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Review

A review of binders used in cemented paste tailings for underground and surface disposal practices

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A B S T R A C T

Increased public awareness of environmental issues coupled with increasingly stringent environmental regulations pertaining to the disposal of sulphidic mine waste necessitates the mining industry to adopt more competent and efficient approaches to manage acid rock drainage. Cemented paste tailings (CPT) is an innovative form of amalgamated material currently available to the mining industry in developed countries. It is made usually from mill tailings mingled with a small amount of binder (customarily Portland cement) and water. The high cost associated with production and haulage of ordinary Portland cement and its alleged average performance as a sole binder in the long term (due to vulnerability to internal sulphate attack) have prompted users to appraise less expensive and technically efficient substitutes for mine tailings paste formulations. Generally, these binders include but are not limited to sulphate resistant cements, and/or as a partial replacement for Portland cement by artificial pozzolans, natural pozzolans, calcium sulphate substances and sodium silicates. The approach to designing environmentally efficient CPT is to ensure long-term stability and effective control over environmental contaminants through the use of composite binder systems with enhanced engineering properties to cater for inherit deficiencies in the individual constituents. The alkaline pore solution created by high free calcium rich cement kiln dust (CKD) (byproduct of cement manufacturing) is capable of disintegrating the solid glassy network of artificial pozzolans to produce reactive silicate and aluminate species when attacked by (OH^-) ions. The augmented pozzolanic reactivity of CKD–slag and CKD–fly ash systems may produce resilient CPT. Since cemented paste comprising mine tailings and binders is a relatively new technology, a review of the binding materials used in such formulations and their performance evaluation in mechanical fill behaviour was considered pertinent in the study.

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1. Introduction

In Canada and several other industrialized countries, issues pertaining to environmental regulatory compliance have become the impetus for comprehensive engineering design and effective management of mining, other wastes and industrial by-products. This has resulted in a renewed interest within the mining industry to explore and evaluate innovative strategies for managing potentially acid generating mining waste.

The environmental impacts of acid rock drainage (ARD) have been well documented in the literature (Down and Stocks, 1977; Ritcey, 1989). The oxidation of iron bearing minerals, in particular the iron sulphides (pyrite and pyrrhotite), produces rock mine drainage (Yanful and Verma, 1999). High reactivity of the iron bearing minerals in the presence of oxidizing fluids coupled with abundant sulphides contained in mining wastes leads to highly acidic drainage.

ARD prevention and control practices are generally based on the anticipated future use of land, as well as on technical, economic, and environmental considerations. These techniques aim at restricting the principal components of the acid generation process (i.e. sulphides, oxygen, and water). The most common approach is under-water storage of tailings such as in constructed surface impoundments and flooded pits (Samad and Yanful, 2005). In order to prevent oxygen ingress in mine waste, researchers have recommended application of covers constructed from low permeability soils, synthetic materials, organic substances and composites (Yanful et al., 1993), oxygen-consuming materials, such as wood waste, straw mulch, etc. (Tassé et al., 1997; Cabral et al., 2000) or capillary barrier materials relying on the high moisture-retention

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capacity (Nicholson et al., 1989). The other control techniques include: (a) segregation of sulphides or desulphurization (Benzaazoua et al., 2008), (b) alkaline amendment, i.e., addition of alkaline materials to control the pH of pore waters (Duchesne and Doye, 2005), and (c) biological treatment, i.e. application of bactericides to inhibit bacterial action (Kim et al., 1999).

In some recent high profile mining projects in the United States and Canada, the alleged adverse environmental impacts associated with conventional approaches to reactive tailings management have led to the abandonment of otherwise feasible ventures (Landriault et al., 1997a). Contrary to the conventional thickened tailings for surface disposal applications, binder agents impart chemical stabilization and physical solidification of CPT. This approach is particularly beneficial for environmentally protected disposal of sulphide mine waste because it can minimize (depending on the binder) the subsequent mobilization of potentially toxic heavy metals and arsenic (As) (Benzaazoua et al., 2004a; Coussy et al., 2012).

Current approaches in mine tailings management, especially in North America, have been influenced most significantly by legislation resulting from mishaps associated with tailings storage facility failures (Cincilla et al., 1997). The cemented paste backfill (CPB) technology was implemented for the first time in 1957 by Falconbridge Nickel Mines Ltd. at the Hardy mine in Sudbury (Espley et al., 1970) and Bad Grund Mine in Germany in late 1970s (Lerche and Renetzeder, 1984). Presently, the Canadian and Australian mining industries are probably leaders in the use of paste technology (Rankine and Sivakugan, 2007).

Cemented paste tailings (CPT) is a pumpable, flowable, non-Newtonian fluid generally consisting of mine tailings, water and ordinary Portland cement. It is normally prepared from dilute slurries of tailings by dewatering it with conventional thickening or filtering. Cemented paste is generally a high density non segregating mixture that contains 70–85% solids by total mass and enough fines (at least 15% particles less than 20 microns) to prevent settlement (negligible bleed water) and particle segregation when transported through a pipeline for disposal (Landriault, 1995; Klein and Simon, 2006). An eminent feature of paste backfills is high water content, which is usually far in excess of hydration requirements of cementitious materials. The paramount reason for such a high w/c ratio (customarily between 2.5 and 7%) is the requisite consistency and flowability in order to transport the paste through pipe lines by pumping (Ramlochan et al., 2004). In contrast, ordinary cement concrete and mortars are commonly designed with a w/c ratio under 0.5 (Mehta, 1999; Malhotra and Bilodeau, 1999). Consequently, the resultant paste backfill matrix can have significant disparity in material properties in comparison with ordinary concretes and mortars. These properties include but not limited to compressive strength, density, porosity, hydraulic conductivity, and microstructure of hardened pastes (Ramlochan et al., 2004; Ouellet et al., 2007; Godbout et al., 2007; Fall and Samb, 2008).

CPT is a composite material whose physical, microstructural and mechanical properties evolve from concoct to its hardening. Typically, after a long-term curing time (longer than conventional concrete and mortars), the paste backfill transforms to a material with physical characteristics between a hard soil and a soft rock (Belem et al., 2000). The material properties (mechanical strength, permeability, etc.) and the contaminants containment capability of the cemented paste can be readily achieved as well as modified by the addition of binder reagents. The selection of binder material (s) largely depends on the disposal scenario (underground or surface) and desired engineering (mechanical) properties of the resultant monolith. In addition, the required environmental control over the leachability of pollutants (metals and arsenic) can also be achieved.

2. Underground disposal of cemented paste tailings and associated benefits

The environmental and economic performance of underground mining operations requires the return of the possible amount of potentially acid generating tailings underground in the form of CPB. Several investigators have highlighted the potential advantages associated with CPB in underground mining operations and have considered it to be indispensable for most underground mines (Benzaazoua et al., 1999, 2002; Hassani et al., 2001; Kesimal et al., 2004; Fall and Benzaazoua, 2005; Ouellet et al., 2006, 2007; Ercikdi et al., 2010). CPB (underground disposal) technology has a number of advantages over other mine tailings management strategies including: (a) deposition into voids created by mine stopes, thus providing an enhanced level of local and regional stability to the ore body in addition to providing a suitable and economical disposal of mining associated waste (Rankine and Sivakugan, 2007); (b) about 60% decrease in the amount of sulphidic waste that has to be disposed on the surface (Benzaazoua et al., 2004a), thus reducing pollution and negative environmental impacts; (c) increase in the available ore reserves by acting as secondary ground support pillars favouring mine stability (Benzaazoua et al., 2004b); and (d) absence of free water in the paste fill system thereby avoiding drainage requirements during curing period and resulting in faster stope cycle time. In underground mining applications, paste backfill can serve as a construction material to create a floor to mine on top of, a wall to mine next to, and a roof or head cover to mine under (Landriault et al., 1997b).

3. Surface disposal of cemented paste tailings and allied benefits

CPT has also been proposed as an innovative approach for surface tailings disposal (Deschamps et al., 2008; Cincilla et al., 1997; Verburg, 2002; Theriault et al., 2003; Shuttleworth et al., 2005; Bussière, 2007). The key benefits of this approach include: (a) improved tailings hydro-geotechnical properties, (b) small amount of free water at the paste surface thereby reducing the dimensions of tailings-retaining structures in the case of underwater storage, (c) homogeneity of paste induces less particles segregation, (d) enhanced strength and durability of the resultant monolith, (e) development of acid neutralization potential and contaminants stabilization capability of the matrix due to addition of alkaline binders (Benzaazoua et al., 2002, 2004a; Cadden et al., 2003).

4. Prospective environmental benefits linked with cemented paste tailings technology

The environmental benefits of cemented tailings paste technology include: (a) solidified monolith of hardened paste encapsulates potentially mobile contaminants (metallic and metalloid elements) thereby reducing prospective negative impacts on receiving water bodies (Benzaazoua et al., 2004a) and biota; (b) alkaline cementing agents provide chemical stabilization and transformation of the pollutants within the paste matrix; (c) low leachate generation due to the colloidal water retention capabilities and extremely low permeability of cemented paste; and (d) decrease in sulphide reactivity due to the high degree of saturation in CPT and/or the formation of oxidative layers (Ouellet et al., 2006). Another benefit of CPT technology is the possibility of co-disposal of mine tailings with a range of industrial byproducts or wastes that can be otherwise chemically challenging for the ecosystem if stockpiled (Landriault et al., 1997a; Benzaazoua et al., 2004a).

5. Binding agents for cemented paste tailings formulations

5.1. Portland cements

Portland cement (CSA Type GU or ASTM Type I) has been the most extensively used binding agent due to its availability and versatility. It has a long history of being considered an adequate solution to mining waste management problems including the disposal of sulphidic tailings (Weaver and Luka, 1970; Aylmer, 1973; Manca et al., 1983; Atkinson et al., 1989; Lamos and Clark, 1989; Benzaazoua et al., 2004a; Rankine and Sivakugan, 2007; Grabinsky et al., 2007).

The binder is used principally to develop sufficient mechanical strength for the paste backfill to meet certain dynamic and static load resistance requirements. In cement based solidification, water in the waste chemically reacts with Portland cement to form hydrated calcium silicate and aluminate compounds, while the solids act as aggregates to form 'concrete' (Conner, 1993). The addition of Portland cement (PC) has been found to enhance the cohesive component of the shear strength, impart tensile strength and intensify the stiffness of mine tailings paste, while the other granular tailings materials provide shear strength (Hassani et al., 2007a; Ouellet et al., 1998). The structural development of PC based solidified waste results in hydration reactions that stiffen and densify as a monolith and impart reasonable structural integrity to the solidified waste. The dominant hydration phases under normal conditions are (a) 60–70% of calcium silicate hydrate (C-S-H), a gel of variable stoichiometry, (b) 20–25% of calcium hydroxide [$Ca(OH)_2$] or portlandite, and (c) 15–20% of gypsum, ettringite, and calcium aluminates (Taylor, 1990).

Sulphate resistant Portland cement (CSA Type HS or ASTM Type V) was developed principally by increasing the iron content (Fe_2O_3) in raw materials in the Portland cement (PC) production processes. Sulphidic CPT containing PC as a sole binder has been established to be vulnerable to internal sulphate attack (Benzaazoua et al., 1999, 2002; Hassani et al., 2001; Fall and Benzaazoua, 2005). Sulphates present in mine tailings pastes perform various functions depending on their concentrations. Such sulphates can contribute to early strength gain by virtue of filling pores with hydrated cement products and through the precipitation of hydrated sulphates along with modification of pore-structure (Benzaazoua et al., 2004b). However, depending on sulphate concentration, cement proportion, and curing time, the positive effect of strength acquisition due to the presence of sulphates can have a negative effect (Fall and Benzaazoua, 2005). In internal sulphate attack, hardened mortars and concrete deteriorate by the action of sulphates present in the original mix in excessive amount, or in those formed from sulphur compounds other than sulphates (Skalny et al., 2002). With regards to the internal sulphate attack in cementitious matrix such as CPT, the composition of the cement is potentially an important factor. Sulphate-related deterioration is generally related to the C_3A content of the cement, with more deterioration typically occurring with higher C_3A content. The low C_3A concentrations reduce the formation of expansive 'ettringite' in sulphate resistant cement concrete materials and hence lessen the damage of hardened mortars and concrete deterioration caused by the sulphates (Puppala et al., 2004; Irassar et al., 2000). However, it should be noted that utilizing specialty cements such as Type HS cement is relatively an expensive option.

Kesimal et al. (2004) determined the strength gain of the tailings with the addition of PKC (Portland composite cement)/B-type binder currently used in the paste plant in Turkey. Additionally, PKC/A-type binder was chosen to compare the tailings in terms of strength gain. It was found that for high sulphide bearing tailings, neither binder was effective nor suitable to provide adequate long-term strength for paste backfilling operations, although paste backfill samples developed high early strength at 28 days of curing. The main conclusion made from this experimental study was that the presence of sulphide-rich compounds can causes deterioration in the hardened paste matrix due to sulphate attack.

Benzaazoua et al. (2004a) investigated the geochemical behaviour of European gold mine tailings CPB. It was observed that the dissolution of portlandite (which forms in excess in lime rich mixtures) was coupled to the precipitation of arsenic containing compounds (calcium arsenates), which immobilizes this toxic element. The transfer of contaminants outside paste samples was minimized due to the low permeability of the paste and the in situ precipitation of calcium sulphates and arsenates. Deschamps et al. (2008) stabilized sulphide-rich acid generating mine tailings (Acidity Potential = 953 kg of $CaCO_3$/t) using surface paste technology by adding 2 wt% of PC. The pH of the leachate from column tests remained above 8 during the entire 30 weeks of the experiment, while the pH of the uncemented tailings became acidic and reached approximately 4 at the end of the leaching tests. These results demonstrated that surface paste disposal could be an effective method to manage acid generating tailings through the addition of small amounts of binder. However, detailed field scale and long-term tests were identified by the authors to be necessary before field application.

5.1.1. Incentives to curtail Portland cement use in sulphidic cemented paste tailings formulations

5.1.1.1. Portland cement price and haulage cost. Binder cost represents a significant fraction of the operational cost of mining operations. Literature substantiates that approximately 69% of the total underground mining operations in Ontario (~65% in Canada) employed some form of backfill support (Mining Sourcebook, 1994). According to Hassani et al. (2007b), backfill accounts for approximately 20% of underground mining operational cost and, from this total amount, 75% is binder cost when PC is used as a sole binding reagent. The Canadian Minerals Yearbook (1993) notes that the Ontario mining industry alone consumed 5–6% of the total Canadian Portland cement production with an estimated cost of CAD $75 million annually in the consolidation of backfill in underground mining operations. The high energy costs associated with cement production along with the remoteness of operating mining sites result in the cost of PC typically ranging between CAN $100–150 per tonne (De Souza et al., 1997). The unit cost of CPT becomes significantly higher, particularly where rich mixes consuming more PC are employed. With regard to the aforementioned statistics, PC appears to be the most expensive component of CPT operations and hence becomes the primary setback in its use as a sole binder. Concomitantly, the cement industry is one of the leading industrial emitters of greenhouse gases, particularly CO_2. Its increased manufacturing cost along with its recognition as a major source of CO_2 emission has made cement production a target of criticism among environmentalists.

5.1.1.2. Robust engineering design requirements and concordant higher cement consumption. The variability and complexity of mine waste materials and behaviour of cement in the individual composite matrices preclude a universally accepted generalized methodology for solidification of mine tailings. The rate of strength acquisition and the ultimate strength at failure are among the key parameters for evaluating the effectiveness of a binder in hardened cemented matrices such a cemented backfills (Thomas et al., 1979). Researchers have reported diverse strength requirements for cemented paste fills depending on their specific applications in mining operations. For instance, Hassani and Bois (1992) suggested 0.24–4.3 MPa, whereas, Ramlochan et al. (2004) reported

0.5–5 MPa. In the light of wide variations that exist in the recommended target strengths, 3–8% PC to total solids ratio is commonly used for the mixture design of paste backfills. Such a high proportion of PC can be a financial burden on mining industry.

5.1.1.3. Significance of sulphates in Portland cement based cemented paste tailings. Several studies (Benzaazoua et al., 1999, 2002; Hassani et al., 2001; Fall and Benzaazoua, 2005; Ouellet et al., 1998, 2006; Ercikdi et al., 2009; De Souza et al., 1997) conducted on CPT have confirmed that sulphates present in tailings water and those produced by the oxidation of pyrite FeS_2 (in a basic pH medium created by cement hydration) can react with free calcium ions produced by the dissolution of unstable portlandite [$Ca(OH)_2$], giving rise to the precipitation of swelling secondary gypsum ($CaSO_4 \bullet 2H_2O$) and highly expansive ettringite ($3CaSO_4 \bullet 3CaO \bullet Al_2O_3 \bullet 32H_2O$). Researchers have confirmed the phenomenon of internal sulphate attack in ordinary PC based sulphidic CPT and have observed secondary gypsum as an ubiquitous phase in such matrices. This secondary gypsum can create softening and swelling effects in the cement solidified matrices such as mortars and concretes and can also be a possible source of backfill internal cracking and subsequent strength deterioration over time (Tian and Cohen, 2000; Mehta, 1983).

Fall and Benzaazoua (2005) argued that sulphate present in CPT significantly influences strength parameters. This effect is intimately related to the sulphate concentration, curing time and the amount and chemical composition of the cement. Sulphates can contribute to early strength gain by virtue of filling pores with hydrated cement products and through the precipitation of hydrated sulphates along with modification of pore-structure below a concentration of 2000 ppm (Fall and Benzaazoua, 2005). If the sulphate contents exceed 10,000 ppm, massive and detrimental precipitation of swelling secondary gypsum may be expected, which can be a source for an internal sulphate attack in cementitious matrix (Belem and Benzaazoua, 2008). The generated volume of hydration products can be far in excess of the available pore volume, thereby creating internal stresses that can lead to expansion and, subsequently micro-cracking. These phenomena can culminate in the loss of initially developed strength within CPT.

The mining industry faces the need to appraise the cost benefits of binding agent addition to upgrade the mechanical properties of cemented backfill in underground mining operations to cope with ground stability issues and to enhance productivity (Scoble and Piciacchia, 1986). Consequently, there exists sufficient incentive to curtail PC consumption without impairing the paste performance. The high cost of PC as well as its alleged poor performance as a sole binder in the long term and today's robust engineering design requirements for CPT has prompted users to appraise less expensive and technically efficient substitutes for such formulations.

5.2. Pozzolanic materials

In recent years, there have been remarkable efforts in utilizing a variety of pozzolanic materials and industrial by-products in formulating CPBs in the mining industry not only to reduce PC consumption but also to upgrade product performance. The matrices incorporating supplementary cementing materials (SCMs), such as CPT with composite binder systems, exhibit unique characteristics that often make them more durable than PC based paste.

Pozzolans represent siliceous or aluminosiliceous materials of amorphous rather than crystalline nature and of sufficient fineness, which are capable of reacting with lime in the presence of water to form insoluble cementitious products such as, hydrated calcium silicates (Taylor, 1990). The beneficial effect of the incorporation of pozzolanic materials on the overall strength and stability of cementitious matrices, such as CPT, can be attributed mainly to the consumption of $Ca(OH)_2$ liberated during the hydration of PC through pozzolanic reactions. The deterioration associated with sulphate attack can be controlled by either limiting or eliminating monosulphate hydrate and calcium aluminate hydrate in cement. This can be accomplished by limiting C_3A content in PC or by substituting a portion of cement by appropriate blending materials such as artificial or natural pozzolans (Mehta, 1986). The latter option can utilize by-products from a variety of sources to not only ameliorate product performance and increase technical benefits but also reduce cement utilization favouring reduced carbon emission and, therefore, supporting sustainable development.

5.2.1. Natural pozzolans

Natural pozzolans, such as volcanic tuff and pumice, used in the manufacturing of blended cements may be considered as alternate and economical pozzolanic materials for CPT (Ercikdi et al., 2010). Natural pozzolan addition enhances the sulphate resistance of low C_3A Portland cements principally due to the calcium hydroxide reduction in mortars, which delays and thwarts gypsum formation. The phenomenon is more pronounced at paste–aggregate interface. Mortars with pozzolans show much reduced expansion and high retention of strength in sulphate rich environments (Irassar et al., 2000).

Ercikdi et al. (2009, 2010) examined the use of natural pozzolans, such as the volcanic tuffs (Akkus Trass and Fatsa Trass) and pumice as a partial replacement for PC in CPB of sulphide-rich tailings (26.2 wt% S). The pozzolanic activity of the natural materials was found to be intimately related to their respective reactive silica content. The incorporation of the natural pozzolans at 10–30 wt% was shown to slow down the rate of development of strength of CPB specimens. Only pumice appeared to mitigate the long-term stability of CPB samples using a higher dose (up to 30 wt %) by virtue of its high pozzolanic activity compared with the other pozzolans tested.

5.2.2. Artificial pozzolans

According to Malhotra and Mehta (1996), artificial pozzolans or SCMs provide engineering, economical, and ecological (environmental) benefits for the cement and concrete industry and some knowledge transposition has also been employed in upgraded CPT formulations as evident by the exhaustive collection reported in the following sections.

5.2.2.1. Pulverized coal ash or fly ash based binders. Fly ash is a by-product of coal burning power plants, and is often composed of predominantly silt-sized, spherical and amorphous ferro-aluminosilicate minerals (Sale et al., 1997). According to the Canadian Standards Association specifications (CSA A3001, 2003) the ashes are classified as low lime Type F ash ($CaO \leq 8\%$), medium lime Type CI ($8\% < CaO \leq 20\%$), and high lime Type CH ($CaO > 20\%$). Two major types of fly ash are specified in ASTM C618 (2003) based on their chemical composition, which is highly dependent upon the type of coal burned: Class C fly ash and Class F fly ash. The sum of three major oxides, namely SiO_2, Al_2O_3 and Fe_2O_3 has a minimum value of 50% for Class C fly ash and 70% for class F fly ash. Class C fly ash possesses cementitious properties in addition to its pozzolanic properties, and is capable of counteracting the acid potential of mine waste due to its high calcium content (Roy and Griffin, 1982). Class F fly ash is also known as low lime fly ash generally contains CaO content less than 10% and usually produced from anthracite and bituminous coals, classified into class F fly ash (Ravindra, 1986). Partial replacement of PC with fly ash in CPT formulations has been investigated by several researchers (Weaver and Luka, 1970; Manca

et al., 1983; Yu and Counter, 1988; Udd and Annor, 1993; Amaratunga and Hein, 1997; Benzaazoua et al., 1999; Hassani et al., 2001, 2007a; Godbout et al., 2007).

Hassani et al. (2001) evaluated the stability of high sulphate paste fill containing cement alone and PC–Class C fly ash in a sulphate-rich environment. It was found that PC alone is not a suitable binder to provide the long-term stability for paste backfill due to the formation of calcium aluminate compounds. However, cement in conjunction with Class C fly ash manifested a more resilient matrix in the long-term despite a longer curing period for strength attainment. In another study, Hassani et al. (2007a) investigated the effect of binder on classified tailings and blended tailings/sand backfill systems. Regarding the binder composition, the use of 50% fly ash as a replacement for PC yielded UCS exceeding that of PC alone at the late stage.

Benzaazoua et al. (1999) conducted physical, chemical and mineralogical characterization of paste backfill using in situ cores collected from a stope. The hardened paste backfill samples contained sulphide tailings (16.8 wt% S) and 4.5 wt% binders (mix of fly ash (40%) and ASTM Type I (60%)). Chemical and mineralogical analysis revealed that the presence of sulphides in the tailings caused dissolution of the calcic phases of the cement hydrates and promoted the formation of swelling phases, which in turn induced a deterioration of the cemented backfill. The partial replacement of fly ash was also shown to improve the sulphate resistance of CPB.

Ramlochan et al. (2004) conducted microstructural investigation and chemical investigations of hardened mixtures of paste backfills using scanning electron microscopy. The binder used for the mixtures consisted of 50% PC and 50% fly ash. The binder content expressed as the mass of cementitious material relative to the total mass of solid constituents (cementitious materials plus tailings) were 0.05, 0.15, and 0.70, respectively. It was concluded that binders with high proportions of a low to moderate lime fly ash are not suitable for use in paste backfill mixtures, whereas, high-lime fly ashes (Class C fly ash) would likely be more appropriate for paste backfills, and can be used in greater proportions for resilient paste backfill matrices.

Amaratunga and Hein (1997) evaluated the effect of mixing fine gold mill tailings in the form of agglomerated tailings pellets with different binders on the strength and stiffness characteristics of a total tailings cemented paste fill. The addition of agglomerated fine tailings pellets to create an agglomerated tailings paste fill, resulted in a 133% increase in UCS and a 466% increase in modulus of elasticity when compared to total tailings paste fills of the same consistency and binder content. Binder dosages of 3 wt%, 5 wt%, and 7 wt% in various PC–fly ash combinations were used. The authors concluded that partial substitution of PC with Class C fly ash to produce high modulus paste fill is economical and does not greatly compromise paste fill strength.

5.2.2.2. Deinking sludge fly ash (DFA). Peyronnard and Benzaazoua (2011) tested pozzolanic properties of Deinking sludge fly ash (DFA) (byproduct of co-combustion of paper deinking sludge and wood biomass) in mine CPB. DFA possesses cementitious properties due to some soluble crystallized phases (C_2S, C_3S, C_4AF, gypsum, portlandite, anhydrite and lime). The observed 28 day UCS by using composite binder (60% PC–40% DFA) in CPB was 0.5 MPa.

5.2.2.3. Slag based binders in cemented paste tailings formulations. Pyrometallurgical processes used to produce iron, zinc, copper and lead generate slag as a byproduct. Metallurgists classify slag as either basic or acidic: the more basic the slag, the greater its hydraulic activity in the presence of alkaline activators (Hewlett, 2001). Slag generally requires grinding to develop the fineness and reactivity when required for use as a partial replacement of cement or other activator (Patzelt, 1993).

5.2.2.3.1. Ferrous slag. Ground granulated blast furnace slag (hereafter SL) is a nonmetallic byproduct of iron manufacturing and consists essentially of silicates and aluminosilicates of calcium and other bases, which is developed in a molten condition simultaneously with iron in a blast furnace, then water chilled rapidly by immersion in water to form glassy granular particles, and then ground to cement fineness or finer (ACI Committee 233; Bouzoubaa and Simon, 2005). Most slags hydrate by themselves, while some need activators (alkalis or lime) for their hydration mechanisms. In order to produce a slag with good pozzolanic properties, it is required to be in an amorphous state, rather than crystalline state.

In PC–slag systems, the PC component begins to hydrate first followed by reaction with slag, which releases calcium and aluminium ions into solution. Later on, slag reacts with alkali hydroxide and is followed by reaction with $Ca(OH)_2$ to form more C-S-H gel (Neville, 1995). The release of alkali (Ca^{2+}) and hydroxyl (OH^-) ions during the hydration of PC raises the pH of the pore solutions that triggers the hydration reactions for cement–slag systems. The silica glasses become soluble in the alkaline solution, giving rise to secondary growths of C-S-H, which further fills the capillary pore space left by prior hydration products of PC (Hooton, 2000). Slag develops its cementitious properties far too slowly to be of practical use unless its hydration is activated by the addition of calcium compound such as PC. Research substantiates that the partial replacement of cement with slag is promising in mine tailings CPB formulations (Nantel and Lecuyer, 1983; Douglas and Malhotra, 1989; Uusitalo et al., 1993; Benzaazoua et al., 2002; Godbout et al., 2007).

Belem et al. (2000) used tailings from a polymetallic mine containing 16% and 5% sulphur to produce various paste backfill mixtures using PC, slag, and fly ash-based binders. The triaxial compression test results demonstrated that the cohesion (C) of the backfill increased and the angle of friction (Ø) decreased with an increase in the percentage of binder material. The slag based binder outranked all the other binders tested in imparting strength parameters of the resultant mine tailings pastes. Ouellet et al. (2007) used ground silica to simulate tailings in paste backfill preparation with cementitious binders. It was observed that CPB specimens made with a mix of PC–slag binder showed the highest percentage of fine pores and the highest UCS values. The fineness of the slag particles induced more effectual water to binder cementitious effect than that of the other binders (PC and PC–fly ash binder). As a result, the reactivity of the slag induced high refinement effect on the pore size distribution of the CPB.

Benzaazoua et al. (2002) demonstrated that CPB specimens produced from sulphide-rich tailings (32 wt% S) using a mixture of PC (20 wt%) and granulated blast furnace slag (80 wt%) as binder at 3–6 wt% binder dosage failed to attain any UCS over 91 days of curing period, while those specimens from the tailings with low (5.2 wt% S) and moderate (15.9 wt% S) sulphide produced relatively higher compressive strength. The authors concluded from these results that slag is not particularly appropriate for CPB of high sulphide tailings but it can be readily used for low to medium grade sulphide tailings (<32 wt% S).

Belem et al. (2001) demonstrated that the addition of blast furnace slag–PC modified tailings pore size distribution in CPB. The addition of only 5 wt% of tailings decreased approximately the threshold diameter from 2 to 1 micron. This refinement of the pore size effectively reduced the hydraulic conductivity of the CPB. However, the hydration process of cement–slag system is slower than that of PC alone (Demirboga, 2007).

Ramlochan et al. (2004) observed that the relative volume of interstitial space occupied by hydration products was greater when a binder consisting of SL and a small amount of PC was used than when one with equal parts of PC and fly ash was used.

Consequently, higher compressive strengths were achieved with the former than with the latter at comparable water-to-cementitious-material ratios. The authors argued that SL can be used in greater proportions in CPB formulations and addition of lime to the binder can be beneficial in the activation of pozzolans such as slag in order to attain finer structure of resultant paste backfill.

Godbout et al. (2007) observed that the proportion of binder has a direct impact on the reduction of hydraulic conductivity of CPB. A higher proportion of binder leads to a correspondingly greater reduction in hydraulic conductivity. Based on the materials used in their research the authors concluded that PC–slag binders outperformed cement–fly ash binders in the reduction of hydraulic conductivity of CPB.

Douglas and Malhotra (1989) evaluated the potential use of SL as a replacement for PC and lime in cemented mine backfill. The research used a variety of slags with different particle sizes, different tailings–binder ratios, along with lime content. It was found that a variety of slag–lime binders produced strength of 1 MPa after 28 days of curing, and the slag–cement binder performance outranked than both the slag–lime and PC binders in formulating cemented tailings matrices. Lea (1970) suggested that with aluminium oxide (Al_2O_3) content of less than 11 wt%, SL can aid greatly in inhibiting the detrimental effects of sulphate attack in cementitious matrices.

5.2.2.3.2. Non-ferrous slag. SL has excellent cementitious properties, whereas base metal (copper, nickel, etc.) slags have limited properties. Thomas et al. (1979) tested non-ferrous slag (air cooled copper converter slag and air cooled dezinced lead smelter slag) for tailings solidification applications and reported those slags as non-pozzolanic. He further experimented and found that such slags can be converted to pozzolanic materials by re-melting and quenching making them capable of replacing some PC. Atkinson et al. (1989) utilized both lime and gypsum to activate a copper slag. A mine backfill mix containing 5.4 wt% copper slag, 0.93 wt% gypsum, and 0.75 wt% lime at 80 wt% solid content attained a UCS of 1 MPa at 28 days of curing.

5.2.2.4. Ground waste glass as a partial replacement of Portland cement. Soda-lime glass is the most frequently manufactured form of container glass (bottles, pots, etc.), blown glass (decorative, etc.), and flat glass (doors, window, etc.). According to US EPA (1990), soda-lime glass production is approximately 77% of the total glass production in the United States, and is generally a mixture of SiO_2 (~75%), Na_2CO_3 (~15%), and $CaCO_3$ (~10%). Waste glass in finely ground state is amorphous and contains relatively large quantities of silicon and calcium, by virtue of which it can be used as pozzolanic material.

Archibald et al. (1999) conducted strength comparison for a range of normal PC and ground waste glass-consolidated slurry and paste backfill products with 100% cement-consolidated products as control standard materials. In the case of slurry and paste backfill mixtures, up to 35% of the PC binder replacement with ground waste glass (GWG) material demonstrated excellent compressive strength characteristics (up to 1.1 MPa). GWG was found to be capable of providing equivalent or better backfill strength characteristics than normal PC up to 224 days of curing. In an another study, Archibald et al. (1995) demonstrated that base metal mine tailings consolidated with both PC and PC–waste glass binders were found to be susceptible to long-term strength deterioration as a result of sulphate attack.

De Souza et al. (1997) studied glass fill for potential use in cemented backfill applications. The investigation indicated that 15% and 25% replacement of cement with glass provided equivalent or improved UCS response and improved the Young's Modulus for most of the backfills studied, albeit, some tailings–binder mixtures experienced considerable strength loss after 28 days of curing as the result of massive sulphate attack. Sargeant et al. (2007) reported that GWG was effective as a replacement for ordinary PC up to 15 wt% in the CPB of low grade sulphide tailings (2.69 wt% S).

5.2.2.5. CAlSiFrit®. Peyronnard and Benzaazoua (2011) studied the use of CAlSiFrit (byproduct from thermal treatment of aluminium smelters' spent pot liners) in mine CPB. The binder containing 50% PC and 50% CAlSiFrit acquired UCS of 0.6 MPa after 28 days of curing. The researchers have attributed the high reactivity of CAlSiFrit by its chemical and mineralogical compositions.

5.3. Functional modifications in cemented pastes tailings using pozzolanic binders

The utilization of pozzolanic additives in CPT performs a variety of functions that can improve the properties of hardened CPT. The dominant modifications induced by the use of pozzolanic additives are discussed in the subsequent sections.

5.3.1. Refinement of cemented paste tailings pore structure
The properties of CPT are largely governed by the volume and distribution of pores in the matrix. Porosity in cemented matrices consists of the space originally occupied by water in fresh mortars and concrete (water-to-cement ratio) minus the volume of new solids formed as the cement hydrates, i.e., the degree of hydration (Hooton, 2000). The calcium silicate glass in the pozzolanic additive, such as blast furnace slag or fly ash, becomes soluble in the alkaline pore solutions provided by the initial hydration of ordinary PC and reacts to form secondary growths of calcium silicate hydrates (*C-S-Hs*). These *C-S-Hs* are analogous to those from PC, but the Ca/Si ratio is lower (Richardson, 1999). These additional hydration products serve to improve the microstructure of CPT, leading to lower porosity and permeability mainly due to mineral precipitation. These hydration products in turn act as barrier against moisture and oxygen ingress, and hence alleviate the oxidation of pyrite present in the matrix (Benzaazoua et al., 2002, 2004a; Fall and Benzaazoua, 2005; Ercikdi et al., 2009).

5.3.2. Densification of interfacial transition zone surrounding tailings grains
The voids created by water particle movement and space not occupied by solid components of CPT are known to make a major contribution to porosity and permeability of matrix. CPT containing ordinary PC alone as a sole binder is characterized by a relatively porous matrix. Hooton (2000) argued that grains of SCMs such as slag near interfacial transition zones react (often later) with the local calcium hydroxide crystals originally produced by cement hydration to generate more *C-S-H*. The secondary *C-S-H* growth fills the weak and permeable transition zones, improving concrete strength and attenuating both flow and ionic diffusion along the pathways within the matrix, such as CPT.

Fall and Samb (2008) investigated the pore structure of CPB containing ordinary PC and reported that the porosity of the interfacial transition zone is intimately related to the strength characteristics of hardened matrix. The higher the porosity of the interfacial transition zone, the weaker the bond between tailings grains. The size of capillary voids is much larger at the interfacial zone (i.e., the region at the interface of the coarse tailings grains and the hydrated cement paste) compared to the bulk cement paste. The incorporation of reactive artificial pozzolans such as fly ash, slag, and natural pozzolans cause both grain and pore refinements. This occurs primarily due to the production of pozzolanic *C-S-H* and efficient packing of cementitious materials particles, leading to

improved concrete microstructure and reduction of hydraulic conductivity (Manmohan and Mehta, 1981). Fall et al. (2010) studied the effect of using slag and fly ash as partial replacement of PC in mine cemented tailings backfill. Fig. 1(a) and (b) shows pore size distribution for the backfill materials prepared with PC, PC–slag and PC–fly ash. It is evident from the figures that the pore refinement effect produced by the slag based binder is greater than fly ash based binder.

5.4. Cemented paste tailings hydration stages and potential interaction with sulphates along with functional role of pozzolanic materials addition

Fig. 2 is a pictorial illustration elucidating the occurrence of PC hydration process within CPT enriched with sulphide minerals (pyrite, pyrrhotite), as well as the potential functional influence of pozzolanic materials and hydration activators when used as partial replacement of ordinary PC. Upon mixing with water OH^- ions are released, which buffer the pore solution at a pH between 12 and 13. Contingent upon the formation of primary *C-S-H*, the rate of hardening of CPT increases. Concomitantly, portlandite forms which then further reacts with SCMs or pozzolans to generate additional *C-S-H*. This could also improve the microstructure producing a denser particle packing with the likely reduction in porosity and permeability. In the absence of pozzolanic additives, high contents of sulphate present in tailings and/or process water can react with portlandite and *C₃A* to form secondary gypsum with swelling properties (Fall and Benzaazoua, 2005). This can result in

an internal sulphate attack, endangering the structural integrity of CPT (Belem and Benzaazoua, 2008).

5.5. Hydration activators

5.5.1. Cement kiln dust

Cement kiln dust (CKD) is an alkaline particulate material collected from cement kiln exhaust gases during the process of cement manufacturing. CKD consists of entrained particles of clinker, un-reacted and partially calcined raw materials, and fuel ash enriched with alkali sulphates, and other volatiles. According to the United States Environmental Protection Agency (US EPA, 2008), 13–17 million short tons of CKD are generated per year. CKD contains the main oxides *CaO*, Al_2O_3, SiO_2, and Fe_2O_3 in proportions that produce intrinsic cementitious properties (Kamon and Nontananandh, 1991; Miller and Azad, 2000; Wang et al., 2002; Pierce et al., 2003). The free lime (*CaO*) present in CKD has been found to be the most effective predictor of the reactivity of a particular CKD and the amount and nature of the hydration products generated, and therefore, is a measure of its effectiveness as a cementitious stabilizer/binder (Boynton, 1980; Bhatty, 1984; Konsta-Gdoutos and Shah, 2003; Lachemi et al., 2008). The quantity of free or available lime as well as alkalis (Na_2O, K_2O) varies broadly between cement kiln dusts (CKDs), which results in making some CKDs more reactive than the others.

The loss on ignition (LOI) is also a controlling parameter in the reactivity of CKDs. Higher LOI substantiates that a particular CKD is high in calcium carbonate ($CaCO_3$) and low in reactive free lime (*CaO*). A lower LOI of a particular CKD indicates lower $CaCO_3$ and higher *CaO* content is available. These $CaCO_3$ particles are inert and, therefore, do not participate in the hydration reactions (Konsta-Gdoutos and Shah, 2003). In addition to the above mentioned factors governing the chemical (richness in sulphates, alkalis, and chlorides, etc.) and physical makeup of CKDs, its storage or disposal scenarios can have pronounced effect on reactivity. Long-term landfilled CKDs can be less reactive and, therefore, less cementitious due to loss of free lime as a result of carbonation (Sreekrishnavilasam et al., 2006). Table 1 presents the composition of different CKDs as reported by several researchers.

5.5.1.1. CKD as an activator and accelerator for pozzolans used in cemented paste tailings. Tariq and Nehdi (2007) conducted preliminary work on the use of CKD in paste backfill formulations and examined the strength development of paste backfill prepared using mine tailings and industrial by-products (CKD and Class C and Class F fly ash) with or without using PC. It was concluded that industrial by-products (used either as single binder or as partial replacement for PC) can be effective in producing more resilient backfill mixtures. Peyronnard and Benzaazoua (2011) concluded that only low amounts of CKD (<5%) can be used as hydration activator (in combination with PC) because of their high fraction inert to hydration reaction (>50% of calcite). It was also observed that the activation potential of CKD cannot be generalized due to its variability depending on origin.

Research has demonstrated that CKD can act as alkaline accelerator for latent hydraulic substances including SL and as alkaline activator for different aluminosilicate materials used in mortars and concretes (Sprouse, 1984; Xu and Sarkar, 1995; Konsta-Gdoutos and Shah, 2003; Buchwald and Schulz, 2005). The solubility of *Si*, *Ca*, *Al* and *Mg* in cementitious matrices are pH dependent. The equilibrium solubility of silica is low at pH below ∼11 (Sreekrishnavilasam and Santagata, 2006). Highly alkaline pore solution created by free calcium rich CKD is capable of disintegrating the solid glassy network of SL to produce reactive silicate and aluminate species when attacked by (OH^-) ions. The
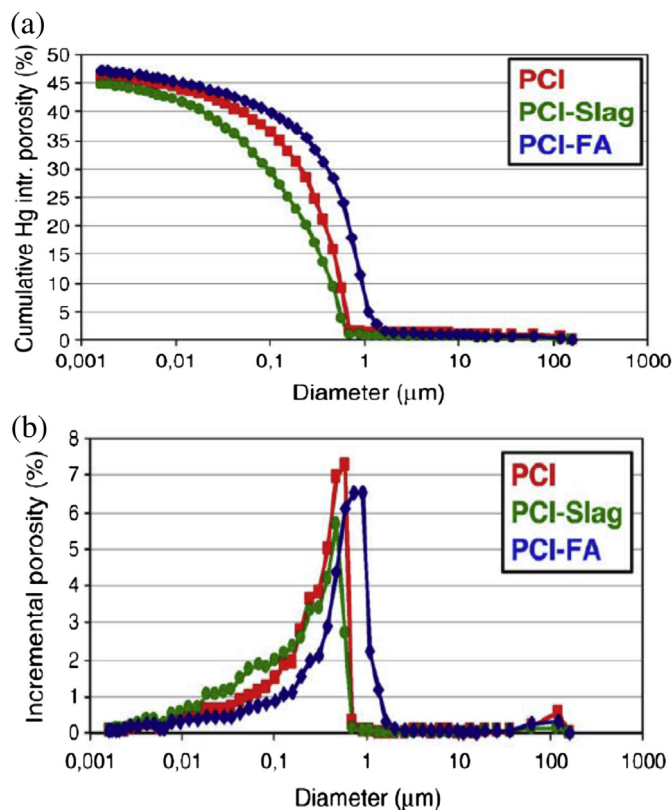

Fig. 1. (a) Mercury intrusion cumulative porosity of 28 days old cemented paste backfill made with Portland cement (100% PCI), Portland cement–slag (50%PCI–50% Slag) and Portland cement–fly ash (50%PCI–50%FA) (after Fall et al., 2010). (b) Mercury intrusion pore size distribution (incremental porosity) of 28 days old cemented paste backfill made with Portland cement (100% PCI), Portland cement–slag (50%PCI–50% Slag) and Portland cement–fly ash (50%PCI–50%FA) (after Fall et al., 2010).
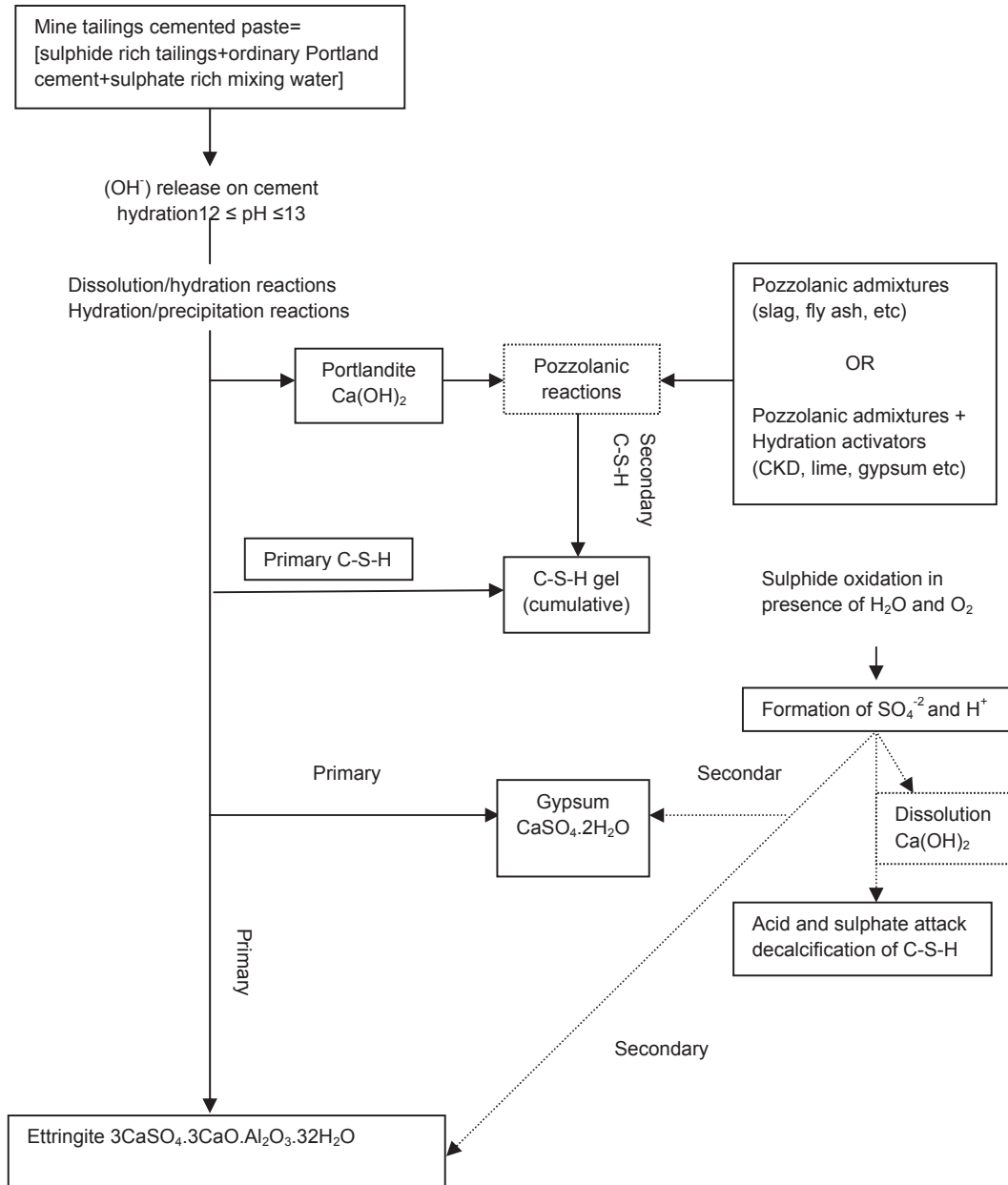
Fig. 2. Schematic diagram elucidating Portland cement based cemented paste tailings hydration stages and potential interaction with sulphates along with functional role of pozzolanic materials addition (modified after Belem and Benzaazoua, 2008; Ercikdi et al., 2009).

Table 1
Range of major oxides for different cement kiln dusts.

Chemical characteristics	Range for major oxides for 63 different cement kiln dusts[a]
Major oxides (wt%)	
Al_2O_3	1.09–10.50
SiO_2	2.16–34.30
Fe_2O_3	0.24–6.00
CaO (total)	19.40–61.28
MgO	0.54–3.50
SO_3	0.02–17.40
K_2O	0.11–15.30
Na_2O	0.00–6.25
CaO (free)	0.00–27.18
Loss on ignition (LOI)	4.20–42.39

[a] Sreekrishnavilasam et al. (2006).

activation or dissolution rate of SCMs with latent pozzolanic properties depends on the alkali concentration of the reacting system (Wang et al., 2007). The total alkalis (Na_2O_{eq}) present in CKDs can effectively trigger the activation mechanism of SL. In cement–slag systems, the slag grains can also accelerate the hydration of PC by acting as nucleation sites for *C-S-H* to precipitate out of solution and grow onto (Hooton, 2000). The activation of the solids contained in pozzolanic materials by the highly alkaline environments created by CKD containing alkaline hydroxides, alkaline silicates and/or alkaline carbonates can result in high UCS in mortars and concretes (Konsta-Gdoutos and Shah, 2003; Buchwald and Schulz, 2005).

CKD with its high alkaline soluble fraction can be added as an activator in blended cements containing fly ash and hydraulic slag enabling them to undergo cementitious reactions (Dyer et al., 1999). Adequate initial alkali concentration and presence of
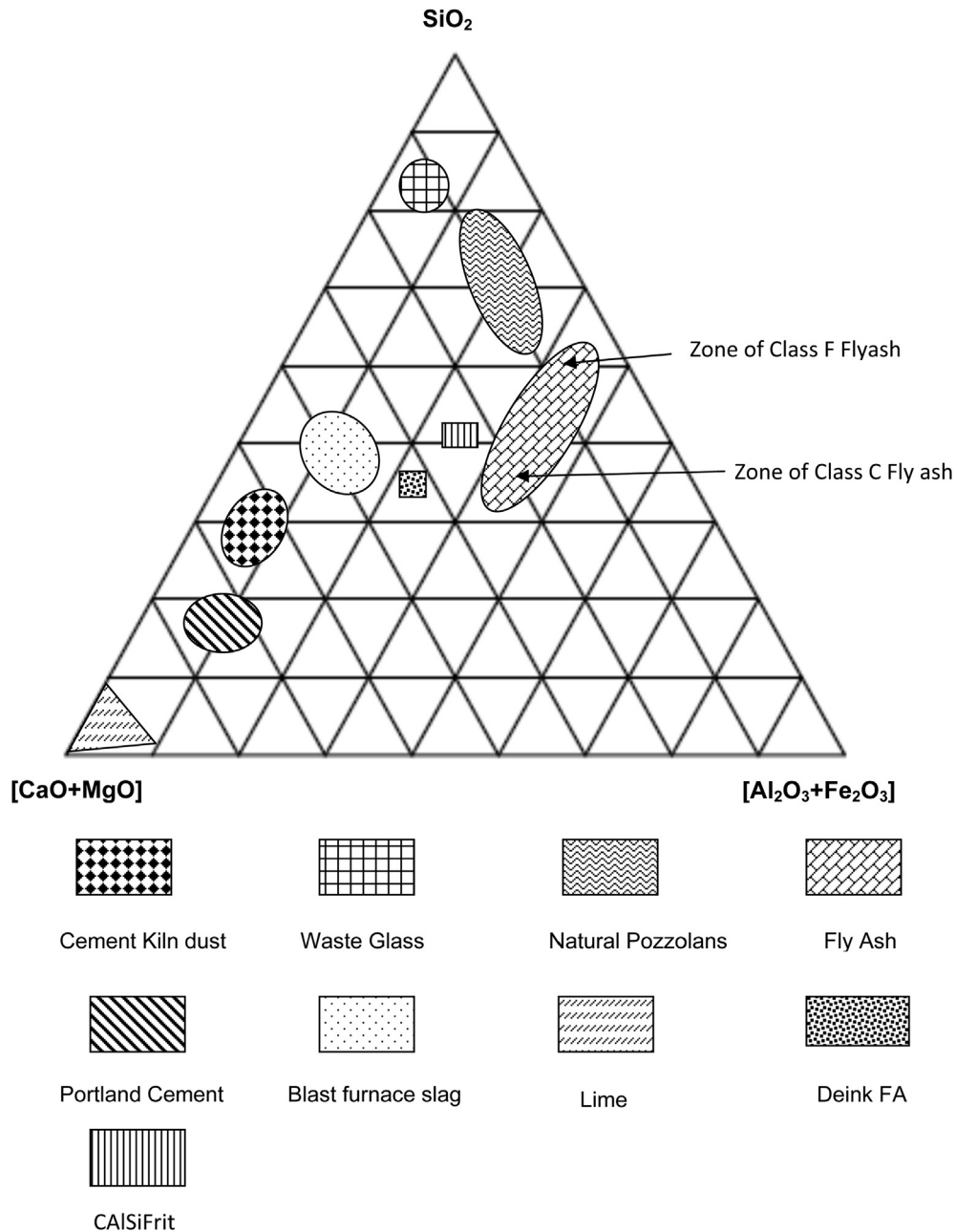
Fig. 3. Ternary phase diagram showing common solidification and chemical fixation reagents (modified after Peyronnard and Benzaazoua, 2011).

sulphates are both considered vital for the activation of slag in CKD–slag systems. The hydration processes, hydration products, and resulting enhanced strength are principally determined by the free *CaO* content of a particular CKD (Amin et al., 1995; Konsta-Gdoutos and Shah, 2003).

SL possesses latent hydraulic reactivity, however; its hydration in pure water is particularly slow under normal conditions due to the development of aluminosilicate coatings on slag grains that prevent hydration reactions from proceeding. Moreover, high glass content of blast furnace slag also requires elevated alkaline conditions for chemical hydration (Zeghichi et al., 2005; Juenger et al., 2006; Sreekrishnavilasam and Santagata, 2006). This can be readily achieved with basic reactors such as calcium hydroxide obtained from the addition of sufficient amount of PC, calcium sulphates or other calcium and alkali rich compounds such as CKD.

5.5.2. Calcium sulphate substances
5.5.2.1. Calcium sulphate or gypsum. Calcium sulphate dihydrate ($CaSO_4 \bullet 2H_2O$) or gypsum is a naturally occurring material and can be calcined to produce calcium sulphate hemihydrate ($CaSO_4 \bullet 1/2H_2O$) and calcium sulphate anhydrite (anhydrous calcium sulphate or $CaSO_4$) (Ridge and Beretka, 1969). Petrolito et al. (1998) tested the UCS of a variety of β-hemihydrate-tailings and PC–tailings cured mixtures. The observed one day UCS attained by gypsum based specimens containing 20 wt% hemihydrates was 1 MPa. Therefore, approximately two and half to four times more hemihydrate than cement was required to achieve a comparable UCS (for cement-tailings specimens). Amaratunga and Hmidi (1997) investigated the use of gypsum β-hemihydrates (the most economical form of calcined gypsum) and PC in cold bonded agglomeration of fine gold mill tailings. It was concluded that a strength of

237 N/pellet can be achieved in the cold bonded agglomeration process by adding 4% binder (20% β-hemihydrate and 80% PC).

5.5.2.2. Waste gypsum. Peyronnard and Benzaazoua (2011) have tested waste gypsum as hydration activator for cemented mine backfill applications. Waste gypsum (fluorgypsum) is anhydrite which comes from fluoric and phosphoric acid production or gas desulphuration. The researchers have demonstrated that using 4.5 wt% binder (42%PC–40%waste glass–18%anhydrite) mixed with mining waste can produce a monolith with UCS of 0.6 MPa after 14 days of curing.

5.6. Significance of ternary oxide combinations for cementitious or/ and pozzolanic reagents in mine tailings solidification applications

The compositional characteristics of PC and other reagents commonly involved in cement based solidification processes can be best depicted with the aid of a ternary diagram using the three oxides combinations, i.e., (SiO_2), $(CaO + MgO)$, $(Al_2O_3 + Fe_2O_3)$ as shown in Fig. 3. All of these reagents have the same active ingredients as far as solidification reactions/processes are concerned (Conner, 1990). This ternary diagram can be used for preliminary screening of materials used as binders and for identifying means for strengthening the cementing and durability characteristics of the resultant cementitious matrices. The more the binder tends towards the SiO_2 pole, the higher would be the durability of the cement-based composite (Skalny and Daugherty, 1972; Conner, 1990; Benzaazoua et al., 2002). For instance, CKD and slag exists adjacent to the zone occupied by the Portland cements enhancing their cementitious properties under normal conditions. Lime (CaO) rich CKD can push slag towards more effective zone when mixed with it. Since pozzolanic materials such as slag and fly ash need excess lime or portlandite or $Ca(OH)_2$ as activator in pozzolanic reactions to exhibit their cementitious properties, the addition of CKD to PC can be advantageous.

5.7. Sodium silicate

Sodium silicate is produced by smelting sand with sodium carbonate at high temperature ($\sim 1200\ °C$) and can be used as a possible replacement for cement. Hassani et al. (2007b) investigated the use of sodium silicate as a partial or total replacement for cement in stabilized sand backfill. It was concluded that the material can be used as an additive to cement in stabilized backfills due to considerable advantages including (a) lower hydration heat compared to cement and, hence, lower risk of thermal cracking in thick structures, (b) reduced setting time, and, (c) higher cement replacement capability.

6. Conclusions

The use of CPT for surface and underground disposal of acid-generating tailings as an alternative to conventional or traditional strategies for mine tailings management is opening a new era in mineral waste management practices. The mining industry faces the need to appraise the cost benefits of binding-agent in addition to upgrading the mechanical properties of CPT operations, namely, (a) underground backfill to cope with ground stability issues and as an effort for higher productivity, and (b) surface disposal application as a control technique aiming at restricting contaminants leaching by solidification/stabilization of sulphidic mine waste.

- Sulphidic CPT containing PC as a sole binder has been established to be vulnerable to internal sulphate attack and subsequent progressive loss of structural integrity under certain conditions. A range of binders/additives have been successfully utilized to ameliorate the performance of sulphidic CPT. The beneficial effect of the incorporation of natural and artificial pozzolans on the overall strength and stability of CPT can be attributed mainly to the consumption of $Ca(OH)_2$ liberated during the hydration of PC through pozzolanic reactions to produce secondary *C-S-H*. It also decreases the capillary porosity of mortars and enhances significantly the paste–aggregate interface Utilization of pozzolanic additives in CPT performs a variety of functions that can improve material properties of the resultant matrices including the refinement of pore structure and densification of interfacial transition zone surrounding tailings grains. The normal range of ordinary PC replacement is 30–50% by fly ash, 20–60% by SL, and 15–35% by waste glass based on dry mass of cement.
- Binders with high proportions of a low lime fly ash are not desirable for use in paste backfill mixtures. Slags and high lime fly ashes (CSA Type C fly ash) would likely be more suitable for paste backfills, and can be used in greater proportions. Other materials including ground waste glass, deinking sludge fly ash, CAlSiFrit, calcium sulphate materials, and sodium silicate have shown promising results in CPT formulations.
- Research into the incorporation of other materials that could chemically activate and accelerate slag and fly ash is also warranted in order to achieve the desirable technical and economic advantages. Both slag and fly ash rely on excess calcium hydroxide produced by the addition of ample PC in order to complete pozzolanic reactions. The rigorous approach suggested by the researchers in the form of a ternary diagram (Fig. 3) for preparing more resilient cementitious matrices for wastes can be applied to evaluate CKD in CPT formulations. Lime (CaO) rich CKD can push slag towards more effective zone when mixed with it. Since pozzolanic materials such as slag and fly ash need excess portlandite [$Ca(OH)_2$] as an activator in pozzolanic reactions to exhibit their cementitious properties, addition of CKD in combination with a small addition of PC can be more advantageous in generating enhanced durable and useful calcium-silica-hydrate (*C-S-H*). These reactions can increase long-term strength of solidified matrices, reduce permeability, thereby increasing the strength and durability. In comparison with the other hydration activators (lime, anhydrite), selective CKDs may perform better in CPT or CPB operations.
- The reported normal range of PC replacement is exclusively applied to binary binder systems containing PC and pozzolanic additives. Ternary and quaternary binder blends may involve different replacement levels for which laboratory optimization is required.
- Site specific cost estimates for cemented paste systems can be prepared based on unit price of binder (s)/reagent (s). The reported unit prices of PC, slag, fly ash and CKD are $104/tonne, $90/tonne, $50/tonne, and $1/tonne, respectively (Tyson, 2012; Rafalko and Giacinto, 2010). The location of a mine restoration site relative to a binder/additive/reagent source can be a key factor in the cost optimization of CPT operations. In the light of unit price of CKD ($1/tonne), substantial cost saving is expected using this material as an activator (in combination with PC) for slag and/or fly ash in CPT formulations. Moreover, the mining industry would achieve greater flexibility with an additional binder option improving binder competitiveness.
- The wide-reaching use of CPT worldwide will continue to increase for ground and surface disposal applications, with innovative, more efficient and cost-effective binder explorations being incorporated to the cemented paste design and implementation.

Acknowledgements

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