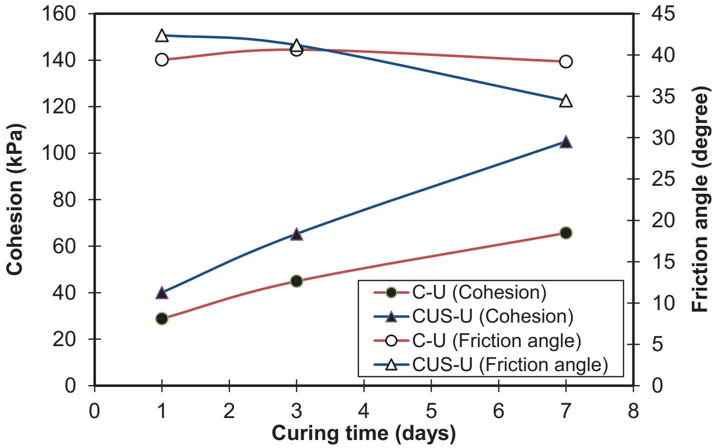


Fig. 4.6 Changes in shear strength parameters in load cell experiments (Ghirian and Fall 2014)

to 150 days decreases despite the continual development of cement hydration due to the effects of deterioration as a result of surface evaporation at the top of the column and associated shrinkage and microcracks. The results of a study by Ghirian and Fall (2015) revealed that cohesion and bonding in the cement matrix can be improved when curing stress is applied, as illustrated in Fig. 4.6.

3.2 Stress–Strain Behaviour of CPB

The stress–strain behaviour of CPB under compression loading was investigated by Fall et al. (2007). They studied the effects of different factors on the stress–strain behaviour and modulus of elasticity of CPB, such as aging, confinement pressure as well as characteristics of the main components of CPB (cement, tailings and water). Figure 4.7 shows that the stress–strain response of CPB is time dependent. Moreover, aging causes stiffening of the material (increase in the modulus of elasticity) which results in a higher peak stress and smaller strain to the peak stress (Fall et al. 2007).

Moreover, the stress–strain behaviour of CPB can be significantly affected by confinement as illustrated in Fig. 4.8. The results of triaxial compression tests showed that as the confinement is increased, the peak stress and strain at failure also increase. Furthermore, at zero or low confinement, distributed microcracks and several macro-cracks developed in the CPB samples, and the stress–strain curves, have a sharper peak at lower strains. However, higher confinement causes elasticity and then prolonged plastic behaviour with higher peak stress and larger strain at failure. This behaviour can be attributed to the friction between the fractured surfaces in the CPB after the initial cracking of the sample. The confining holds the fractured surface together and results in additional resistance of the sample (Fall et al. 2007).

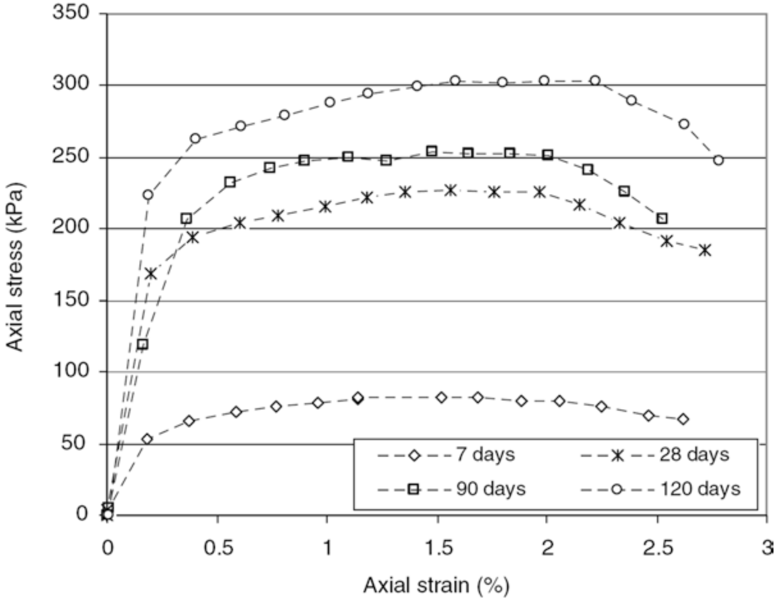


Fig. 4.7 Effects of aging on stress–strain behaviour of CPB samples with 3.0% PCI/slag (Fall et al. 2007)

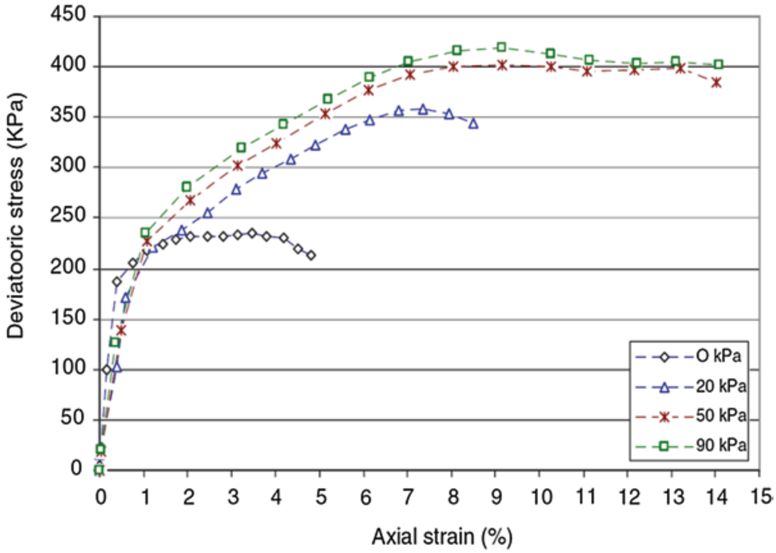


Fig. 4.8 Effect of confinement on stress–strain behaviour of 28-day CPB samples with 7% PCI (Fall et al. 2007)

Figure 4.9 shows that the cement content also considerably influences the stress–strain behaviour of CPB. It can be seen that the peak stress and modulus of elasticity of the CPB samples increase as the binder content is increased for a specific curing time. A higher binder content results in a well-defined peak stress and softening after failure, while a lower binder content causes relatively ductile failure of the sample (Fall et al. 2007).

The *w/c* ratio significantly affects the stress–strain behaviour of CPB as shown in Fig. 4.10. At a given strain, a lower *w/c* can sustain higher stress before and after the peak stress, as well as contribute to higher elasticity in the CPB samples. This is attributed to the fact that CPB prepared with a lower *w/c* has an overall lower porosity and denser microstructure, which will result in an increase in strength and modulus of elasticity (Fall et al. 2007).

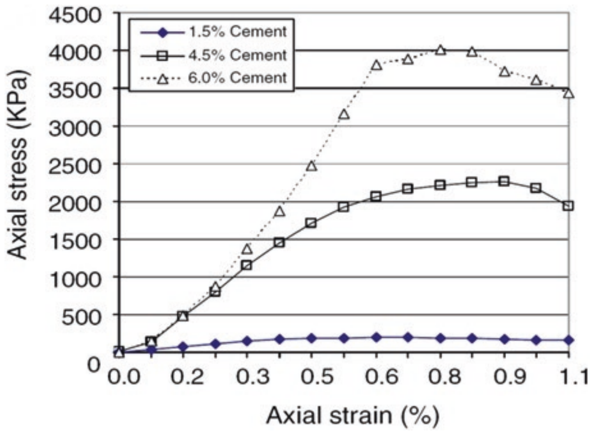


Fig. 4.9 Effect of binder content on stress–strain behaviour of 28-day CPB samples with PCI (Fall et al. 2007)

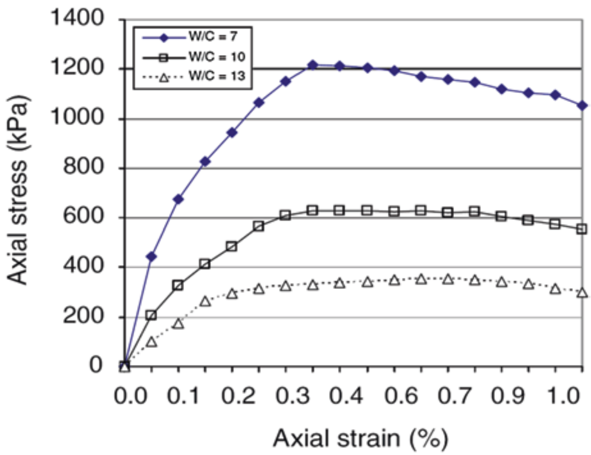


Fig. 4.10 Effect of *w/c* on the stress–strain behaviour of 28-day CPB samples with 4.5% PCI/slag (Fall et al. 2007)

The effect of the fine content of the tailings on the stress–strain behaviour of CPB is presented in Fig. 4.11. It can be observed that the peak stress and modulus of elasticity increase as the fine content of the tailings material is decreased. The failure modes of the samples prepared with different fine content are almost similar. However, a reduction in the fine content to less than 50% of fines does not considerably change the peak stress and modulus of elasticity. The fine content effect can be attributed to the fact that CPB with finer particles requires more water to sustain the required consistency (or slump), thus resulting in a higher *w/c* and thereby lower strength of the CPB (Fall et al. 2007).

3.3 Strength (UCS) of CPB

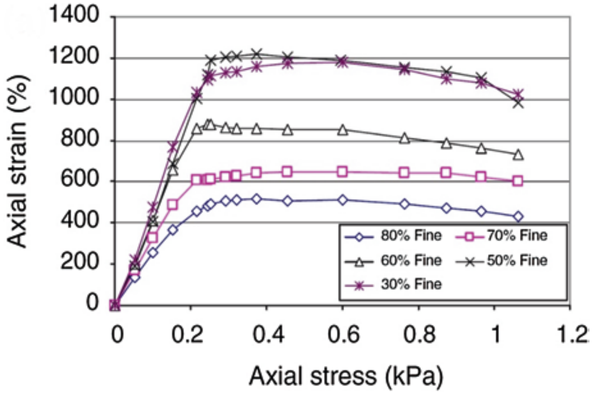
The required UCS for a CPB structure varies and mostly depends on several factors, such as the application of backfill and the subjected loading conditions. For example, CPB used for void filling typically requires very low compressive strength (e.g. 150–300 kPa), while free-standing or roof support backfill demands a high compressive strength between 1 and 4 MPa (Fall et al. 2005).

Numerous studies have been conducted on the compressive strength of CPB (e.g. Klein and Simon 2006; Pokharel and Fall 2011; Cihangir et al. 2012; Ercikdi et al. 2014). The main outcomes of these studies are that the short-term and long-term mechanical strength of CPB can be significantly affected by variations of several internal and external factors. The internal factors include the physical, chemical and mineralogical characteristics of CPB components such as the tailings, cement and mixing water. The external factors refer to the curing temperature, curing conditions (including curing time and curing stress), drainage condition, consolidation as well as placement technique such as filling rate.

The tailings characteristics, including the mineralogy content, chemical properties (e.g. amount of sulphide), fine content, density and grain size, can affect the mechanical strength of CPB (Fall et al. 2005, 2008). Also, the binder type and content, a blend ratio of two or more binders as well as the chemical properties of the binder can influence the development of the mechanical strength (Kesimal et al. 2005; Fall et al. 2008). The water content (with respect to the *w/c*) and chemistry of the mixing water (e.g. mine processing, lake or saline water) also affect the mechanical properties of CPB.

The effects of the *w/c* ratio and binder content on the compressive strength of CPB are shown in Fig. 4.12. It can be observed that at any given binder content, a reduction in the *w/c* ratios results in an increase in the UCS values (Fall et al. 2008). This effect is mainly because a reduction in the *w/c* ratio decreases the overall porosity of the backfill and consequently increases the UCS value (Fall et al. 2008). Also, an increase in the binder content increases the UCS values. A higher cement content produces more cement hydration products, which in turn increases the cohesion and reduces the porosity and packing density, and thus there is an increase in the UCS. The fine content (particles <20 μm) in tailings can also significantly influence the strength,

Fig. 4.11 Effect of fine content of tailings on the stress–strain behaviour of 28-day CPB samples with 4.5% PCI/slag (Fall et al. 2007)



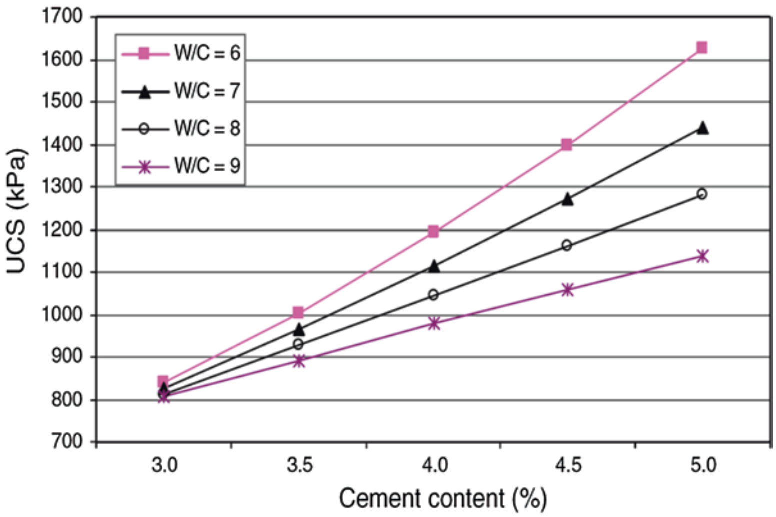


Fig. 4.12 Effect of *w/c* ratio on UCS of 28-day CPB samples with different binder contents (Fall et al. 2008)

as illustrated in Fig. 4.13. In general, a higher compressive strength is obtained when tailings contain 40–45% fine particles (Fall et al. 2008). A reduction in the fine content of the tailings (coarse tailings) reduces the void ratio and leads to the pore refinement of the CPB matrix. This in turn can result in reductions in the *w/c* ratio to sustain the CPB consistency, as well as reduced packing density of the backfill, which can consequently lead to strength gain (Fall et al. 2004, 2005).

Figure 4.14 shows the effect of the tailings density and sulphur content in the tailings on the UCS development of the CPB samples with increased curing time. It can be seen that a higher tailings density results in greater mechanical strength due

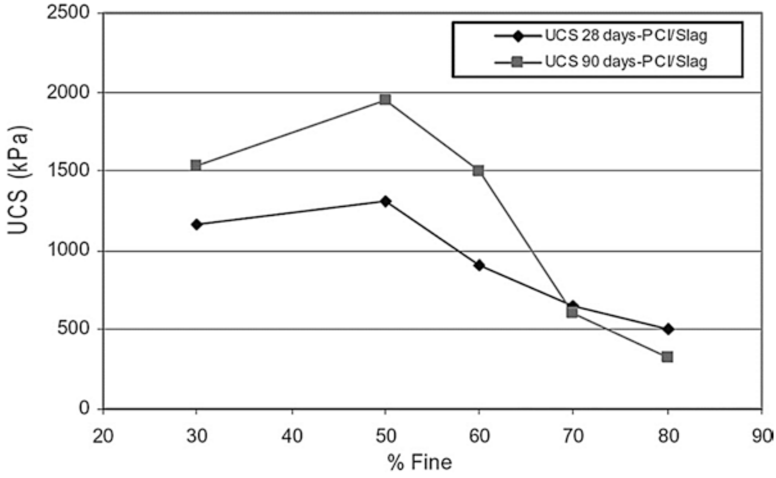


Fig. 4.13 Effect of proportion of fines in tailings on strength development of CPB (Fall et al. 2004)

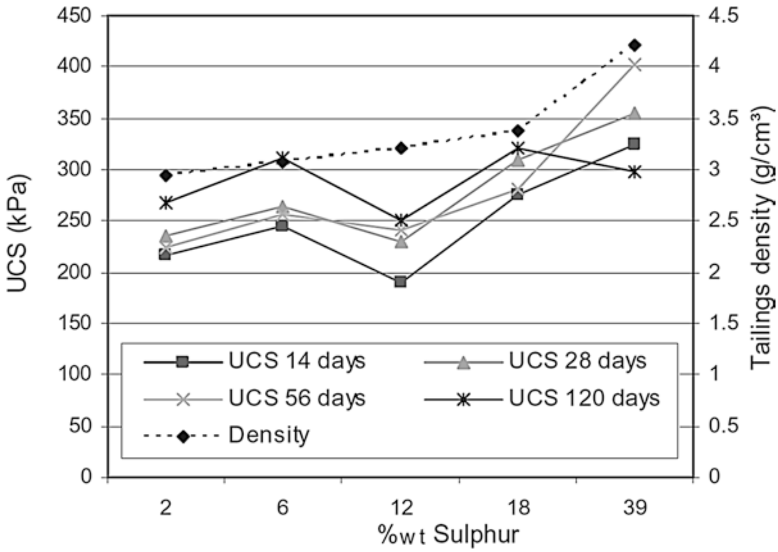


Fig. 4.14 Effect of tailings sulphur content on tailings density and strength development of CPB with PC I/PC V (50/50) (Fall et al. 2004)

to higher binder consumption (Fall et al. 2004). The figure also shows that an increase in the sulphur content results in increased UCS for a given curing time. However, the sample with a large amount of sulphur (39%) at an advanced age (120 days) has the lowest strength compared to the other samples (Fall et al. 2004). This is attributed to the presence of sulphur compounds, such as sulphide minerals and soluble sulphates, which negatively affect the CPB strength due to sulphate attacks (Kesimal et al. 2004; Pokharel and Fall 2011). Similar findings can also be obtained in a study conducted by Li and Fall (2016) on the early age strength development of CPB that contains sulphate; see Fig. 4.15. This figure shows that a higher volume of sulphate results in the development of lower strength of the backfill at the early ages, which is due to the inhibition of cement hydration reactions and fewer hydration products developed. Figure 4.16 shows that the weight loss or peak at 400–450 °C of the CPB sample without sulphate is greater than that with a sulphate content of 25,000 ppm. This indicates that fewer hydration products, such as CH, are produced in CPB with high amounts of sulphate. Other factors, such as the formation of expansive minerals (e.g. ettringite), coarsening of the CPB pore structure and sulphate absorption by calcium silicate hydrate (C–S–H), contribute to the strength loss of CPB (Li and Fall 2016).

The binder characteristics, such as type, content, blend ratio and chemical properties (e.g. the soluble sulphate concentration), have a significant role in the strength development of CPB. Benzaazoua et al. (2002) investigated the UCS development in CPB samples with three different sulphur contents (5, 16 and 32 wt.%) and different binder types and ratios [i.e. ordinary PC (types I and V), slag and fly ash (FA)]. They reported that for tailings with low to medium sulphur contents, only binders with a mix of PC type I and FA, mix of PC type I and slag, and slag provide better UCS in CPB samples compared to binders with a mix of PC types I and V. However, binders with a mix of PC types I and V are more appropriate for tailings with high contents of sulphur and can deliver better compressive strength. Slag-based binders or a mix of PC and slag was not recommended by Benzaazoua et al.

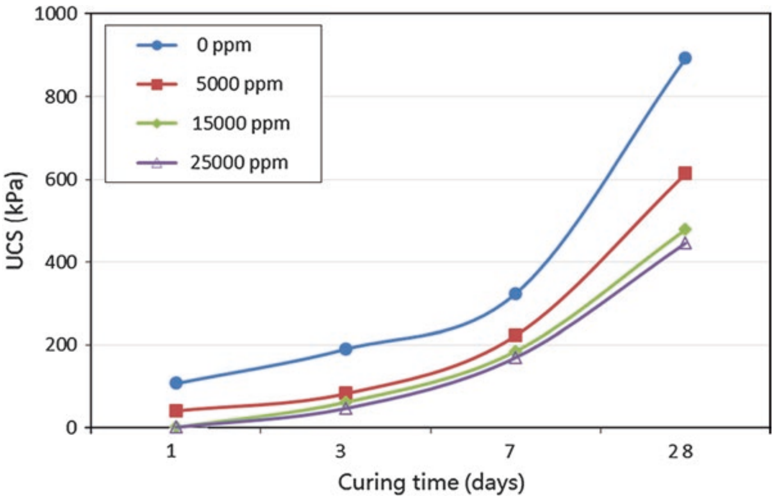


Fig. 4.15 Effect of initial sulphate content on development of UCS of CPB at early ages with 4.5% PC I (Li and Fall 2016)

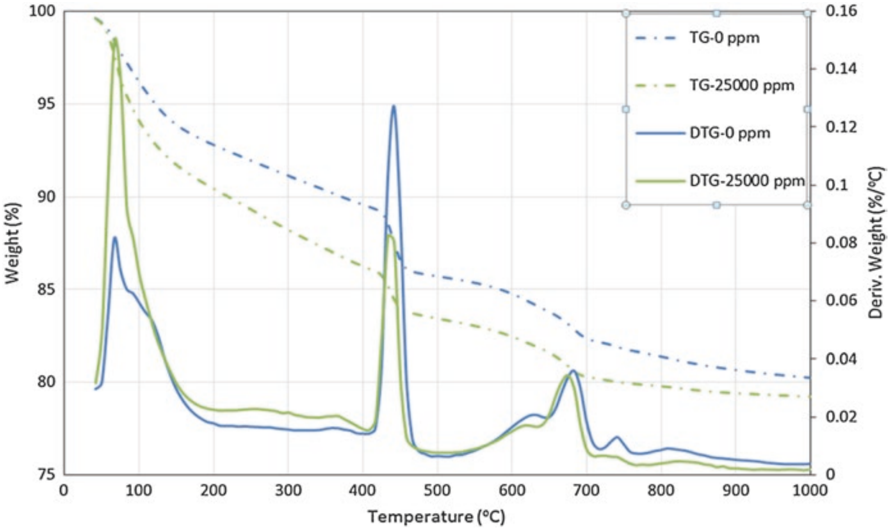


Fig. 4.16 Effect of sulphate content on thermal behaviour of the cemented pastes of 3-day CPB samples (Li and Fall 2016)

(2002) for such tailings. Kesimal et al. (2005) reported that binders that contain lower contents of pozzolanic additives (14%) deliver higher short-term mechanical strength to CPB compared to binders with a large amount of pozzolanic additives (29%). However, a large amount of pozzolanic additives in the binder can provide higher long-term strength to CPB made of sulphide-rich mine tailings.

Benzaazoua et al. (2004) discussed the effect of the blend ratio of the binder on UCS development in CPB samples with different combinations of PC type I (PC I) and type V (PC V), while the mass proportion was kept constant at 4.5%, and mixing water with a sulphate concentration of 2000 ppm was used. The results of the UCS tests showed that ratios of 50/50 and 60/40 provide the highest strength to the CPB samples at 28 days, due to the difference in the rate of strength gain between PC I and V, and the volume of C_3A and CH as a result of the cement hydration reactions (Fall et al. 2005). However, the sample with a 70/30 ratio delivered high strength at 7 days. Ultimately, high concentrations of C_3A and/or C_3S in PC I led to decreases in the sulphate resistance of CPB and therefore reductions in strength at 28 and 56 days. The binder ratio with a more sulphate-resistant cement (PC V) had low early strength, but the highest UCS at an advanced age (Fall et al. 2005, Fig. 4.17).

The mixing water chemistry and properties, including the chemical concentration and water-to-binder ratio, can affect the strength acquisition process. The water chemistry (e.g. mine processing water can contain large amounts of sulphate) can significantly change the chemical composition of cement and the hydration process. It can also affect the formation of primary and secondary cement hydration products, which are responsible for strengthening the backfill and its durability in the long term (Benzaazoua et al. 2002; Fall and Pokharel 2010; Pokharel and Fall 2011, 2013).

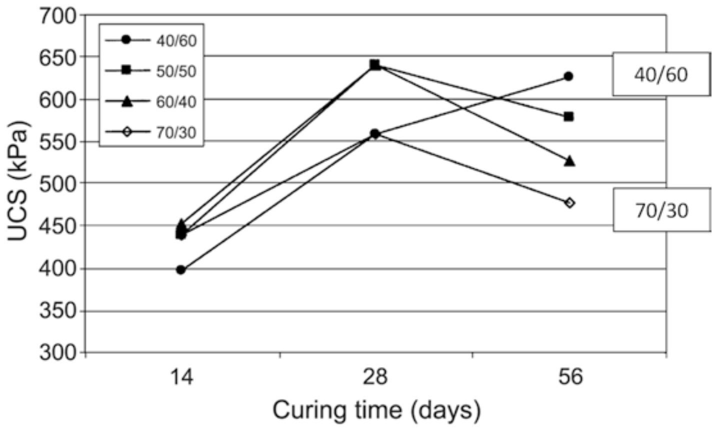


Fig. 4.17 Effect of binder mixing ratio (PC I/PC V) on strength development of CPB with 4.5% binder content and mixing water with 2000 ppm sulphate (Fall and Benzaazoua 2005; modified)

As discussed earlier, in addition to the internal factors (tailings, cement and mixing water properties), several external factors can also influence the UCS development in the backfill. One of the most important external factors is temperature (e.g. curing and initial backfill temperatures) which can significantly influence the short-term and long-term mechanical strength, pore structure and performance of CPB materials (e.g. Fall and Samb 2008; Fall et al. 2007, 2010).

Fall et al. (2010) studied the effect of the curing temperature on the short-term and long-term UCS development, as well as the tensile strength. Figure 4.18 shows that UCS increases as the curing temperature is increased. The reason is that a higher temperature causes a rapid hydration reaction in the cement, and thereby the formation of more hydration products (e.g. C–S–H, CH) in the backfill. This can then lead to pore refinement and a denser CPB matrix. Figure 4.19 shows that regardless of the binder type, the CPB strength increases with curing time up to 150 days, except for the PC I/slag samples cured at temperatures above 35 °C. This loss of strength of the PC I/slag samples is due to the "crossover effect", in which curing at a higher temperature produces a coarser pore structure in the cementitious materials (Fall et al. 2010). Then, the hydration products are not uniformly distributed in the pores, thus resulting in higher porosity and lower strength (Alexander and Taplin 1962).

Fall et al. (2010) also investigated the combined effects of fine content and temperature on UCS development. It is observed in Fig. 4.20 that for a low curing temperature (≤20°C), the CPB strength is reduced with increased fine content. The increased fine content results in an increase in the porosity, which eventually produces CPB with lower mechanical strength. However, after 28 days of curing at high temperatures (≥35 °C), CPB with 35% fine tailings has a higher strength than CPB with 45% fine tailings because the former has the optimal number of pores to accommodate the hydration products formed (Fall et al. 2010).

Fall and Pokharel (2010) studied the coupled effect of temperature and sulphate on CPB strength. This interaction of temperature with sulphate in cement reactions

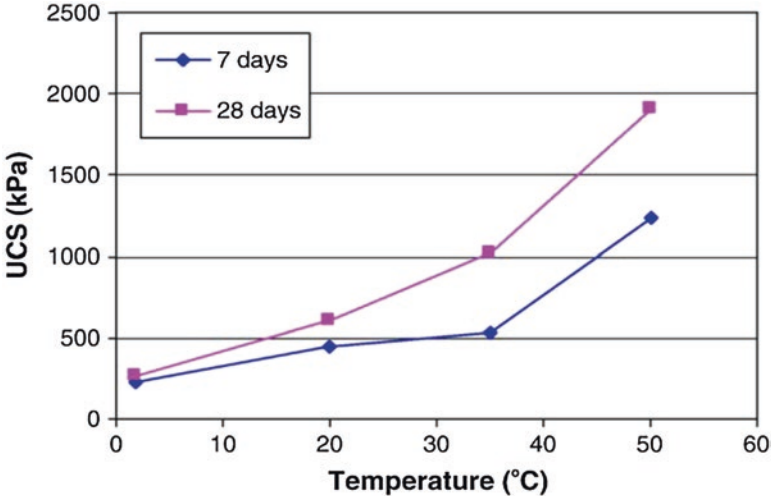


Fig. 4.18 Effect of temperature on UCS development of CPB with 4.5% PC I and *w*/*c* = 7.6 (Fall et al. 2010)

can have positive or negative effects on the UCS depending on the amount of sulphate and the curing temperature, as illustrated in Fig. 4.21. Fall and Pokharel (2010) reported that temperatures over 20 °C and sulphate concentrations up to 15,000 ppm contribute to the UCS development in CPB samples cured for 28 and 150 days. However, the samples with an initial sulphate content of 25,000 ppm generally show much lower strength, especially at a curing temperature of 50 °C, regardless of the curing time. Higher curing temperatures (≥35°C) and initial sulphate contents (≥15,000 ppm) lead to absorption of a larger amount of sulphate ions by the C–S–H, which may lead to the formation of lower quality C–S–H, and thus results in reduced CPB strength.

CPB structures can be subjected to high temperatures due to the self-heating of sulphidic rock masses (oxidation of the sulphide minerals) or accidental fires (Fall and Samb 2008, 2009). This loading condition under an extreme temperature can significantly impact the UCS development in CPB. Figure 4.22 shows that the UCS increases as the temperature is also increased, up to 200 °C. However, there is lower UCS from 200 to 600 °C due to the thermal decomposition of the hydrates as well as the development of microcracks at the interface between the tailings particles and cement matrix as a result of excess vapour pressure in the CPB pores (Orejarena and Fall 2008). However, Orejarena and Fall (2008) indicated that the adverse thermal effects can be reduced by using more binder in the backfill.

One of the most important external factors that significantly affects the UCS of CPB structures are the curing conditions, including the curing stress (or self-weight pressure) and drainage conditions, as well as the filling rate of the backfill. The effect of curing under stress on UCS development is presented in Fig. 4.23. This figure shows that samples cured under stress in an undrained condition show higher

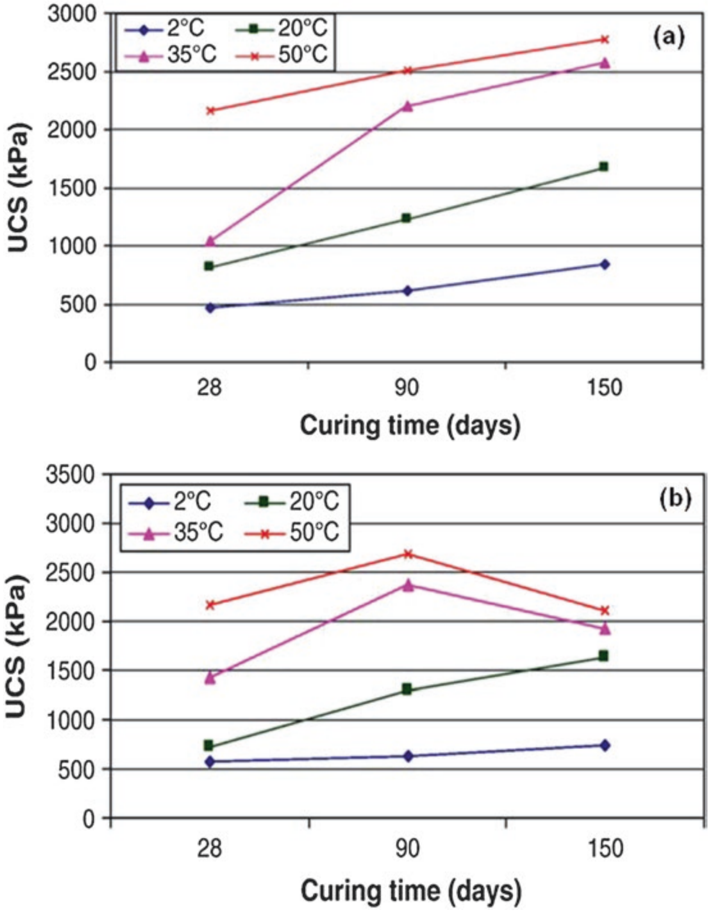


Fig. 4.19 Effect of curing temperature on the development of long-term strength of CPB with: (**a**) PC I, (**b**) PC I/slag (50/50), *w*/*c* = 7.6 and cement = 4.5% (Fall et al. 2010)

early-age mechanical strength compared to those cured under zero stress, due to the effect of the application of pressure on the microstructure or pore structural changes. Curing under stress causes particle rearrangement which then increases the packing density of the CPB material. Then, there is a reduction in the total porosity and void ratio, which can lead to compressive strength gain (Ghirian and Fall 2015). In contrast to the undrained condition, consolidation can take place if CPB samples are cured under stress in a drained condition. The effect of consolidation and drainage (cured under zero stress) on UCS development is shown in Fig. 4.24. It can be observed that the drained samples (cured with and without stress) exhibit higher mechanical strength compared to the sample cured under zero stress and the undrained sample. The UCS of the consolidated sample (drained and cured under stress) has the highest value for all of the curing times. Also, drainage itself, without the

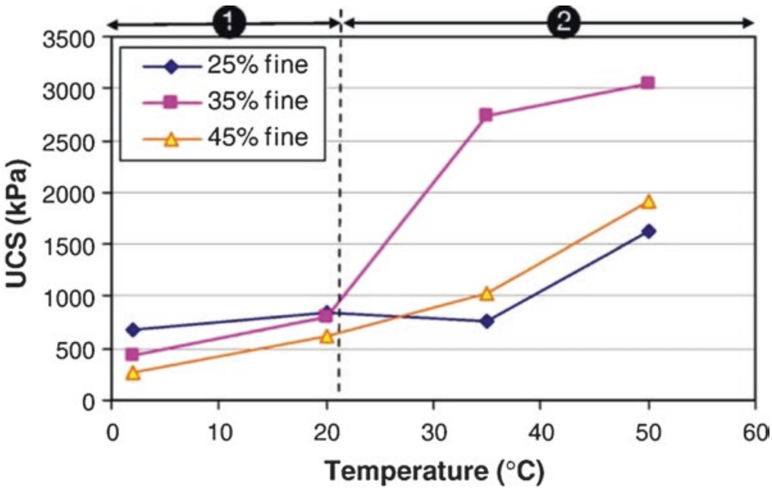


Fig. 4.20 Combined effect of fine content of tailings and curing temperature on strength of CPB at 28 days of curing with w/c = 7.6 and 4.5% PC I (Fall et al. 2010)

application of curing stress, significantly improves the mechanical strength of the backfill. The gain in strength of the consolidated samples is from the pore pressure dissipation due to the compression of the CPB pores, and as a result, there is development of effective stress in the backfill. This provides stronger cementation and bonding in the CPB matrix. Moreover, water drainage can result in curing of CPB under a lower *w/c* ratio. As explained earlier, a lower *w/c* ratio helps with the formation of denser CPB pores, eventually delivering higher strength to the backfill (Ghirian and Fall 2016). Figure 4.25 presents the effect of the filling rate on the UCS development in the undrained condition. It can be observed that CPB with a higher filling rate exhibits somewhat higher UCS values, except for the CUS 0.62-U sample on the first day of curing. The 0.62 m/h corresponds to the filling rate, which is fast and thus generates high pore pressure in CPB at a very early age, which results in almost zero effective stress development in the CPB. This, in turn, causes low mechanical strength development in CPB (Ghirian and Fall 2016).

4 Hydraulic Properties of CPB and Influential Factors

The primary hydraulic properties and processes in CPB materials include hydraulic conductivity (saturated and unsaturated) of the backfill and generation of pore water pressure (PWP; positive or negative) in the cemented backfill. The hydraulic conductivity of CPB can be expressed in two states: saturated and unsaturated conditions.

Some of the previous research works have examined the saturated hydraulic conductivity (e.g. Godbout and Bussière 2007; Fall et al. 2009; Pokharel and Fall 2013; Ghirian and Fall 2013), as well as the unsaturated hydraulic conductivity (e.g.

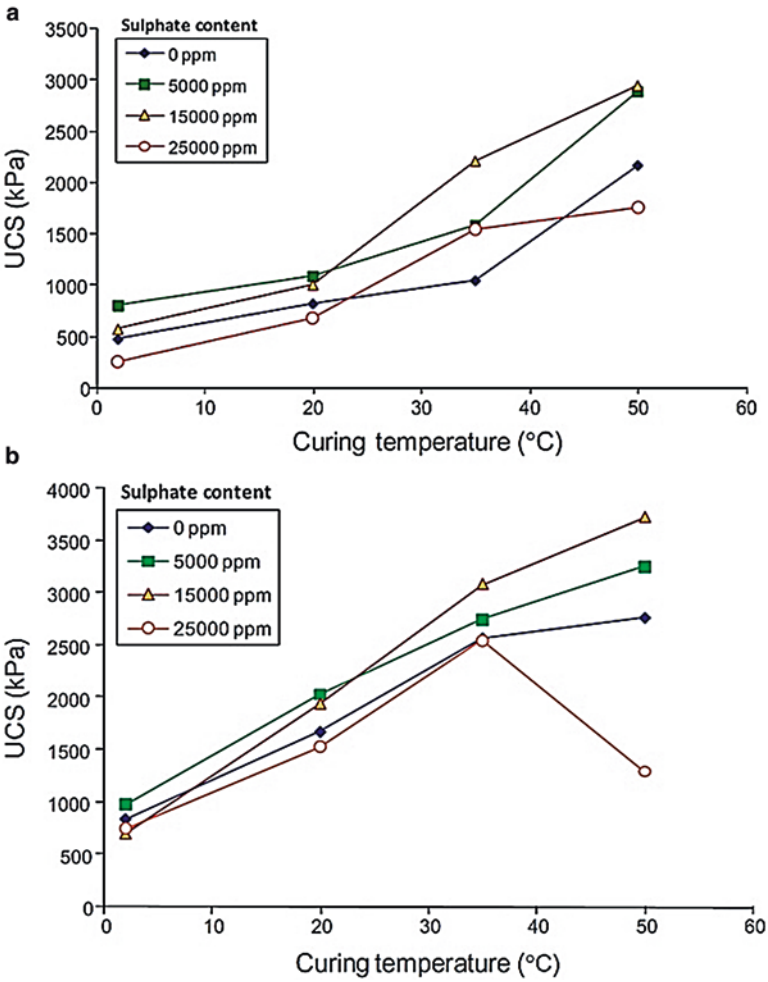


Fig. 4.21 Coupled effect of temperature and initial sulphate content on UCS of (**a**) 28-day and (**b**) 150-day CPB samples with *w*/*c* = 7.6 and 4.5% PC I (Fall and Pokharel 2010)

Witteman and Simms 2011; Abdul-Hussain and Fall 2011) of CPB materials. Saturated hydraulic conductivity (k_{sat}) is necessary to examine the consolidation behaviour and drainability as well as assess the transportability of backfill in a fluid state, such as groundwater flow in the backfill and/or between the CPB and its surrounding environment. Information on the unsaturated hydraulic conductivity (k_{unsat}) and properties [e.g. water retention capacity (WRC) and air entry value (AEV)] is necessary to assess the environmental performance of backfill structures, such as the generation of acid rock drainage and leakage potential of the mine backfill (specifically, backfill with sulphate-bearing tailings). A review of the available and recent body of research work related to the hydraulic properties of CPB materials is presented in this section.

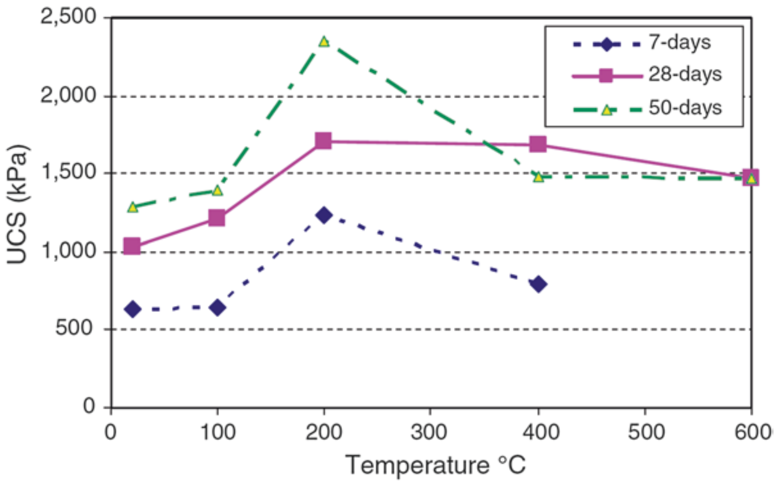
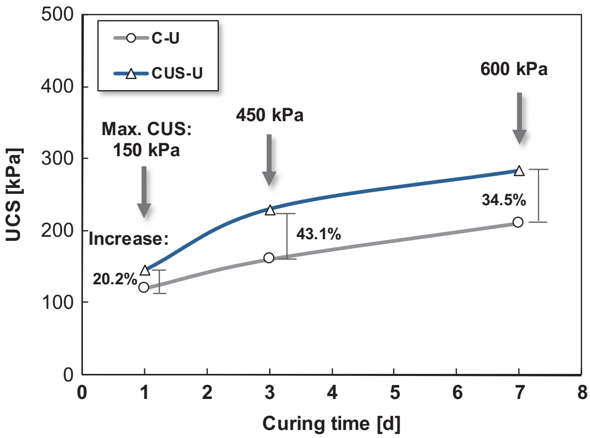


Fig. 4.22 Effect of high temperature on strength development of CPB with PC I (4.5% and *w*/*c* = 7.0) (Orejarena and Fall 2008)

Fig. 4.23 Effect of curing under stress on UCS development (Ghirian and Fall 2015)



The saturated hydraulic conductivity of CPB is a property that changes with curing time. The changes can be observed in the hydraulic properties obtained from the column experiments performed by Ghirian and Fall (2013). Figure 4.26 shows that the saturated hydraulic conductivity values decrease as the curing time is increased, due to the refinement of the pores as a result of the cement hydration process. Also, Ghirian and Fall (2013) observed that the variations in the saturated hydraulic conductivity are not uniform inside the columns. The saturated hydraulic conductivity of the CPB samples located at the top of the column at the more advanced ages is significantly reduced. This is due to the effect of the microcracks from surface evaporation, which leads to the creation of preferential liquid paths in the CPB, and thus higher permeability (Ghirian and Fall 2013).

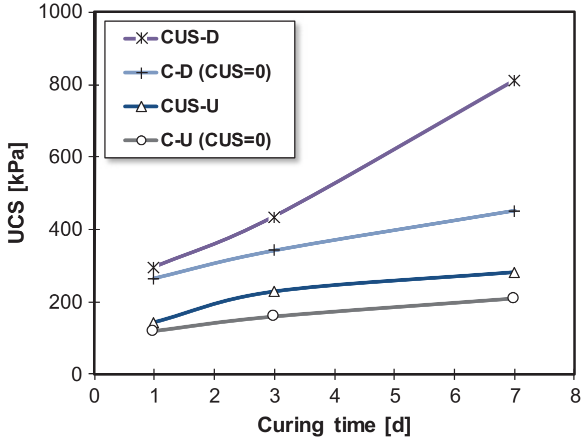


Fig. 4.24 Effect of curing under stress and drainage (consolidation) on UCS development at the early ages (Ghirian and Fall 2016)

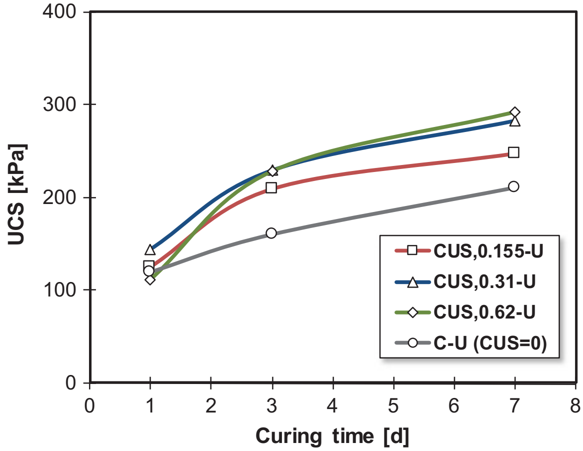


Fig. 4.25 Effect of filling rate on UCS development at the early ages (Ghirian and Fall 2016)

There are many factors that affect the saturated hydraulic conductivity of CPB. Internal factors such as the fine content of the tailings, *w/c* ratio, binder content and type, and sulphate content, as well as external factors such as the curing temperature and curing stress, can affect the hydraulic properties of CPB. Figure 4.27 shows the effect of the fine content of tailings on the changes in the saturated hydraulic conductivity, where medium tailings with 45% fine particles reduce the hydraulic conductivity of CPB, compared to coarse tailings (≤32% fine content), for a given consistency. This is due to a reduction of the packing density of the tailings materials and coarsening of the pore structure as the fine content is reduced (Fall et al. 2009).

Figure 4.28 shows that the permeability of CPB is reduced with a lower *w/c*. This is more evident at the early ages of curing compared to the advanced ages because a lower *w/c* leads to reduced porosity and faster binder hydration. These then cause pore refinement and result in the reduction of the transportability of backfill in the

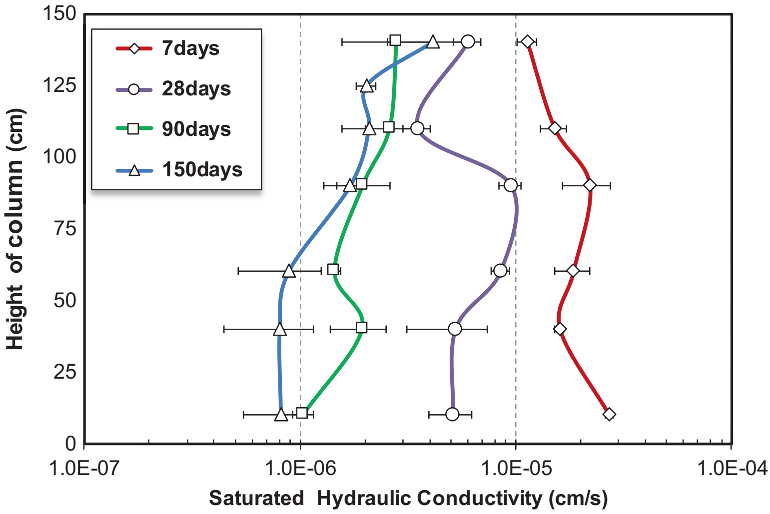


Fig. 4.26 Changes in saturated hydraulic conductivity in column experiments (Ghirian and Fall 2013)

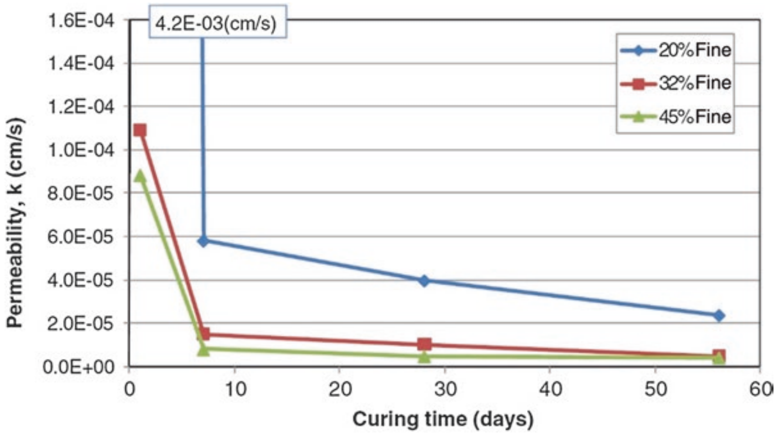


Fig. 4.27 Effect of fine content on saturated hydraulic conductivity of CPB with 4.5% PC I and slump = 18 cm (Fall et al. 2009)

fluid state (Fall et al. 2009). Pokharel and Fall (2013) studied the combined effects of temperature and sulphate content on the saturated hydraulic conductivity of CPB. Generally, a higher curing temperature results in lower hydraulic conductivity, regardless of the sulphate content (except for samples with 25,000 ppm of sulphate and cured at 50 °C); see Fig. 4.29. High curing temperatures increase cement hydration and thereby more hydration products are generated that fill the pores in the CPB matrix. Also, a moderate sulphate content and temperature produce secondary hydration products. These products then fill the CPB pores and reduce the

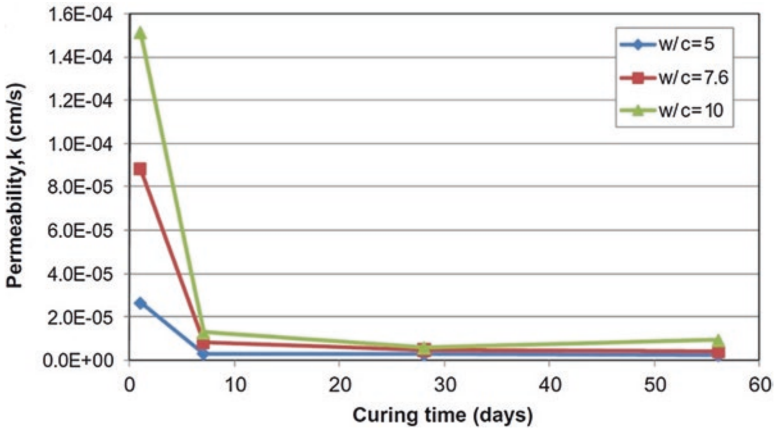


Fig. 4.28 Effect of *w/c* ratio on saturated hydraulic conductivity of CPB with 4.5% PC I and slump = 18 cm (Fall et al. 2009)

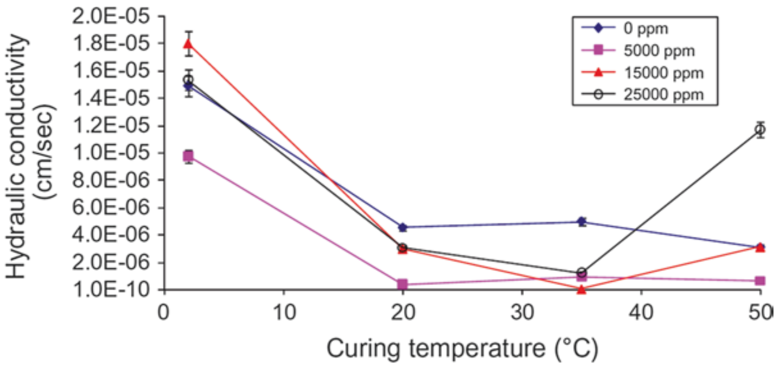


Fig. 4.29 Coupled effects of sulphate and curing temperature on hydraulic conductivity of 90-day CPB samples with 4.5% PC I and slump = 18 cm (Pokharel and Fall 2013)

permeability. However, there is an increase in the hydraulic conductivity of the samples with a high sulphate content at 50 °C, due to the adsorption of the sulphate by the C–S–H gel, as well as destabilisation of the ettringite at a high curing temperature, which results in less precipitation of ettringite in the CPB pores and thereby greater permeability (Pokharel and Fall 2013).

An important external factor that can affect the changes in the saturated hydraulic conductivity is the curing stress. Ghirian and Fall (2015) reported that at any curing time, the application of stress has a significant effect on reducing the hydraulic conductivity at the early ages; see Fig. 4.30. This is due to the particle rearrangement and porosity reduction in the CPB matrix caused by the curing stress, which in turn results in reduced permeability of the CPB sample. However, mechanical damage induced by high levels of applied stress (more than 80% of the UCS) can

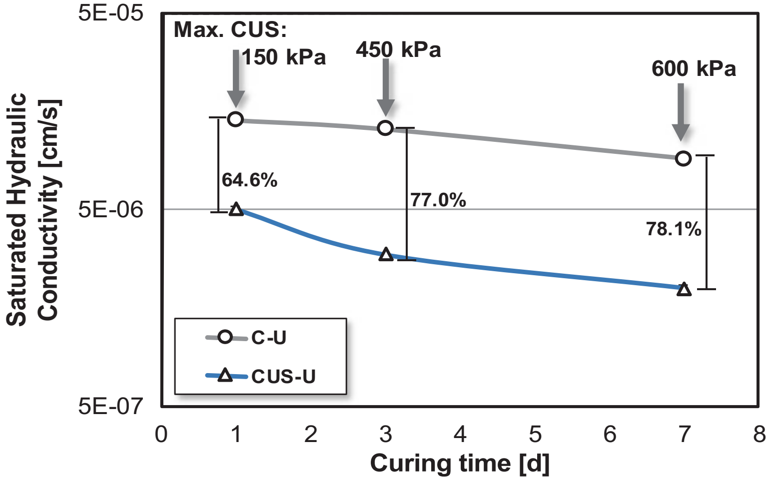


Fig. 4.30 Effect of curing under stress on saturated hydraulic conductivity of CPB with 4.5% PC I and *w*/*c* = 7.6 (Ghirian and Fall 2015)

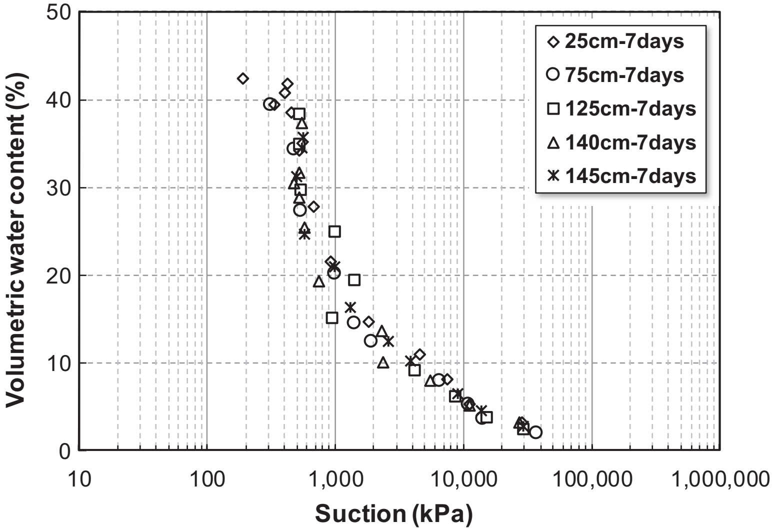


Fig. 4.31 Water retention properties of 7-day CPB samples in column experiments (Ghirian and Fall 2013)

increase the hydraulic conductivity, mainly due to the formation of microcracks in the CPB matrix under high external stress (Fall et al. 2009).

In unsaturated conditions, factors such as the degree of saturation, water retention capacity (WRC; water content versus suction) and AEV control the unsaturated hydraulic properties of CPB. Figure 4.31 illustrates the WRC of 7-day CPB samples with respect to height in column experiments. WRC is the capacity of an unsaturated porous medium to retain water, which can be determined from the variation of the water content with matric suction. Also, the changes in the AEV with curing time are shown in Fig. 4.32. The AEV is the matric suction at which air enters the large pores in a porous medium and causes desaturation. It can be seen that the AEVs increase with curing time and degree of hydration because the pore structure of CPB is refined during the hydration process. Moreover, a higher binder content leads to higher AEVs for a given curing time, except at 90 days (Abdul-Hussain and Fall 2011).

Figure 4.33 illustrates the computed unsaturated hydraulic conductivity of the CPB sample cured for 3 days with different binder contents. The technique in van

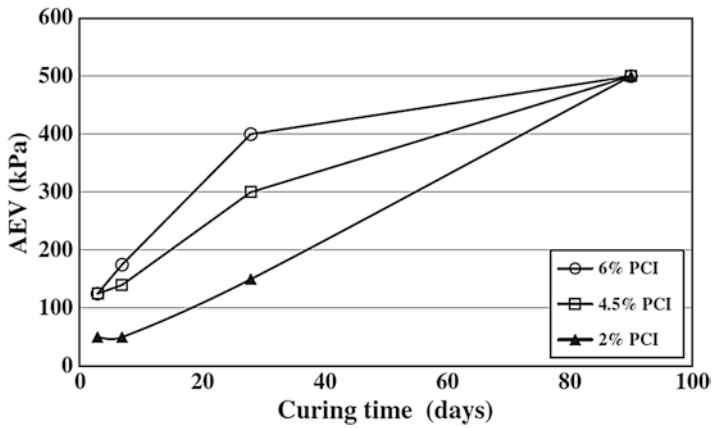


Fig. 4.32 Changes in air entry values of CPB samples with curing time (Abdul-Hussain and Fall 2011)

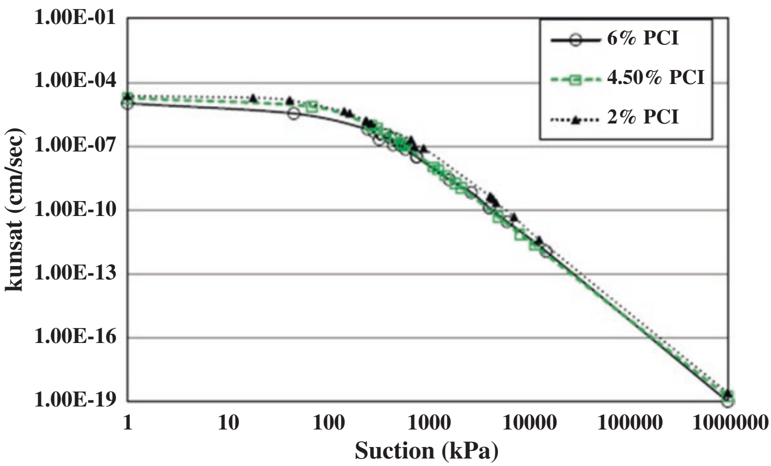


Fig. 4.33 Unsaturated hydraulic conductivity of 3-day CPB sample with different binder contents (Abdul-Hussain and Fall 2011)

Genuchten (1980) is used by Abdul-Hussain and Fall (2011) to examine the changes in hydraulic conductivity versus suction based on the obtained WRC. It can be observed that a higher binder content results in slightly lower k_{unsat} for a given suction because as the binder content is increased, more cement hydration products are produced, thus resulting in pore refinement as well as changes in the WRC of CPB (Abdul-Hussain and Fall 2011).

An understanding of the development and changes in the positive and negative (suction) PWP in CPB is essential for a reliable assessment of the mechanical strength and stability of CPB from the early to the advanced ages, liquefaction potential of CPB, stability of barricades as well as quantification of the deformation behaviour and stress distribution in the CPB. The PWP that develops in CPB influences the magnitude of the effective stresses. The principle of effective stress is one of the most important concepts of soil mechanics. Therefore, effective stress has considerable impacts on the behaviour of porous media, such as soil, CPB and rocks, because it affects their mechanical behaviour.

Experimental measurements of the changes in the PWP in CPB have been rarely addressed in previous studies. Helinski (2007) conducted a centrifuge experiment to investigate the relationships among consolidation, pore pressure changes (due to cement hydration) and total stress. Despite the fact that the apparatus monitored the stress and pore pressure changes in the backfill, it could not fully couple the studied parameters. Simms and Grabinsky (2009) modified a triaxial cell with a miniature tensiometer to measure the changes in the negative pore pressure (suction) during consolidated undrained (CU) triaxial tests. CPB samples cured for 2 days were subjected to triaxial shear testing, and the stress–strain and suction were monitored during shearing.

Despite the very limited number of experimental studies on pore pressure measurements, the field instrumentation of backfill has received increasingly more attention among researchers (e.g. Yumlu 2008; Thompson et al. 2009; Grabinsky 2010; Veenstra et al. 2011; Thompson et al. 2012). Field monitoring has been conducted by installing different sensors, such as piezometers and pressure cells, in different locations of mine stopes (different stope heights and proximity to barricades). Different parameters, such as PWP, and vertical and horizontal total stresses are measured up to 150 days of curing. The related literature has also discussed the effects of the filling sequence (effects of a plug) and filling rate. These studies consequently provide an understanding of the fundamental behaviours of CPB with regard to changes in the pore pressure, effective stress, cement hydration reaction, self-desiccation and hardening process in the field stopes. Yet a review of the previous works in the field shows that there is still a lack of understanding of the effects of THMC factors on pore pressure and the stress state. Also, external factors, such as drainage conditions, arching effects, curing temperature and chemical composition of CPB components, have not been controlled and therefore their effects on the studied parameters are not well understood.

To address these issues, Ghirian and Fall (2013) carried out column experiments that investigated the changes in suction (negative pore pressure) with curing time; see Fig. 4.34. The rate of suction development quickly increases with curing time up to approximately 80 h after loading of the column. Beyond this point, there is a gradual

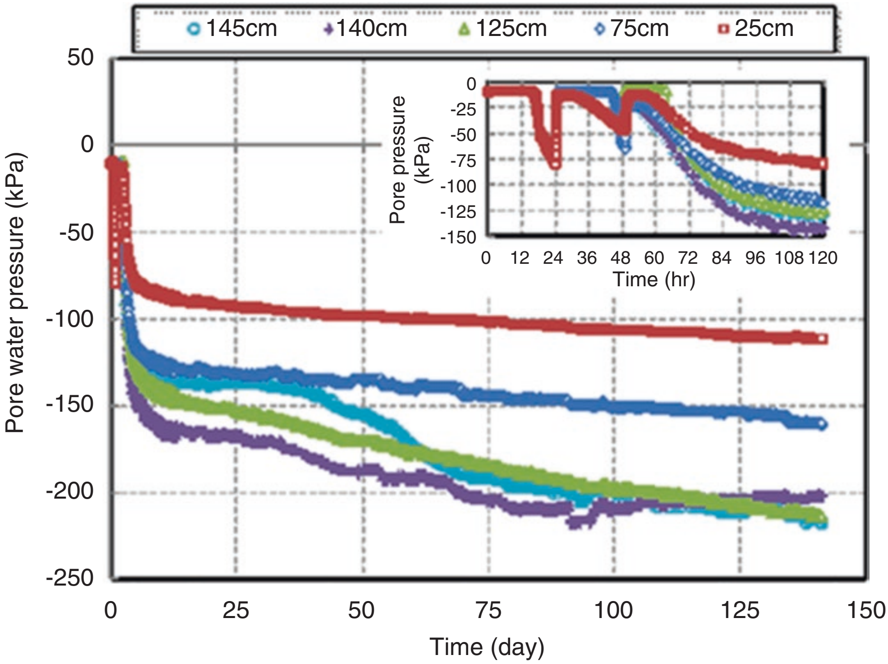


Fig. 4.34 Changes in suction with curing time in column experiments (Ghirian and Fall 2013)

change in the suction with time. The suction is primarily due to self-desiccation as a result of the cement hydration reaction. The faster rate of hydration at the early ages results in the rapid development of suction. Also, it can be noticed that the magnitude of the suction differs with respect to the height of the column. For example, the suction that develops at the bottom of the column is lower compared to the middle (and top) of the column which is due to the self-weight of CPB (i.e. self-weight-induced effective stress), as well as the drainage of water from the middle to the bottom of the column. Also, a significantly higher magnitude of suction was measured by the suction meters located near the top of the column at approximately 40 days to the end of the experiment because the development of suction resulted from the effects of self-desiccation due to the binder reaction and surface evaporation.

One of the main factors that can influence the development of suction in CPB is the sulphate content in the mine tailings and/or mine process water, as reported by Li and Fall (2016). Figure 4.35 shows that the sulphate content significantly influences the self-desiccation of CPB at the early ages. Increases in the initial sulphate content result in reduced suction in the samples (Li and Fall 2016). This is evident when the changes in suction are compared between the samples with no sulphate and 25,000 ppm of sulphate. Also, it can be observed that a higher sulphate content delays the onset of suction. For example, suction developed in the sample with no sulphate almost immediately after placement, but the suction of the sample with a high sulphate content started to change 1 week after the testing started. This is due to the

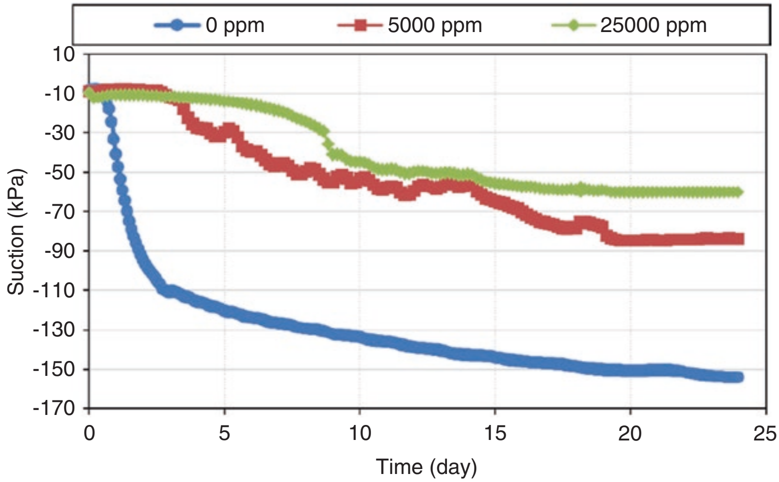


Fig. 4.35 Effect of sulphate on self-desiccation of CPB at early ages (Li and Fall 2016)

adverse effect of sulphate content (tailings chemistry) on cement hydration. The sulphate acts as an inhibitor and reduces the rate and degree of hydration, thereby resulting in less consumption of water and self-desiccation (Li and Fall 2016).

Other factors such as binder content, binder type and curing temperature can also affect the development of suction due to self-desiccation, as illustrated in Fig. 4.36. Figure 4.36a shows that an increase in the binder content will lead to increased development of suction in the CPB sample because this increases the binder hydration, so that a large volume of pore water is consumed, thus resulting in greater self-desiccation (Wu et al. 2014). Also, Fig. 4.36b shows that the binder type affects the degree of self-desiccation in the CPB samples. For example, the sample with PC I has a greater self-desiccation compared to the sample with PC I and slag or FA, which is most likely due to the fact that the rate of hydration changes with the type of binder, thus resulting in differences in the degree of self-desiccation (development of suction). Curing temperature can also affect the development of suction as higher temperatures increase hydration reactions, which in turn increases the rate of pore water consumption. This rapid consumption of the pore water increases self-desiccation (Wu et al. 2014). Therefore, it can be concluded that a combination of different factors (such as the coupled effects of curing temperature, binder content, sulphate content) can result in different degrees of self-desiccation (greater or less self-desiccation) in CPB materials, which in turn results in variations in the hydro-mechanical properties of CPB structures.

The effect of different external factors such as the curing stress, filling rate and drainage condition on the development of PWP is illustrated in Fig. 4.37. In mine backfills, the filling rate directly affects the PWP, stress regime and applied forces on the barricade. It can be observed that a faster filling rate (e.g. 0.61 m/h) produces a higher PWP in the samples. Another issue is mechanical damage induced by rapidly applied stress. Cemented paste subjected to excessive curing stress has a weak

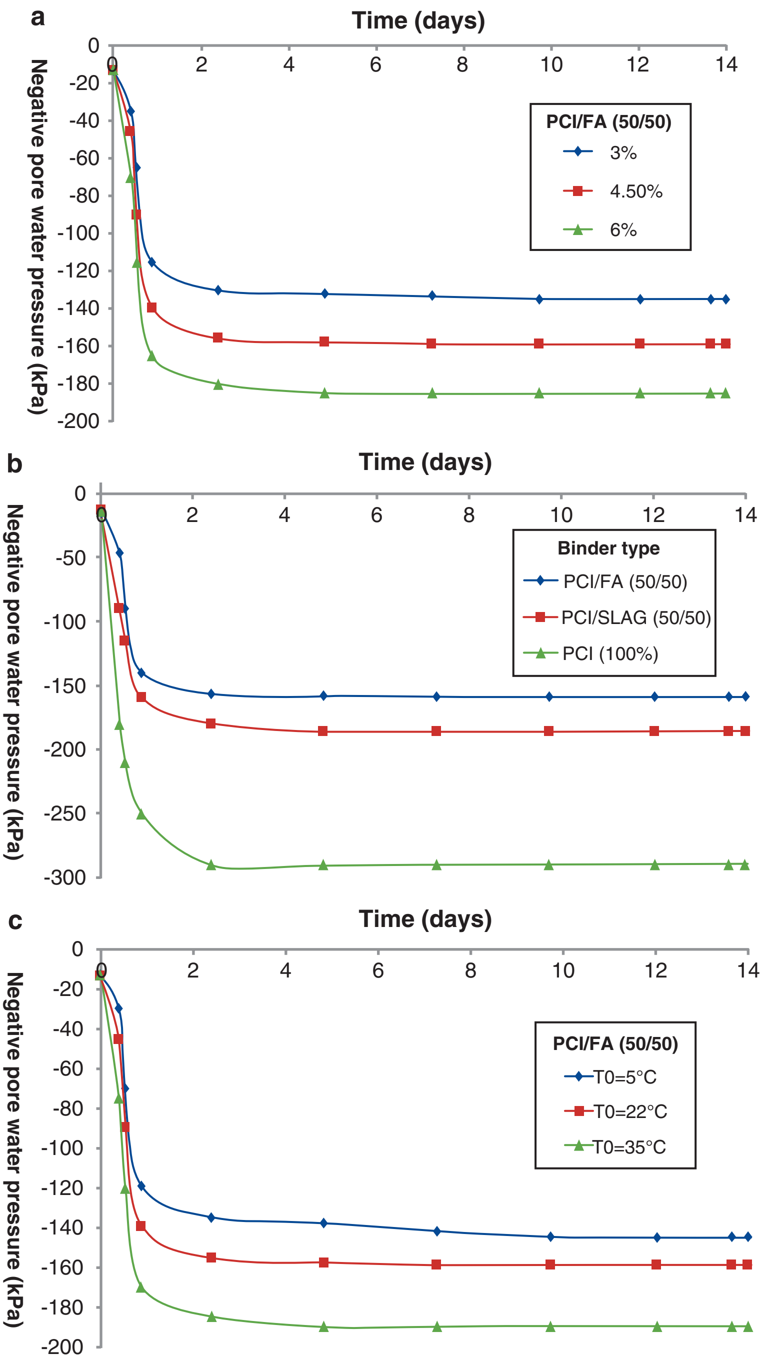


Fig. 4.36 Effects of (**a**) binder content, (**b**) binder type and (**c**) curing temperature on suction development due to self-desiccation in CPB (Wu et al. 2014)

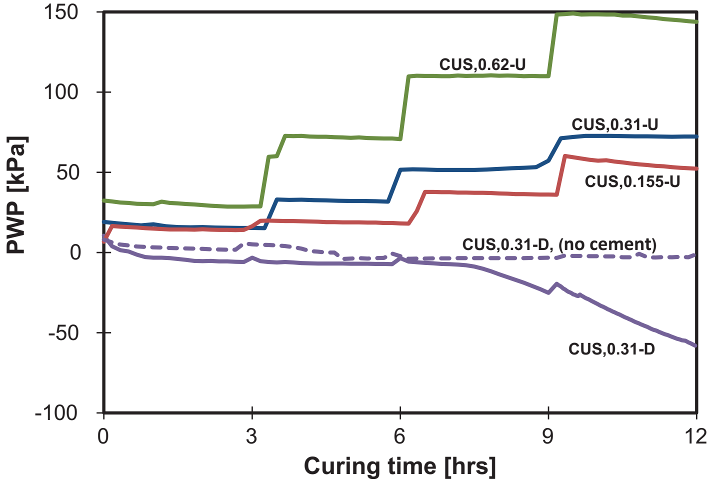


Fig. 4.37 Changes in pore water pressure of CPB samples cured under stress. Filling rates and drainage conditions obtained from load cell experiments (Ghirian and Fall 2016); (U: undrained conditions; D: drained condition); 0.31: filling rate of 0.31 m/h

microstructure at the early ages and thereby the points of contact between the cement hydration products and tailings/hydration particles during hydration are prone to damage due to the excessive stress. Also, it can be observed that the drainage condition has significant effects. For instance, the PWP is reduced for CUS 0.31-D (sample cured in drained condition), which is cured under stress (consolidated sample). The drainage condition also changes the positive PWP in CUS 0.31-D to a negative PWP (suction). These changes in suction can significantly increase the effective stress, which in turn leads to higher development of mechanical strength of the CPB. The results show the importance of drainage conditions on the stability of backfill and barricades (Ghirian and Fall 2016).

A review of the previous studies on the hydraulic properties of CPB shows that the hydraulic characteristics, such as saturated hydraulic conductivity, suction development (due to self-desiccation, drainage and evaporation), pore pressure changes and unsaturated properties of CPB, are important factors in the design and performance assessment of backfill structures and barricades.

5 Thermal Properties and Temperature Development in CPB and Influential Factors

The thermal properties and thermal processes of CPB materials are grouped into two main categories, including (1) the intrinsic thermal properties of CPB, such as the thermal conductivity, and (2) external thermal factors, such as the curing temperature and heat of binder hydration. Both are necessary to gain a better understanding of the thermal behaviour of cemented backfill structures. Thermal conductivity is required for the thermal analysis of CPB structures and heat transfer between the CPB and surrounding environment (rock mass, mine, etc.) (Celestin and Fall 2009).

There are some factors that do not significantly affect the thermal conductivity of CPB, as indicated in Celestin and Fall (2009), such as the binder type, binder content, curing age, *w*/*c* ratio and sulphate concentration of the tailings. However, there are many factors that affect the thermal conductivity of CPB, especially the tailings mineralogy (e.g. quartz content) (Celestin and Fall 2009; Ghirian and Fall 2013), and others, such as the fine content, curing temperature, porosity and degree of saturation. Figure 4.38 shows that the thermal conductivity of CPB increases with increased quartz content because the thermal conductivity of quartz is much higher than that of the many other available minerals found in tailings (e.g. $K = 7.7$ W/m °C for quartz, 2.25 W/m °C for feldspar) and other components of CPB (water and binder). Therefore, for a given CPB recipe, the tailings materials which contain less quartz or minerals with a high thermal conductivity will produce a less conductive material (Celestin and Fall 2009).

The thermal conductivity of the CPB also increases as the fine content of the tailings is decreased, as shown in Fig. 4.39, because an increased fine content reduces the packing density of the tailings, which in turn contributes to increasing the overall porosity of the hardened cement matrix (Celestin and Fall 2009).

However, the thermal conductivity of CPB decreases with an increase in the curing temperature, as shown in Fig. 4.40, due to the effect of the degree of saturation. CPB samples that are cured at a higher temperature (35 °C, 50 °C) have a higher rate of water consumption due to faster hydration. Furthermore, the samples most likely become more quickly desaturated with higher curing temperatures due to some

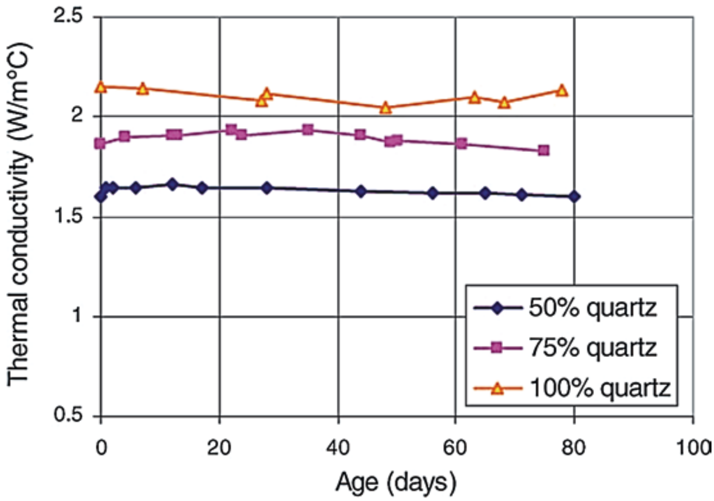


Fig. 4.38 Effect of mineralogical composition (proportion of quartz) of tailings on thermal conductivity of CPB (Celestin and Fall 2009)

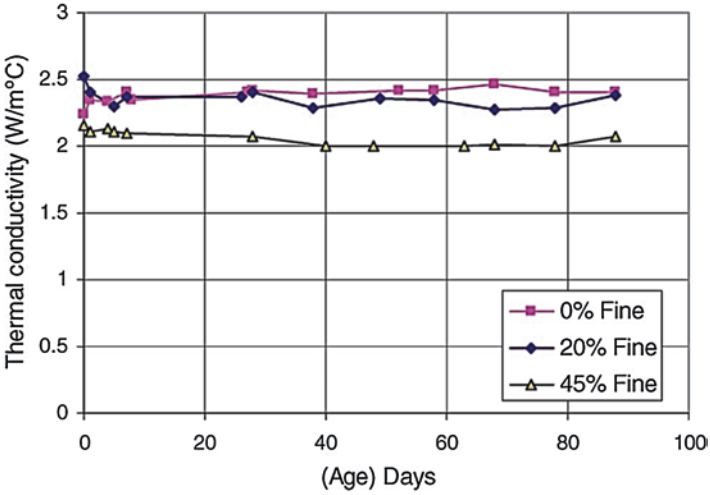


Fig. 4.39 Effect of tailings grain size with constant slump on thermal conductivity of CPB (Celestin and Fall 2009)

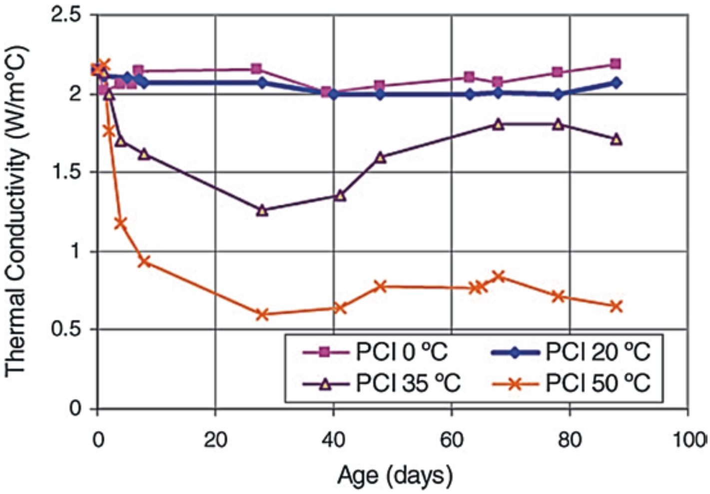


Fig. 4.40 Effect of curing temperature on thermal conductivity of CPB (Celestin and Fall 2009)

evaporation of the water from the pores. The combined effects of water loss caused by self-desiccation and evaporation reduce the degree of saturation. The degree of saturation of the samples cured at 2 °C and 50 °C is determined to be about 94 and 88%, respectively (Celestin and Fall 2009). Through desaturation, air substitutes the water in the pores, and since water has a thermal conductivity about 25 times that of air, it is obvious that when the air content is increased, the thermal conductivity of the CPB is reduced. This is shown in Fig. 4.41 (Ghirian and Fall 2013), which demonstrates that the degree of saturation significantly affects the thermal conductivity of CPB structures.

There are various sources of temperature variation (or thermal loads) in mine backfill operations. They comprise the heat generated by binder hydration, heat in the host rock and deep mines, the self-heating of sulphidic rock (and tailings), initial temperature of the CPB mix components and heat generated by blasting and mine fires. The rock temperature (i.e. hot rock temperature in deep mines and cold rock temperature in permafrost mines) mostly depends on the type of rock, depth of the mine and geographical location (Fall et al. 2010; Fall and Pokharel 2010). The self-heating of rocks/tailings is dependent on the type and quantity of sulphide and pyrrhotite minerals as well as accessibility to oxygen and water for oxidation (Bernier and Li 2003). Among the different sources of temperature variations in mine backfills, the heat produced by binder hydration is the most significant source of variation. Since CPB structures are usually massive, the temperature due to binder hydration can increase to 50 °C or even higher (Fall et al. 2010; Thompson et al. 2012). The amount of heat generated in the backfill depends on factors such as the *w/c* ratio, mixing water chemistry, and binder type and quantity. It can also be affected by external factors such as the stope size, binder content, filling rate and placement temperature (Nasir and Fall 2009).

This is demonstrated by column experiments carried out in Ghirian and Fall (2013), in which the changes in temperature with curing time for different heights of the column are presented in Fig. 4.42. The column is 1.5 m in height and filled with CPB. The temperature changes at the top, middle and bottom of the column were measured with a thermometer. For these three different depths of the column, the heat of hydration rapidly reaches the highest value after approximately 20 h of curing, and then remained constant for at least another 72 h. Afterwards, the temperature gradually decreased up to 7 days. It can also be seen in Fig. 4.42 that the temperature measurement taken close to surface of the column shows the lowest temperature compared to the rest of the column because a large amount of heat is lost through the evaporation process, which in turn reduces the temperature. Eventually, after moisture and thermal equilibrium is reached between the CPB and surrounding environment, the temperature at the surface becomes ambient. Details on the results and experimental method can be found in Ghirian and Fall (2013).

The literature review here shows that the thermal properties and behaviour of CPB materials are affected by several factors and processes, such as the physical properties of the tailings and degree of saturation. Moreover, the temperature variations due to binder hydration can be affected by the binder type and content. Temperature variations also significantly affect the hydromechanical and chemical properties or behaviour of CPB.

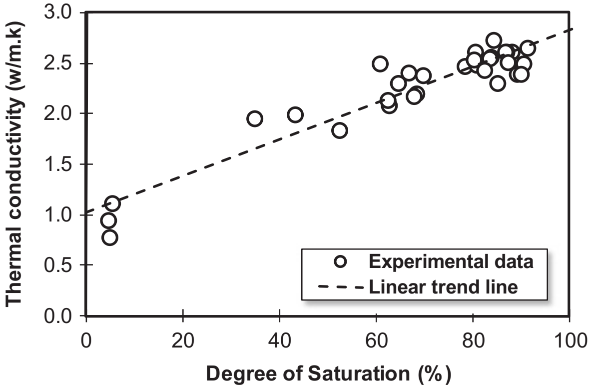


Fig. 4.41 Effect of degree of saturation on thermal conductivity of CPB (Ghirian and Fall 2013)

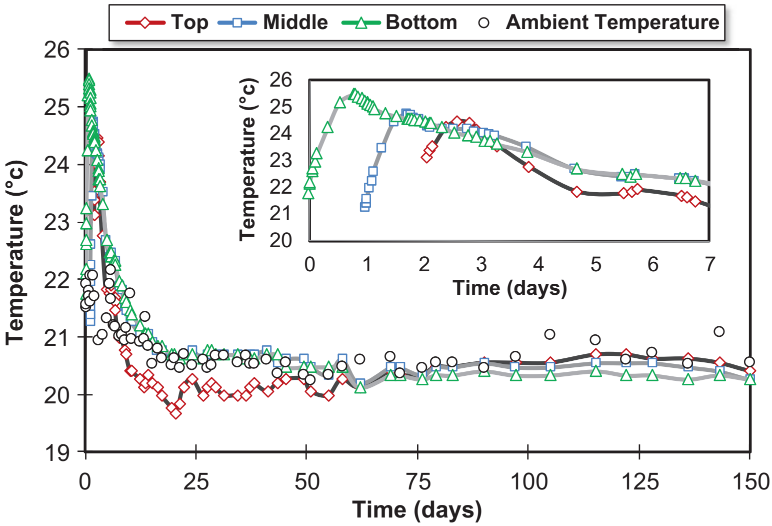


Fig. 4.42 Changes in temperature with curing time in column experiments (Ghirian and Fall 2013)

6 Chemical Properties of CPB and Influential Factors

The chemical characteristics and chemical processes of CPB are primarily controlled by the chemistry and mineralogy of its constituents, including the tailings, binder and mixing water. External factors such as the curing temperature (which has a strong effect) and curing stress (has a weak effect) can also influence the chemical properties or behaviour of CPB.

The chemical characteristics or chemical processes of CPB, in turn, can significantly affect the thermo-hydro-mechanical properties and processes in CPB structures. Therefore, understanding these coupled THMC processes is necessary when the stability and performance of a backfill structure are assessed. Also, this understanding provides valuable knowledge on the binder hydration reactions and processes in CPB, which can be used to examine the changes in the CPB materials and their behaviour when subjected to THMC loads and processes.

To do so, there are different ways and techniques to measure and monitor the chemical processes in CPB and the properties of CPB. For example, measuring the pore water chemistry (e.g. ion concentration analysis) can show the changes in the chemistry of a CPB sample. This approach is found in Ghirian and Fall (2014) in which a high-pressure pore water extractor apparatus was developed, and then used to analyse the pore water to study the different anion and cation concentrations in the solution, pH, etc. An example of the results is presented in Fig. 4.43, which are obtained from column experiments in Ghirian and Fall (2014). The figure shows the changes in the pore water solution of CPB with different chemistries which was mechanically extracted from different heights of the column, as well as the different curing times. More details can be found in Ghirian and Fall (2013, 2014).

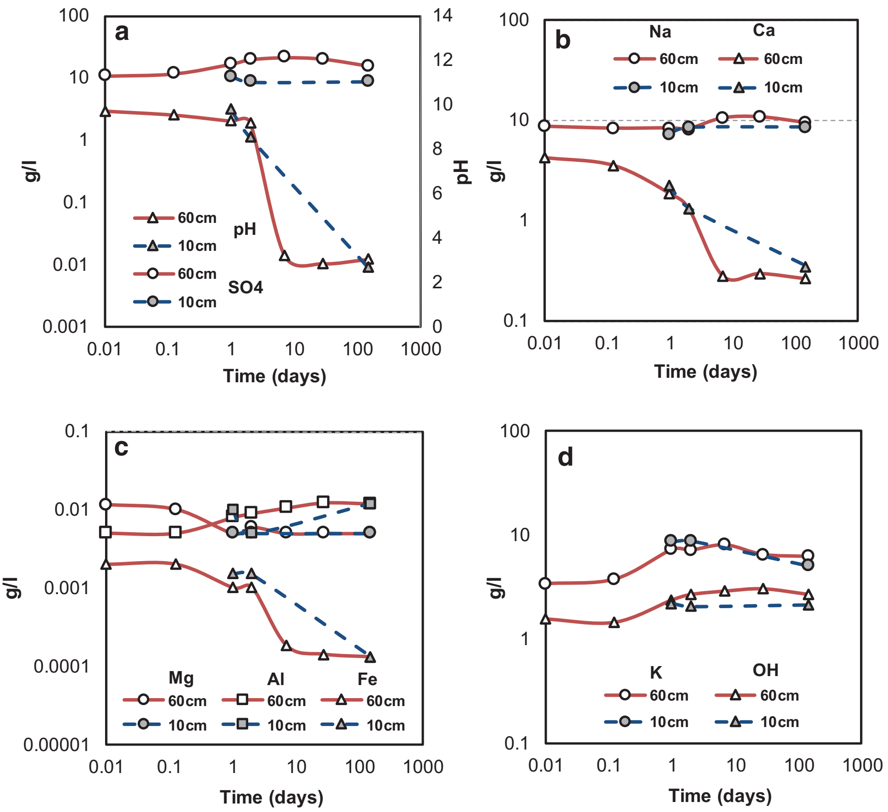


Fig. 4.43 Changes in ion concentration of pore fluid with curing time (Ghirian and Fall 2014)

Other techniques, such as analyses of cement dissolution and process water obtained from mine tailings, can also be subjected to chemical analysis when the effects of chemical processes on CPB properties and performance are being investigated (Benzaazoua et al. 2004). Some researchers used metal leaching tests to study the potential of metal generation of CPB made with arsenopyrite-rich tailings. These techniques can be used when the long-term geo environmental performance of a CPB structure needs to be investigated.

In addition to laboratory testing, other indirect techniques can also be used to study the chemical properties of CPB and chemical processes in CPB material, particularly when continuous monitoring of the chemical reactions with curing time is required. These also provide information on the setting time and rate of hydration of the CPB, as well as qualitative information on the total depletion rate of ions from the CPB pore solution. Successful field and laboratory applications of these techniques have been reported in Thottarath (2010) and Ghirian and Fall (2015), respectively. The change in the ion concentrations in the pore fluid of CPB as a result of cement hydration reactions can be measured by the electrical conductivity (EC) of the backfill. Figure 4.44 shows the changes in the EC of CPB with curing time and different sulphate contents (Li and Fall 2016). It can be observed that soon after mixing, the EC starts to gradually increase up to the peak value, regardless of the initial amount of sulphate. This increase in the EC is due to the ion concentration increase in the pore fluid as well as temperature increase as a result of exothermic cement reactions. The peak of the EC corresponds to the initial setting (transforming from the paste phase to the formation of the solid skeleton) of the backfill (Ghirian and Fall 2015). However, a longer time is required to reach the peak as the sulphate content is increased, because sulphate delays the hydration of the binder (Li and Fall 2016). Afterwards, the EC values start to decrease with time which is due to the reduction in the volume of unbound water as a result of self-desiccation and fewer connected capillary pores, which in turn increase the path of the ion flow (Ghirian and Fall 2015).

As explained above, changes in the chemical properties of CPB and chemical processes in CPB can significantly affect the other properties of CPB. For example, direct or indirect chemical processes can take place that affect the mechanical strength of backfill. In the former, CPB prepared with sulphide-rich tailings (e.g. pyrite) can be oxidised in the presence of oxygen (also called weathering). The degree of oxidation is mainly a function of the percentage of pyrite and degree of saturation. The weathering causes release of the metal ions and acid mine drainage into the environment (Ouellet et al. 2003). In the latter, the initial chemical compositions (e.g. sulphides, sulphate) in the CPB ingredients (i.e. tailings, binder and mixing water) can negatively affect the strength development of CPB due to sulphate attacks (Fall and Pokharel 2010; Li and Fall 2016). For example, sulphate in the initial CPB matrix can inhibit cement hydration reactions at the early ages and therefore reduce the strength (Fall and Benzaazoua 2005; Pokharel and Fall 2011). In advanced ages, the formation of secondary expansive minerals in the backfill pores, such as ettringite and gypsum, can cause internal cracks and eventually lead to strength deterioration (Fall and Benzaazoua 2005).

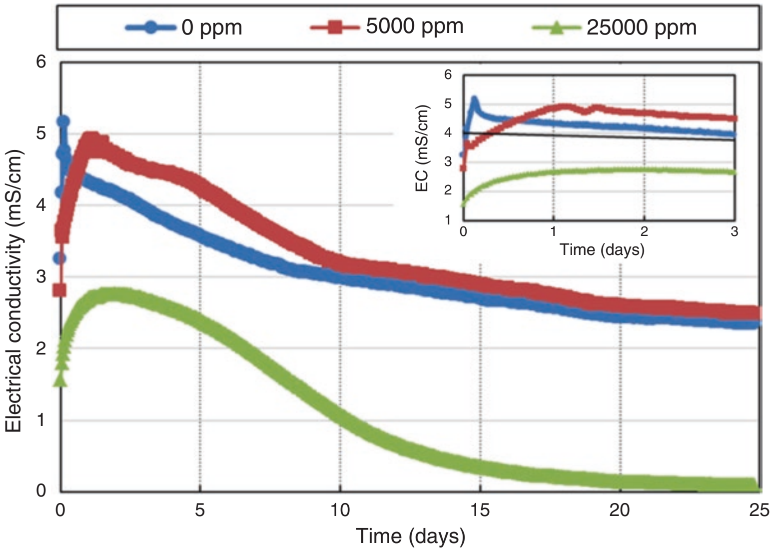


Fig. 4.44 Changes in electrical conductivity with curing time and different sulphate contents (Li and Fall 2016)

In the tailings chemical or mineralogical composition, the presence of sulphide minerals (e.g. pyrite) and sulphate ions as well as the chemical characteristics of the mixing water, which may have soluble sulphates, can affect the strength acquisition of backfill (Kesimal et al. 2005). Benzaazoua et al. (2004) used different types of binders (ordinary Portland cement (OPC), blast furnace slag and FA) with different chemical compositions, five types of tailings with different percentages of pyrite and sulphur, and mixing water with different percentages of soluble sulphate to prepare CPB samples. They found that the chemical properties of the three main components of the CPB are interrelated and play an important role in mechanical strength acquisition. Also, the chemical composition and concentration of dissolved ions in the pore water are the main factors that influence the hardening process in cemented materials (Benzaazoua et al. 2004).

7 Microstructural Properties of CPB and Influential Factors

The microstructural properties of CPB, such as the porosity, pore size distribution, interconnectivity of the pore system, and types and mechanisms of formation of hydration products, significantly influence the other properties of CPB materials, such as strength, durability and permeability (Fall and Samb 2008). An understanding of the microstructural properties of CPB is necessary to determine the main mechanisms and processes that take place during the hardening process of CPB.

There are different testing methods and techniques to examine the CPB microstructural properties, such as mercury intrusion porosimetry (MIP), thermal analysis

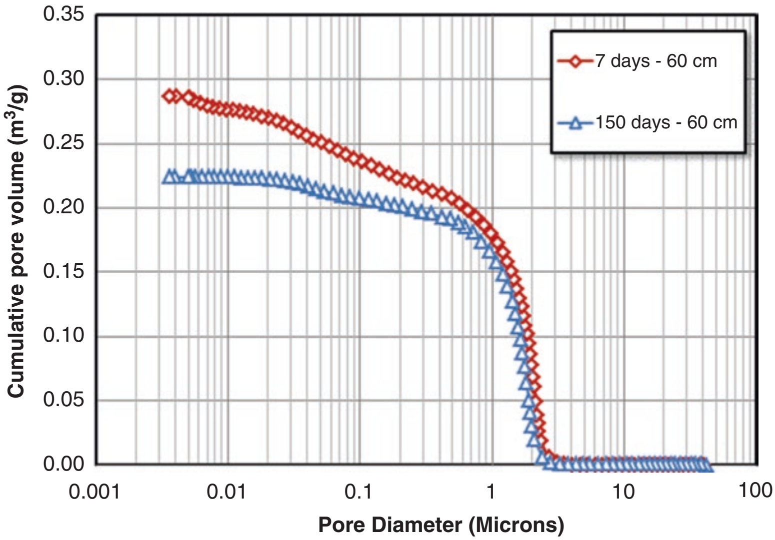


Fig. 4.45 MIP test results of column experiments with 7- and 150-day CPB samples (Ghirian and Fall 2013)

[differential thermal analysis/thermal gravimetric analysis (DTA/TGA)], X-ray diffraction (XRD) and scanning electron microscopy (SEM). MIP is used to study the pore size distribution and total porosity of the CPB materials, while DTA/TGA and XRD are used to study the mineralogy of CPB as well as the type and quantity of binder hydration products. SEM is a useful technique to visually identify the density and type of hydration product, and examine the pore structure, pore connectivity and microcracks in the CPB matrix. Figure 4.45 shows the results of MIP tests performed on 7- and 150-day CPB samples. The cumulative pore volume as a function of the pore diameter is compared. A sample cured for 150 days has a much lower cumulative pore volume compared to the 7-day sample, which means that the former has a finer pore size distribution (Ghirian and Fall 2013). Figure 4.46 shows the changes in the pore structure of the samples cured for 7 and 150 days with time. The refinement of the CPB pores at an advanced age (150 days) is mainly due to the increases in cement hydration products such as C–S–H, CH and ettringite with time as shown in the SEM images. Figure 4.47 presents the mineralogical composition of cement paste samples (after undergoing XRD) performed on 28-day cement paste with a sulphate content of 25,000 ppm and without sulphate. It can be observed that more ettringite is produced in the cured sample with a sulphate content of 25,000 ppm compared to that with no sulphate. Also, the plot shows that the peak intensities of C–S–H and CH are higher in the cemented paste with no sulphate as opposed to the samples with sulphate, which means that greater proportions of C–S–H and CH have formed in the sample with no sulphate. Therefore, this can lead to higher strength in the sample (Li and Fall 2016).

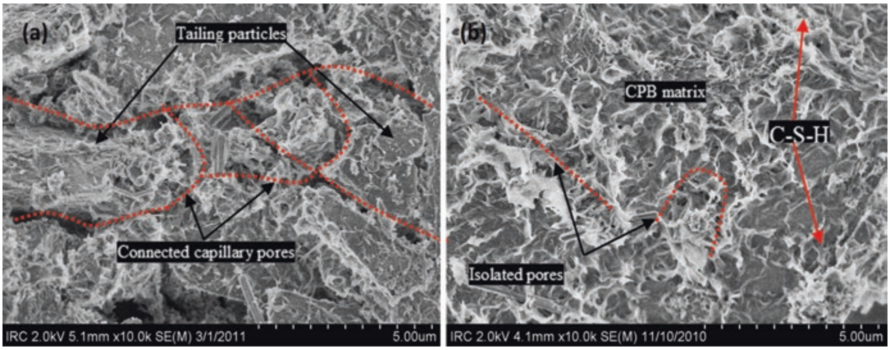


Fig. 4.46 SEM images of CPB microstructure after (**a**) 7 days and (**b**) 90 days of curing (Ghirian and Fall 2013)

Figure 4.48 shows the results of a thermal analysis performed on 7-day cement paste samples cured at different temperatures (20 °C, 35 °C). Generally, typical peaks can be seen in the temperature range of 50–150 °C, and at 450 °C and 750 °C. These peaks indicate the presence of C–S–H gel, ettringite, CH and calcite (CaCO3). Furthermore, it can be observed that a high curing temperature significantly increases the hydration rate of the cement paste. This is demonstrated by the increase in the amount of C–S–H, ettringite, CH and CaCO3 formed with increased curing temperature. This means that weight losses at the temperature range of 50–150 °C and at 450 °C and 750 °C are greater with higher curing temperatures (Fall and Samb 2008).

The results of these studies show that the mix components (such as *w/c* ratio, cement type and proportion, tailings grain size), curing time, curing temperature, sulphate content and curing stress significantly affect the pore structure of CPB materials.

8 Primary Coupled THMC Processes and Factors in CPB

In this section, the importance of coupled THMC processes or factors in understanding the properties and behaviour of CPB is discussed and highlighted, which contribute to the cost-effective designs of CPB structures. The coupled processes that mainly occur in the geotechnical systems of CPB poured into mine stopes can be classified as thermal (T), hydraulic (H), mechanical (M) and chemical (T) processes or factors. These factors are related and coupled (interact). The magnitude of the effect of coupling in one direction may be different from that in the opposite direction. Therefore, coupled factors have either weak or strong interactions. Strong interactions control the geotechnical performance of backfill structures. Figure 4.49 schematically illustrates the primary THMC processes in CPB structures as well as the strong and weak interactions between these processes.

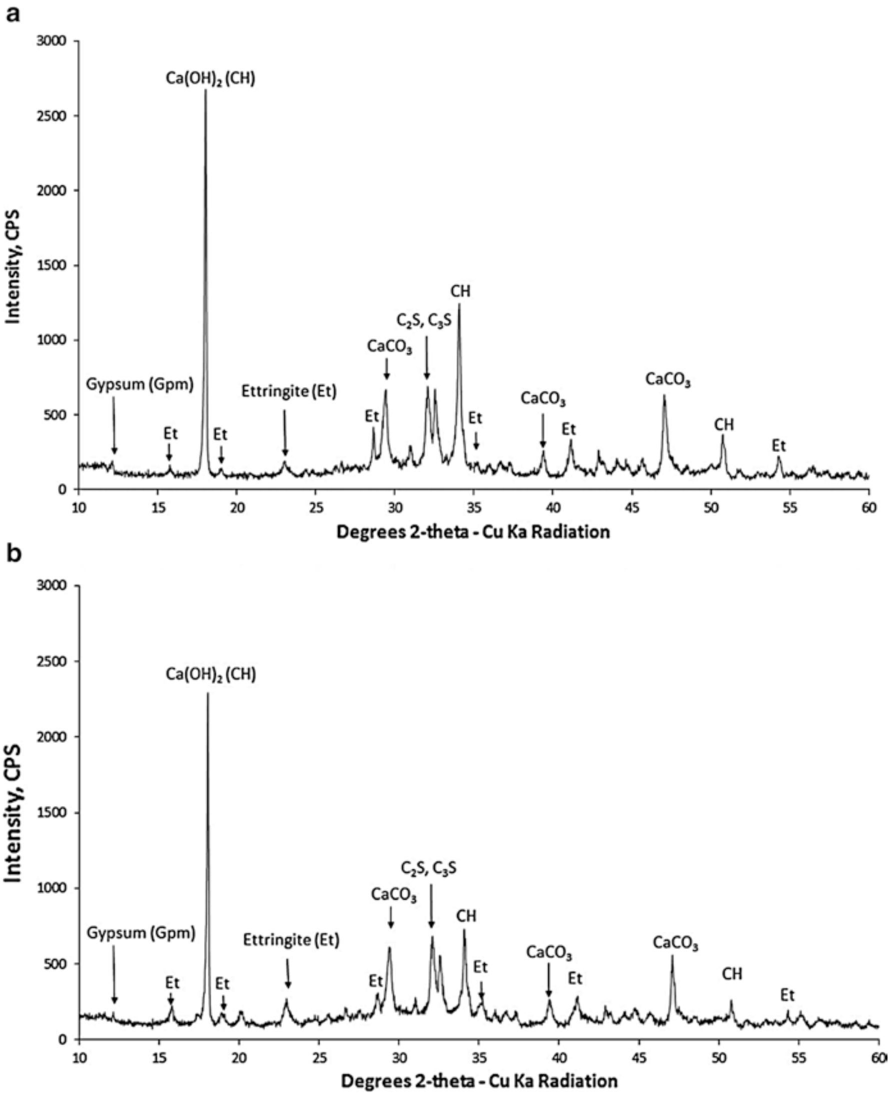


Fig. 4.47 XRD plots of cured cement paste samples with sulphate content of (**a**) 0 ppm and (**b**) 25,000 ppm at 28 days (Li and Fall 2016)

The primary THMC interactions are summarised below. It should be noted that although these are the most important interactions that can take place in a backfill structure, there are also others that are relevant.

- $T \rightarrow H$: The primary source of temperature increase in mine backfill is from binder hydration reactions. A higher temperature induces the rapid development of suction and reduction of the PWP in mine backfills. Also, temperature increases can lead to a reduction in the transportability of backfill in the fluid state because the rates of binder hydration and pore refinement of CPB are both increased.

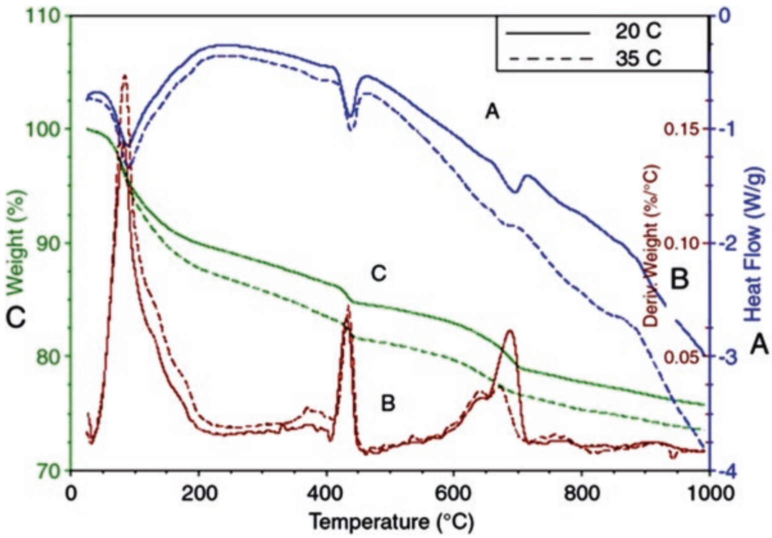


Fig. 4.48 Thermal analysis on CPB samples with *w*/*c* = 2 (Fall and Samb 2008)

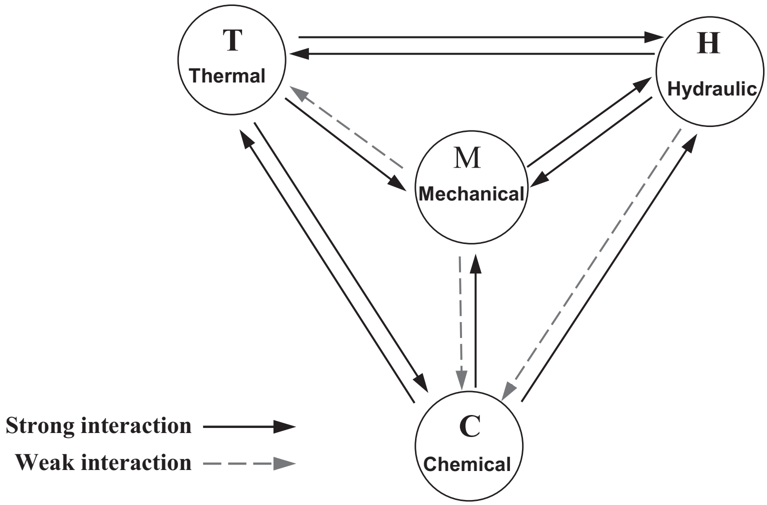


Fig. 4.49 Primary multi-physics processes in CPB material and their interactions

- $T \rightarrow M$: Temperature increases in mine backfill will increase the rate of binder reaction, which in turn leads to the production of more cement hydration products. More hydration products result in a finer and denser CPB pore structure, which consequently delivers higher mechanical and shear strength properties to CPB.
- $T \rightarrow C$: Temperature increases in a CPB structure can induce a faster rate of binder hydration. This is a strongly coupled interaction that influences the chemical concentration of pore water as well.

- $H \rightarrow T$: Hydraulic factors, such as the degree of saturation, directly influence thermal factors, such as the thermal conductivity of backfill. Reductions in the degree of saturation (or desaturation—increase of air voids in the CPB matrix) due to self-desiccation and/or evaporation reduce the thermal conductivity of backfill.
- $H \rightarrow M$: Suction development as a result of self-desiccation can affect the mechanical properties. Self-desiccation induces suction as a result of binder reactions and thereby results in the decrease of the PWP and increase in the effective stress (strength increase).

Evaporation as a hydraulic factor also results in the development of surface shrinkage and associated microcracks. The presence of microcracks then reduces the mechanical strength of CPB by creating preferential failure planes of weakness in the CPB structure. This process is considered to be weak interaction as long as the CPB remains in a saturated or near-saturation state, or the air-backfill interface cannot be identified in the mine stope.

- $H \rightarrow C$: Hydraulic factors, such as drainage, evaporation and self-desiccation, can indirectly influence ion concentrations in pore fluid. Removing water from the CPB pore structure results in increases in ion concentration by reversing the dilution effect. This is a weak interaction.
- $M \rightarrow T$: Not a significant interaction.
- $M \rightarrow H$: Consolidation is a strongly coupled interaction that can take place in mine backfill. Backfill is consolidated under the pressure of its own self-weight in drained conditions. During this process, the water expelled from the CPB pores lead to a reduction in the PWP. A reduced PWP increases the effective stress in the CPB, which is similar to curing backfill under stress, and significantly contributes to the strength improvement of CPB. Consolidation also reduces the porosity of backfill, which results in reduction of permeability.

Mechanical damage can induce microcracks. Crack propagation at a micro-scale might be found in CPB cured under (excessive) sustained stress. The connected microcracks act as preferential liquid paths in CPB, which results in decreases in tortuosity, and increases in the permeability.

- $M \rightarrow C$: Curing under stress induces a slightly faster rate of binder hydration. However, due to the relatively low amount of stress in the backfill, the effect of stress on the rate of hydration is not significant. This can be considered as a weak interaction in the backfill.
- $C \rightarrow T$: Binder hydration reactions are an exothermic reaction. Therefore, cement hydration produces heat and increases the temperature in mine backfill. This is one of the most important and strong interactions in CPB.
- $C \rightarrow H$: Binder hydration reactions, as a chemical factor, directly influence the porosity of mine backfill. Binder reactions produce hydration products, such as CH and CSH, and therefore cause refinement of the pore structure of backfill. A lower porosity results in reduced water permeability in backfill. This is therefore a strong reaction in CPB.
- $C \rightarrow M$: As explained above, binder hydration reactions cause pore refinement. A lower porosity also increases the mechanical strength of backfill. Furthermore,

as binder hydration progresses, cement hydration products (e.g. C–S–H, CH) are produced, which facilitate cohesive strength in CPB. This is therefore a strong interaction.

THMC-coupled processes in CPB material mostly take place as changes in the intrinsic properties. However, several external factors can also induce and/or initiate a process. A comprehensive list of the main coupled THMC factors and the main intrinsic and external factors that can affect them is shown in Table 4.1. Some related sources for each individual interaction are also provided in the table for reference purposes. Also, Fig. 4.50 illustrates the primary and important THMC processes and factors that control and affect the CPB properties and performance.

9 Conclusion

A comprehensive review of the properties of CPB materials and the factors that can affect them has been provided in this chapter. A summary of the obtained results from testing carried out in previous studies and recent laboratory and field experiments has been outlined. The findings are relevant for understanding how these properties change in backfill, as well as how they can affect the overall behaviour and performance of cemented backfill and the degree that they do so. The properties of CPB are mainly affected by thermal, hydraulic, mechanical and chemical factors and processes, as well as physical and microstructural characteristics. Physical (such as porosity, void ratio, degree of saturation, density), mechanical (such as compressive and shear parameters, stress–strain behaviour); hydraulic (such as saturated and unsaturated permeabilities, suction development due to self-desiccation, pore pressure), and thermal (such as thermal conductivity, heat of binder hydration)

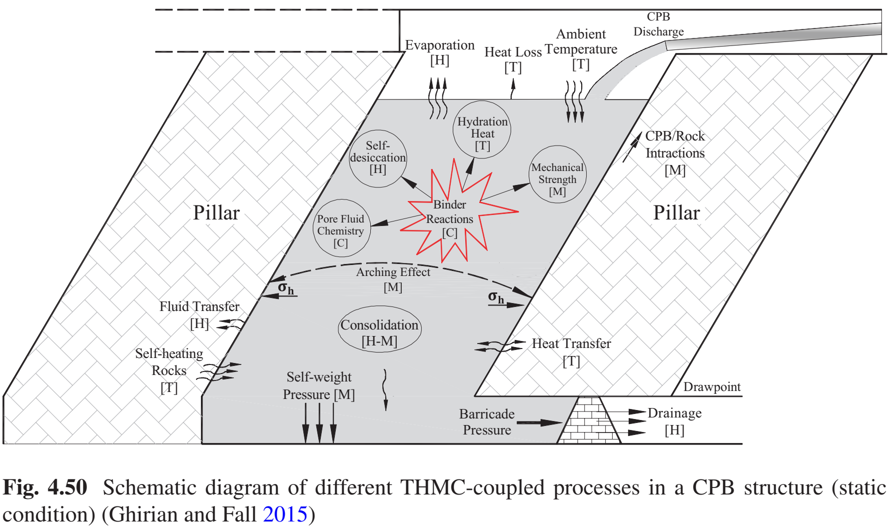


Fig. 4.50 Schematic diagram of different THMC-coupled processes in a CPB structure (static condition) (Ghirian and Fall 2015)

Table 4.1 Coupled THMC processes and factors that affect behaviour of CPB structures

Process/factor		Source	Influential property/parameter[a]		Source
			Intrinsic property	Parameter	
Thermal (T)	Intrinsic thermal properties	Thermal conductivity and heat capacity	Tailings type and fine content; CPB porosity and degree of saturation	–	Celestin and Fall (2009), Ghirian and Fall (2013)
	Thermal loading	Heat of binder hydration	Chemical reactions, binder content and type	Stope size, filling rate	Nasir and Fall (2009), Fall and Pokharel (2010), Fall et al. (2010); Fall and Samb (2009), Pokharel and Fall (2013), Wu et al. (2012)
		Self-heating mechanism	Host rock mineralogy, oxidation and chemical reaction		
		Environment temperature (cold/hot mining)	–	Geographic location, mine depth	Orejarena and Fall (2008)

Hydraulic (H)	Intrinsic hydraulic properties/factors	Saturated and unsaturated hydraulic conductivities	Porosity; intrinsic permeability; degree of saturation; water retention properties	Binder content and type; tailings fine content; temperature	Abdul-Hussain and Fall (2011), Fall et al. (2009), Ghirian and Fall (2013)
		Suction	Self-desiccation, cement reaction rate; temperature	Drainage	Ghirian and Fall (2013), Li and Fall (2016)
		Pore pressure	Consolidation	Drainage, consolidation	Ghirian and Fall (2015)
		Evaporation	Ambient humidity and temperature	Geographical location; depth of mine; exposed backfill	Ghirian and Fall (2013)
	External hydraulic loading	Groundwater flow (after mine closure)	–	–	Levens et al. (1996)
Mechanical (M)	Intrinsic mechanical properties/factors	UCS; shear strength; deformation	Porosity; tailings fine content; binder type/content; density of tailings; sulphate content; *w/c* ratio; self-desiccation	Curing stress; external heat	Fall et al. (2004), Benzaazoua et al. (2004), Fall et al. (2005, 2007, 2008, 2010), Fall and Pokharel (2010), Li and Fall (2016)
		Consolidation	Hydraulic conductivity; self-desiccation	Drainage; filling rate	Ghirian and Fall (2014, 2016)
		Shrinkage and cracks	Evaporation	Sustained stress	Ghirian and Fall (2014)
	Mechanical loading	Self-weight pressure	Backfill density	Drainage; filling rate	Yilmaz et al. (2009), Ghirian and Fall (2015)
		Stress regime and arching	Consolidation	Stope geometry; drainage condition	Yilmaz et al. (2015)
		Traffic loads	–	Stope design	Belem and Benzaazoua (2008)

(continued)

Table 4.1 (continued)

Process/factor		Source	Influential property/parameter[a]		Source
			Intrinsic property	Parameter	
Chemical (C)	Intrinsic chemical properties/factors	Pore fluid chemistry	Chemical reactions; binder content; binder type, sulphate content	–	Ghirian and Fall (2014)
		Electrical conductivity	Cement reactions; tailings chemistry, temperature	–	Thottarath (2010); Li and Fall (2016)
		Tailings and chemical composition of mixing water	Tailings/water mineralogy and chemistry	–	Benzaazoua et al. (2004)
		Rate of chemical reaction	Stress; binder content and type; temperature	–	
	Chemical loading	Sulphate effect	Sulphate concentration; temperature	–	Li and Fall (2016)
		Tailings reactivity; leaching	Tailings mineralogy and chemistry	–	Fall and Benzaazoua (2005); Pokharel and Fall (2011), Coussy et al. (2011)

[a]Only key influencing factors shown, other factors may also have effects

factors, as well as the microstructural properties of CPB, belong to the most important internal factors that control CPB behaviour. Furthermore, it has been shown that several external factors (or at the field scale) also influence the properties of CPB, such as self-weight pressure, external heat, drainage of the stope and self-heating rock masses. It has been shown that all of these THMC processes and factors are related and control the CPB behaviour. Information on the CPB properties and the factors that influence them will provide a better understanding of the THMC-coupled processes in CPB and their behaviour, and contribute to the designing of safe, economical and durable backfill structures.

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