Utilization of industrial waste products as pozzolanic material in cemented paste backfill of high sulphide mill tailings

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ABSTRACT

In this study, the potential use of the industrial waste products including waste glass (WG), fly ash (FA), granulated blast furnace slag (GBFS) and silica fume (SF) as pozzolanic additive for the partial replacement of ordinary Portland cement (OPC) in cemented paste backfill (CPB) of sulphide-rich mill tailings was investigated. The influence of these industrial waste products on the short- and long-term mechanical performance of CPB was demonstrated. The rate of development of strength of CPB samples tended to slow down when the pozzolanic wastes were incorporated or increased in dosage in the binder phase. Severe losses (by 26%) in the strength of CPB samples produced from exclusively OPC occurred after an initial curing period of 56 days. The addition of WG (10–30 wt%) as a partial replacement of OPC was observed to aggravate further the strength losses of CPB samples. GBFS, FA and SF appeared to improve the long-term performance of CPB samples; albeit, only GBFS and SF could be incorporated into the binder phase only at certain levels i.e. up to 20 wt% GBFS and 15 wt% SF in order to maintain a threshold strength level of 0.7 MPa over 360 days. SEM studies have provided further insight into the microstucture of CPB and confirmed the formation of deleterious gypsum as the expansive phase. These findings have demonstrated that the industrial waste products including GBFS and SF can be suitably used as mineral additives to improve the long-term mechanical performance of CPB produced from sulphide-rich tailings as well as to reduce the binder costs in a CPB plant.

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1. Introduction

The mining and milling of sulphide ores generate significant quantities of sulphide-rich mine wastes and mill tailings. These wastes/tailings are often rich in pyrite and contain toxic metals such as arsenic (As), copper (Cu) and zinc (Zn). The oxidation of pyrite in presence of water and oxygen generates acidity (i.e. the formation of AMD) and facilitates the release of metals contained in the mine waste or mill tailings. In recent years, cemented paste backfill (CPB) of potentially hazardous sulphide-rich mill tailings into underground mine openings has gained importance for the environmental management of such wastes [1–4]. Environmental problems associated with the storage of sulphide-rich wastes under atmospheric conditions (i.e. the formation of acid mine waters and the release of heavy and toxic metals with the concomitant risk of contamination of soils and underground/drinking waters) can be considerably reduced by the placement of such wastes safely in underground. Further benefits of CPB technology are (i) to provide

ground support for the surrounding mine structures, (ii) to allow a safe working environment and recovery of the ore from pillars, and (iii) to reduce the tailings disposal and rehabilitation costs [5–7].

CPB is essentially an engineered mixture of wet fine mill tailings (75–85% solids by weight), a hydraulic binder (3–7% by dry total paste weight) and mixing water. The physical, chemical and mineralogical properties of these components (the tailings, binder and mix water) of CPB exert a profound effect on its performance for strength and stability [8–10]. When the mill tailings are rich in sulphide (pyrite), some strength and stability problems associated presumably with the undesired oxidation of pyrite may be experienced in practice [7,11,12]. The oxidation of pyrite by the ingress of air and moisture leads to the formation of acid and sulphate, which then react with the hydration products (e.g. $Ca(OH)_2$) of binder used (e.g. the formation of expansive phases such as ettringite and gypsum due to sulphate attack). These chemical interactions could result in the loss of stability and the eventual collapse of the backfill with the concomitant losses in workforce and halt in the ore production. Therefore, binder properties i.e. its sulphate resistance are of practical importance for CPB of sulphide-rich tailings [13,14].

Calcium rich binders (high in C_3A and C_4AF) such as ordinary Portland cement (OPC, e.g. ASTM Type I) are often characterized particularly by their low resistance to sulphate attack [6,7,10–12].

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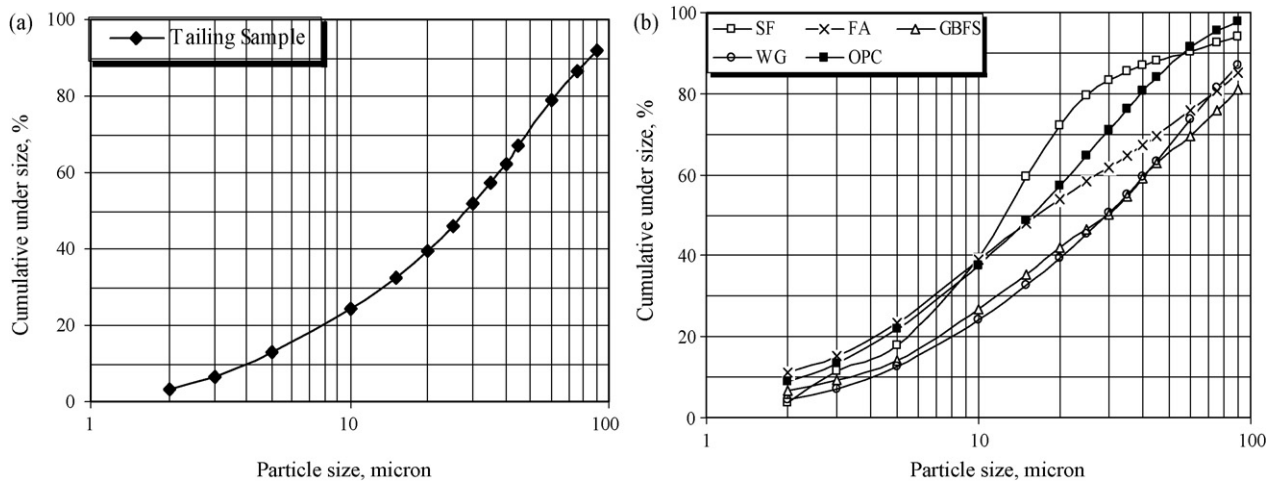*E-mail address:* bercikdi@ktu.edu.tr (B. Ercikdi).

Fig. 1. Particle size distribution of the tailings sample (a) and binders (b).

Sulphate resistant cements (e.g. ASTM Type V) with its low C_3A content ($\leq 5\%$) may be used in sulphate environments including CPB of sulphide-rich tailings to reduce the potential formation of secondary ettringite (but not secondary gypsum since it forms as a result of the chemical reaction between sulphate and portlandite) [11,14]; albeit, their high cost could be prohibitive. The sulphate resistance of CPB can be improved by the partial replacement of Portland cement with pozzolanic mineral admixtures, which contribute to pore refinement, dilution of C_3A and consumption of $Ca(OH)_2$ by pozzolanic reactions [14–17]. Furthermore, the utilization of pozzolanic admixtures can reduce the binder costs (which may constitute up to 40–70% of the operating costs in a CPB plant) since many industrial wastes with pozzolanic characteristics are available at large quantities and at low cost [18,19]. Benzaazoua et al. [11] demonstrated the beneficial effect of the partial replacement of OPC with slag only for low- to medium-grade sulphide tailings, but not for sulphide-rich tailings ($\geq 32\%$ S). Fly ash as pozzolanic additive was found to be not particularly suitable for CPB [15] while ground waste glass could replace up to 35 wt% of OPC with a 38% improvement in the strength of CPB samples [20].

Large quantities of industrial wastes such as slag, fly ash, waste glass and silica fume with pozzolanic characteristics are generated as a by-product of industrial operations in Turkey [21–23]. To illustrate, it is estimated that annually 13 million tons of fly ash is produced in Turkey [24]. Disposal of such large quantities of these industrial wastes often presents waste management problems since they are potentially hazardous in character since they contain toxic metals. In view of the ever strict regulations, treatment costs and limited availability of disposal sites, the exploitation of these wastes as pozzolanic additive may be of practical importance for the cost-effective management of them and also for the CPB of sulphide tailings with the potential technical, economical and environmental benefits.

In this study, the performance of various industrial wastes (granulated blast furnace slag, fly ash, silica fume and waste glass) as pozzolanic additive for the partial replacement (up to 60 wt%) of OPC in CPB was evaluated over 7–360 days of curing periods. The physical, chemical, mineralogical and pozzolanic characteristics of the industrial waste products were examined and correlated with their performance in CPB. SEM studies were also performed to provide an insight into microstructure and mineralogy of CPB samples linked with the mechanical performance of the pozzolanic additives.

2. Material and methods

2.1. Tailings sample

Approximately 2000-kg of representative tailings sample was collected from the feed of the backfill plant in a sulphide mill. Sub-samples were prepared to determine the physical, chemical and mineralogical characteristics of the tailings. The particle size analysis of the sample using a Malvern Mastersizer (S ver. 2.15 particle size analyzer) revealed that 40% of the tailings was finer than 20 μm (Fig. 1a) and hence, the tailings can be classified as a medium size tailings material [25]. The results of chemical and mineralogical analyses showed that the tailings were rich in sulphide (26.2% S) (Table 1) and contained pyrite as the main sulphide phase present (Fig. 2).
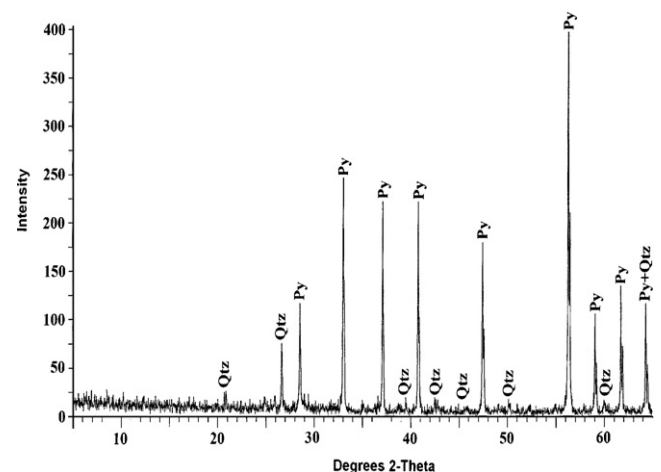
Table 1
Chemical composition of the sulphide tailings used in the tests.

Compound	%	Compound	%
MgO	1.19	K_2O	0.23
Al_2O_3	3.27	Na_2O	0.17
SiO_2	11.39	TiO_2	<0.01
CaO	0.95	SO_3	2.83
FeO	22.92	Cl^-	0.0025
S	26.22	Loss-on-ignition (LOI)	29.02
Total	98.2025		

Fig. 2. XRD profile of the tailings sample (Py (pyrite); Qtz (quartz)).

Table 2
Chemical and physical properties of ordinary Portland cement (OPC Type I) and the artificial pozzolans (granulated blast furnace slag, GBFS; waste glass, WG; fly ash, FA; silica fume, SF) used in the tests.

Characteristics	OPC (%)	WG (%)	FA (%)	GBFS (%)	SF (%)
Chemical composition					
SiO_2	20.31	72.76	12.21	38.25	90.62
Reactive SiO_2	–	46.69	11.38	37.98	88.18
Al_2O_3	5.93	1.32	6.13	12.60	0.64
Fe_2O_3	2.82	0.39	2.80	0.84	0.68
CaO	61.02	8.09	50.56	37.60	0.25
MgO	1.15	4.38	1.57	7.28	0.33
SO_3	2.95	0.12	11.38	0.15	1.04
Na_2O	0.32	10.75	0.09	0.52	0.53
K_2O	1.14	0.05	0.25	0.80	3.07
TiO_2	–	0.27	0.69	1.00	0.40
Cl^-	0.0101	0.0004	0.0124	0.0050	0.19
Free CaO	1.14	–	13.86	–	–
Residue	1.18	–	–	–	–
Loss-on-ignition	3.78	0.01	13.90	0.12	1.79
Total	99.43	98.14	99.59	99.17	99.54
Physical properties					
Specific gravity (g/cm^3)	3.01	2.51	2.42	2.87	2.39
Specific surface (cm^2/g)	4345	3318	7950	3128	24175
Grinding time (min)	–	180	30	180	–
Retained on 90 μm sieve (%)	2.16	13.04	14.99	19.05	5.88
Retained on 45 μm sieve (%)	15.84	36.62	30.41	37.04	11.89

2.2. Binder reagents

The ordinary Portland cement (Type I) was used alone and in combination with the artificial pozzolans (fly ash (FA), granulated blast furnace slag (GBFS), waste glass (WG) and silica fume (SF)) as mineral admixtures at different replacement levels (5–60% by weight). FA and GBFS were obtained from Afşin–Elbistan thermal power plant and Kardemir iron and steel plant, respectively. SF was supplied by Antalya-Etibank Ferro-Chrome Factory in Turkey. The type of WG used in this study is clear colored soda-lime windows glass obtained from a local glazier. These artificial pozzolans except SF were dried and crushed in a roll crusher (−4 mm) followed by dry-grinding of the crusher product in a laboratory ball mill. Preliminary grinding tests were carried out to determine the grind time required to achieve the desired fineness of grind ($\geq$3000 cm^2/g). The grind time was kept constant at 180 min for the GBFS and WG and at 30 min for FA. After grinding, the physical, chemical and mineralogical characterization of the artificial pozzolans (Table 2 and Figs. 1b and 3) were performed according to the methods specified in TS EN 196-2 [26] and TS EN 196-6 [27]. Reactive silica content of the artificial pozzolans was also determined as specified in TS EN 197-1 [28].

2.3. Pozzolanic activity tests

The pozzolanic activity of the FA, GBFS, WG and SF was determined based on ASTM C 311 and ASTM C 989 test methods [29,30]. In the control mixture, 500 g of Portland cement, 1375 g of graded standard sand and 242 ml of water were used. In the test mixtures, 20% of Portland cement was replaced by WG, FA or SF while the replacement level of Portland cement with GBFS was set to 50%. After 24 h of initial curing in a humidity room (23 ± 2 °C) with a relative humidity of higher than 95%, the specimens (5 cm × 5 cm × 5 cm) in triplicate were placed in a saturated lime water for 6 and 27 days. The compressive strength of the specimens was determined at 7 and 28 days.

2.4. Preparation of CPB samples

CPB samples (312 in total) were prepared by blending and homogenizing the tailings, binder (OPC, OPC/pozzolanic waste) and tap water in a mixer (Univex SRMF20 Stand model) equipped with a double spiral. The solids content of paste mixtures was set to 77 wt% to achieve the desired consistency of 7 in. slump. Ordinary Portland cement alone and as partially replaced (by 5–60 wt%) with the pozzolanic wastes at a fixed dosage of 5 wt% were used as binder agents. The mixing water (the tailings residual water remaining after the filtration process and tap water) had a sulphate concentration of 1283 mg/l. It should be noted that the high sulphate content of mixing water could lead to the inhibition of the binder hydration at early curing ages [11]. The CPB mixtures were thoroughly mixed and poured into plastic cylinders ($D \times H$: 10 cm × 20 cm). The cylinders were then sealed and allowed to cure in a humidity room (~80% humidity). Following a curing period of 7–360 days, the CPB samples were subjected to UCS tests according to ASTM C 39 [31] using a computer-controlled mechanical press (ELE Digital Tritest), which had a load capacity of 50 kN and a displacement speed of 0.5 mm/min.

2.5. SEM studies on CPB samples

The microstructure and texture of some 360-day CPB samples were examined under a LEO scanning electron microscope operated at an accelerating voltage of 15 kV. Energy dispersive spectrometry (EDS) of an X-ray probe coupled to the SEM was also used to aid the identification of mineral phases present. The fractured samples obtained from UCS tests were used in SEM studies. The samples were dried in an oven controlled at 50 °C and treated with acetone to cease further hydration prior to SEM analysis.

3. Results and discussion

3.1. Characterization of the artificial pozzolans

The chemical and physical properties of the pozzolanic wastes, which are regarded as an indication of their suitability for potential use as pozzolanic admixture, are presented in Table 2. Based on these properties, Table 3 was also compiled to compare with the specifications for different classes of pozzolanic materials (fly ash and raw or calcined natural pozzolans) as indicated by ASTM C 618 [32]. Accordingly, the industrial wastes used in the current study appeared to have "non-standard" properties
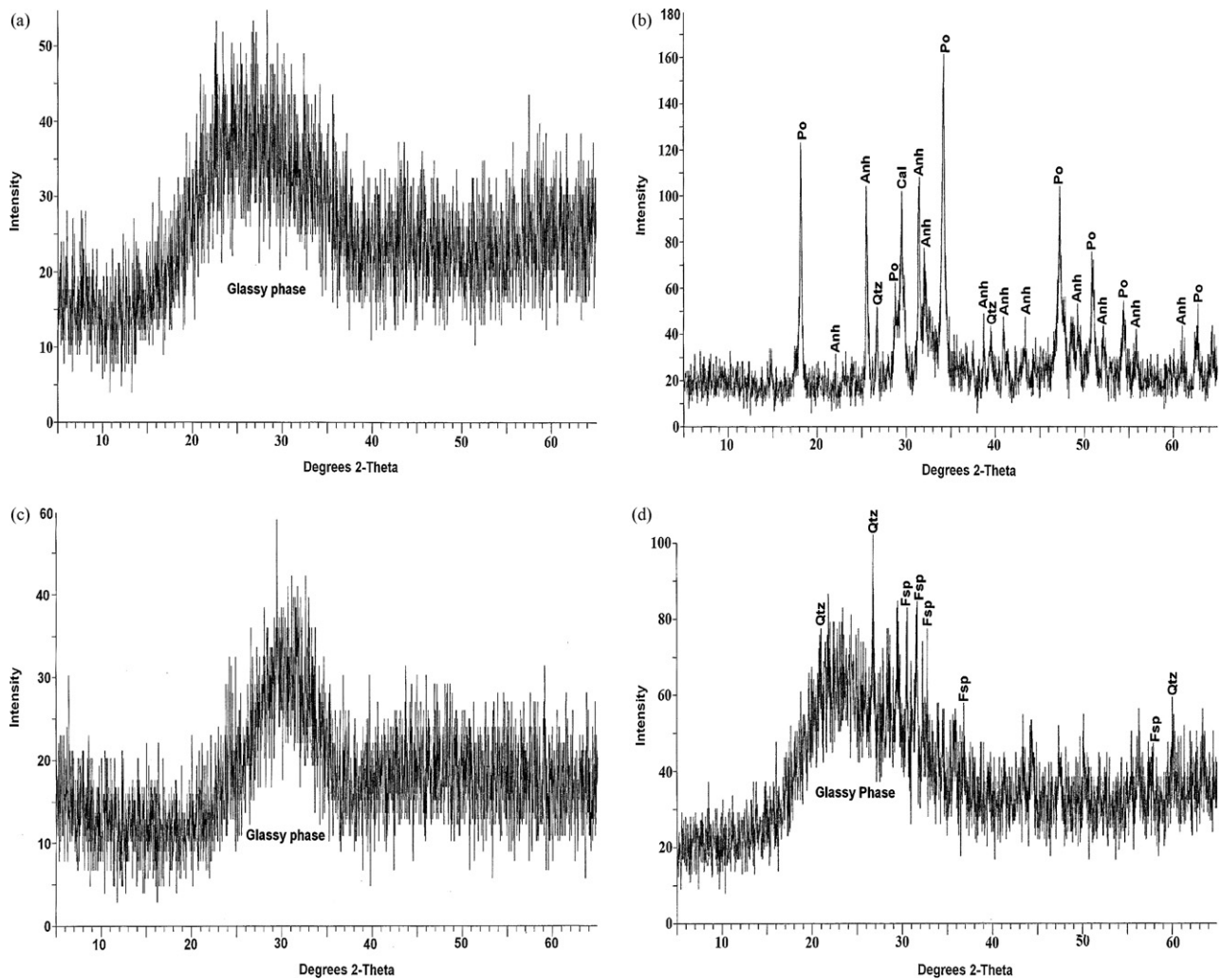
Fig. 3. XRD profiles of WG (a), FA (b), GBFS (c) and SF (d) (Qtz (quartz), Fsp (feldspar), Po (portlandite), Anh (anhydrate), Cal (calcite)).

(Table 3) that could have influenced their performance in CPB. To illustrate, FA used in the current study had a significantly low content of $SiO_2 + Al_2O_3 + Fe_2O_3$ (SAF) (21.14%). It also contained a high amount of sulphate (11.38% SO_3) and calcium (50.56% CaO), 13.86% of which was in the form of free lime. Furthermore, WG was determined to contain a significantly high level of alkali (10.75% Na_2O) (Table 2) with its potential for the detrimental alkali–silica reactions [33]. These wastes were also found to contain different levels of reactive silica (Table 2) probably as the most important component largely controlling their pozzolanic activity. Earlier studies [34,35] demonstrated that the reactive silica content of a natural pozzolan was of practical importance since it could be the indication of the degree of its pozzolanic

activity, which tended to increase with its reactive silica content.

Table 3 presents the results of pozzolanic activity tests for the waste materials. Despite the very low content of reactive components (SAF), the pozzolanic activity index of FA was sufficiently high for its qualification as supplementary material according to ASTM C 618 [32]. Except FA, the pozzolanic activities of the waste materials were consistent with their reactive silica content (Table 3). In this regard, SF showed the highest pozzolanic activity with its reactive silica content of 88.18% while GBFS had the lowest reactive silica content (37.98%) and activity index of only 70% (Tables 2 and 3). Cavdar and Yetgin [36] also noted that the pozzolanic activity decreased with an increase in Al_2O_3, Fe_2O_3, MgO and K_2O contents of natu-

Table 3
Chemical and mechanical properties of the artificial pozzolans compared with ASTM C 618 [32].

	Materials				Class (ASTM C 618-05)		
	WG	FA	GBFS	SF	N	F	C
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	74.47	21.14	51.69	91.94	Min. 70.0	Min. 70.0	Min. 50.0
SO_3 (%)	0.12	11.38	0.15	1.04	Max. 4.0	Max. 5.0	Max. 5.0
Loss-on-ignition (%)	0.01	13.90	0.12	1.79	Max. 10.0	Max. 6.0	Max. 6.0
Retained on 45 μm sieve (%)	36.62	30.41	37.04	11.89	Max. 34.0	Max. 34.0	Max. 34.0
Strength activity index							
7-day (% of control)	79	75.5	70	106	Min. 75	Min. 75	Min. 75
28-day (% of control)	86	80.5	74	124	Min. 75	Min. 75	Min. 75

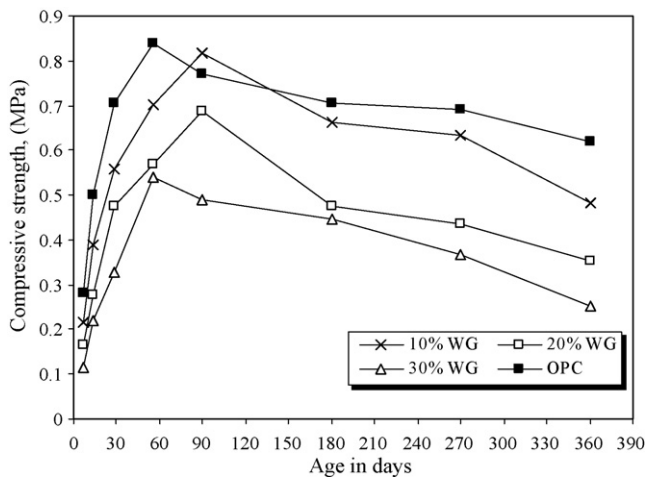**Fig. 4.** Effect of WG addition on the short- and long-term strengths of CPB samples.

Fig. 6. Effect of GBFS addition on the short- and long-term strengths of CPB samples.

ral pozzolans. However, it appears extremely difficult to account further for the interconnection of pozzolanic activity with these phases present due to the variation in the chemical composition of the waste materials.

3.2. Effect of addition of artificial pozzolans on the performance of CPB

The addition of binder is essential to provide strength and stability of CPB. Furthermore, binder characteristics and dosage exert a profound effect on the short- and long-term performances of CPB [10,11,13,14,35]. The most extensively used binder in CPB, OPC, often exhibits poor performance presumably due to its vulnerability to the sulphate attack when the sulphide-rich tailings, in particular, are involved [6,7,10,12,37]. Sulphate resistance of OPC may be ameliorated by the incorporation of pozzolanic materials (i.e. natural pozzolans such as volcanic tuffs and artificial pozzolans such as slag) into the binder phase, which also reduces the binder costs [38,39].

Figs. 4–7 illustrate the effect of addition of the pozzolanic industrial wastes (WG, FA, GBFS and SF) as a partial replacement (up to 60% by weight) of OPC on the strength and stability performances of CPB samples over a curing period of 360 days. The strength acquisition of all CPB samples was similar in character in that the samples gained strength over an initial curing period of 56–90 days; thereafter, the strength of CPB samples tended to decrease. When the
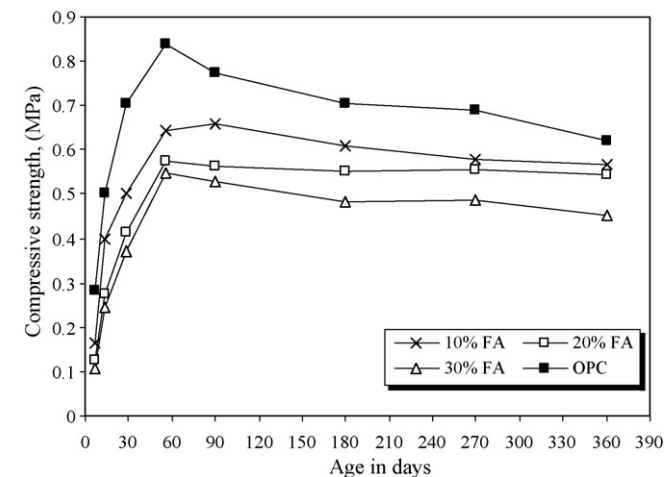
binder phase contained only OPC i.e. no addition of the pozzolanic waste materials, the development of the unconfined compressive strength (UCS) of CPB was rapid producing a maximum value of 0.840 MPa at a curing period of 56 days (Fig. 4). A trend of decline in the strength of CPB samples was observed leading to a strength loss of 26% between the 56th and 360th days though these samples were able to maintain their higher strengths than the industrially accepted threshold level of 0.7 MPa until 270 days of curing periods. The incorporation of WG (up to 30 wt% of OPC) into the binder phase did not produce the desired effect with severe losses in the strength (>41%) of CPB samples following an initial period of 56 or 90 days (Fig. 4). Visual inspection of 28th- and 360th-day CPB samples containing 30 wt% WG revealed the severity of the development of cracks in the long term (Fig. 8) in accordance with very poor long-term performance of WG for stability. This could be interrelated with its high content of alkali although further detailed studies are required to draw firm conclusions. It should be noted that the alkali present in the binder phase is known to be responsible for the undesired reactions (e.g. alkali–silica reactions) leading to the formation of phases with expansive properties in long term [33,40]. On the contrary to the current findings, Sargeant et al. [41] reported that the ground WG was effective for the replacement of OPC up to 15 wt% in the CPB of low grade sulphide tailings (2.69% S). This was confirmed by Archibald et al. [20] who reported up to 1.16-fold improvement in the strength gain of CPB samples of the tailings
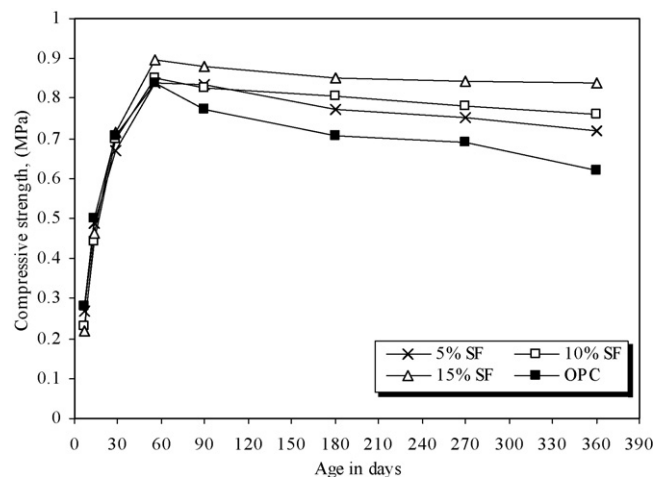

Fig. 5. Effect of FA addition on the short- and long-term strengths of CPB samples.

Fig. 7. Effect of SF addition on the short- and long-term strengths of CPB samples.
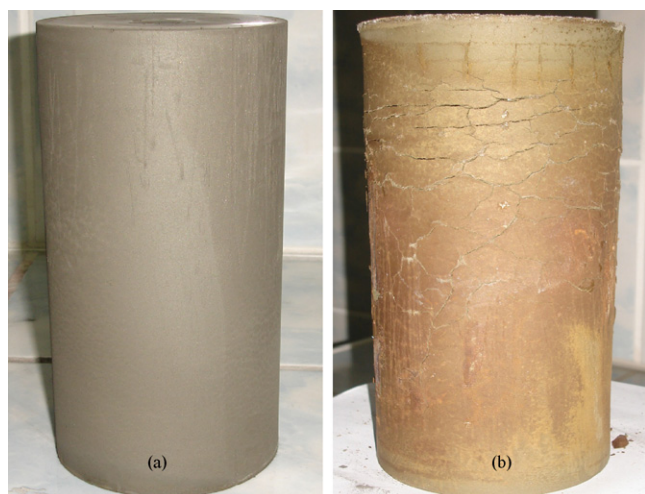
Fig. 8. Visual appearance of 28th- (a) and 360th-day (b) cured CPB samples containing WG as mineral additive at a 30 wt% replacement level.

with a low content of sulphide (0.92% S) over 224 days when OPC was partially replaced (up to 15 wt%) by WG. Similar to the findings in this study, they also reported severe strength losses in the long term for CPB samples of sulphide-rich tailings at ≤25% WG; albeit, no strength loss occurred at a higher replacement level of 35 wt%.

Despite the ameliorating effect of the addition of FA on the strength losses after 56 days of curing, CPB samples of FA produced consistently lower UCSs than those of OPC over a curing period of 360 days (Fig. 5). Furthermore, increasing the dosage of FA in the binder phase resulted in the deterioration of the acquisition of strength of CPB samples though the improvement in the long-term stability was most discernible at a replacement level of 20 wt% FA. It

can be inferred from these findings that the binder dosage needs to be increased beyond 5 wt% to improve the development and maintenance of strength of CPB samples beyond the 0.7 MPa. Although the use of FA as pozzolanic additive in CPB was reported by several researchers [11,16,17], none can be compared with the current findings due to the inherently different chemical characteristics (i.e. its high CaO but low SiO$_2$ content) of FA used in this study. In this regard, despite its low reactive SiO$_2$ content and thus, limited contribution to the strength acquisition of CPB samples, the beneficial effect of FA on the long-term stability could be related with its high neutralizing capacity for the generation of acid by the oxidation of sulphide tailings [42].

Fig. 6 shows the short- and long-term UCS results of CPB samples prepared from OPC containing 20, 40 and 60 wt% GBFS as an admixture at 5 wt% binder dosage over 360 days. The rate and extent of the development of strength of CPB samples decreased with increasing the amount of GBFS in the binder phase. Only the CPB samples containing 20 wt% GBFS were able to produce the desired strengths (>0.7 MPa) over the curing periods although the addition of GBFS remarkably mitigated the deterioration in the stability of CPB samples i.e. only 4.7% loss in strength at 20% GBFS, but none at 40% and 60% GBFS. The strength acquisition characteristics of CPB samples at the replacement levels higher than 20 wt% GBFS may be improved by increasing the total binder dosage. Benzaazoua et al. [11] found that CPB samples prepared from sulphide-rich tailings (32.2%) using a mixture of OPC (20 wt%) and GBFS (80 wt%) as binder at 3–6 wt% binder dosage failed to acquire any strength over 91 days of curing time while those samples from the tailings with low (5.2% S) and moderate (15.9% S) produced relatively high strengths. They concluded that GBFS is not suitable for CPB of high sulphide tailings but it can be readily used for low to medium grade sulphide tailings.

The strength development performance of SF was consistent with its high pozzolanic activity (Table 3) in that only CPB samples of SF were able to generate the short-term strengths even higher
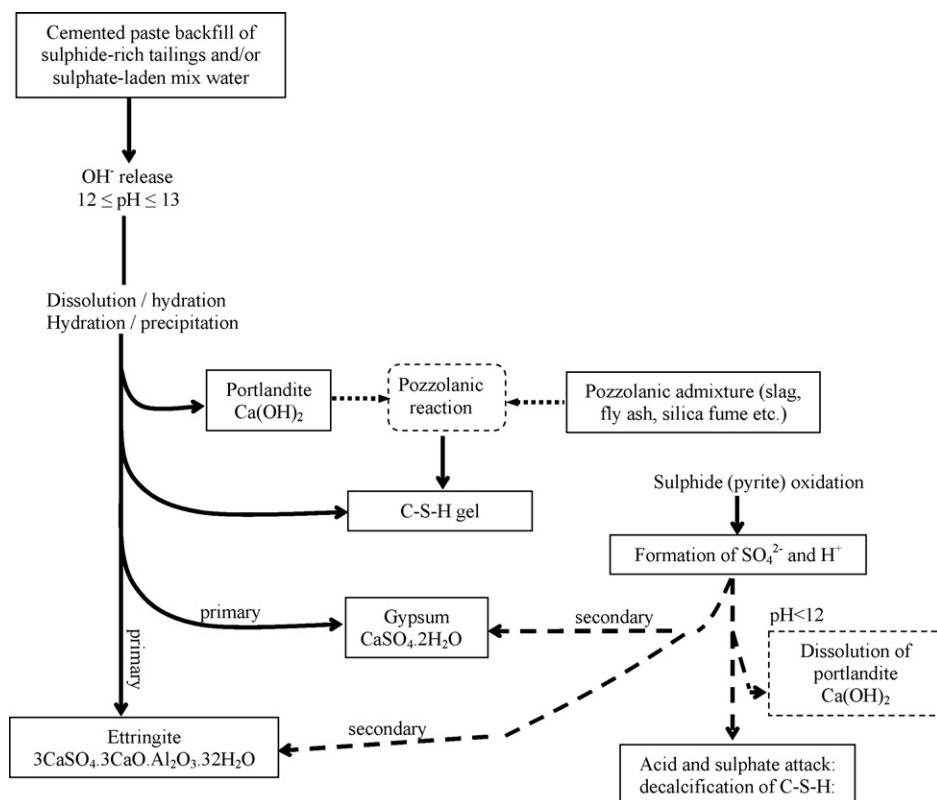

Fig. 9. Schematic diagram of the hydration and decomposition process in paste backfill (modified after Belem and Benzaazoua [44]).
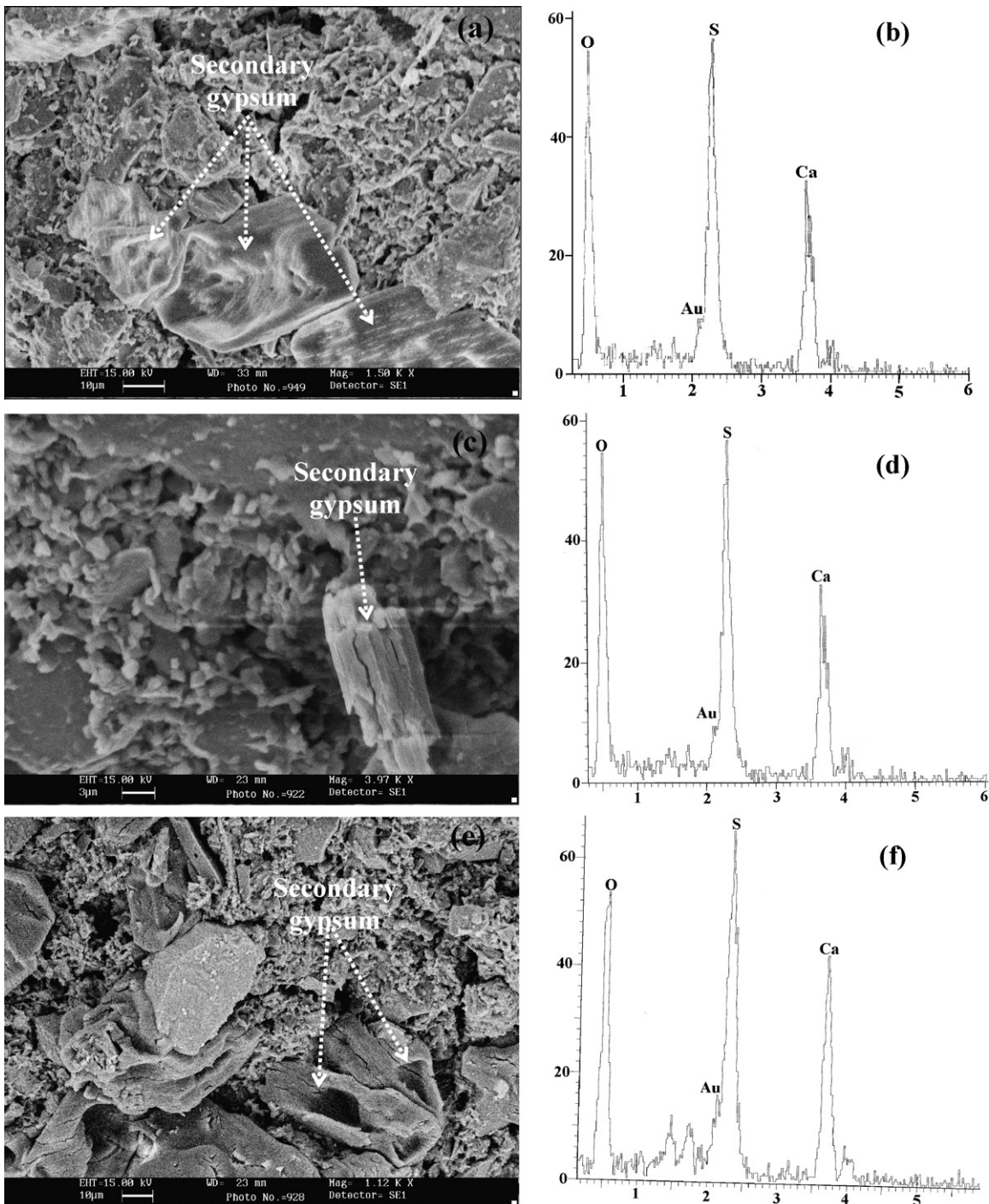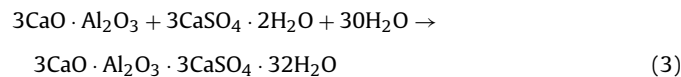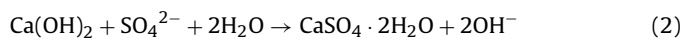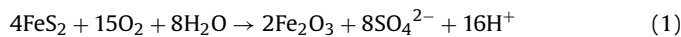
Fig. 10. SEM images of the CPB samples prepared using OPC alone (a and b) and pozzolanic wastes; WG (c and d) and GBFS (e and f) as pozzolanic additive at a replacement level of 20 wt%.

than OPC (Fig. 7). In this study, the highest strength of 0.898 MPa was obtained for CPB samples containing 15 wt% SF. The addition of SF also reduced the severity of the strength losses observed after 56 days i.e. 14% and 6.8% losses in strength at 5% and 15% SF, respectively, *c.f.* 26% with no SF. Despite these strength losses in the long term, all CPB samples containing SF maintained the strengths higher than 0.7 MPa between 56 and 360 days of curing periods. It is also pertinent to note that the addition of SF was only tested up to 15 wt% replacement levels in order to avoid potential problems associated with the flowability of CPB mixtures. Lee et al. [43] reported the beneficial effect of partial replacement OPC with SF (at

5–15 wt%) on the resistance of mortar samples to sodium sulphate attack in that the strength loss was reduced from 45% for OPC only to 15–20% for 5–15 wt% SF over one year of exposure.

Fig. 9 presents a schematic diagram illustrating the development of hydration process, mod of potential interactions of hydration products with sulphide moiety of the tailings and the potential role of pozzolanic additives [44]. Ouellet et al. [45] and Tarig and Nehdi [46] demonstrated that the sulphide phases such as pyrite present in CPB could undergo oxidation under the curing conditions in the presence of air and moisture. The oxidation of pyrite yields acid and sulphate (Eq. (1)). The former can attack and destruct C–S–H

bonds while the latter can react with portlandite ($Ca(OH)_2$) (as the hydration product) and three calcium aluminate (C_3A) to form secondary gypsum (Eq. (2)) and ettringite (Eq. (3)) with these leading to the expansion and development of microcracks in cured CPB [10,39,45–49]. Acid and sulphate attacks can culminate eventually in the loss of stability of CPB. In SEM studies, secondary gypsum was identified to be the ubiquitous phase in CPB matrix though no ettringite phase was clearly detected (Fig. 10). Fall and Benza-azoua [50] and Tarig and Nehdi [46] also observed the formation of secondary gypsum, which was claimed to be responsible for the reduction of strength of CPB samples after 56 and 90 days, respectively, due to its expansive properties. It is pertinent to note that the formation of secondary gypsum does not always produce an adverse effect on the strength of CPB since the secondary gypsum in certain quantity could also fill the voids within CPB. This in turn leads to a decreased porosity and higher strength of CPB in short and long terms [11,50].

$$4FeS_2 + 15O_2 + 8H_2O \rightarrow 2Fe_2O_3 + 8SO_4^{2-} + 16H^+ \tag{1}$$

$$Ca(OH)_2 + SO_4^{2-} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + 2OH^- \tag{2}$$

$$3CaO \cdot Al_2O_3 + 3CaSO_4 \cdot 2H_2O + 30H_2O \rightarrow$$
$$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \tag{3}$$

The beneficial effect of addition of the pozzolanic wastes can be ascribed to the consumption of the hydration product (portlandite) to form secondary C–S–H phases with bonding properties [35,39,51]. Furthermore, the addition of pozzolanic materials into the binder phase is expected to ameliorate the microstructure of CPB leading to a denser packing with lower porosity and permeability. This, in turn, alleviates the oxidation of pyrite present in CPB due to the likely mitigation of ingress of moist and air. The importance of microstructure for the strength and stability of mortar and CPB has been highlighted in many studies [11,13,52–54].

4. Conclusion

This study highlights the strength and stability problems associated with CPB of sulphide-rich tailings in the long term and the potential use of various industrial waste products having pozzolanic properties as mineral additives for the partial replacement of ordinary Portland cement to improve the binder properties/performance and to reduce binder costs in CPB. These wastes were found to show a varying degree of pozzolanic activity apparently linked with their chemical properties though only SF was able to produce a strength activity index of >100%. A general trend of loss in the strength of CPB samples occurs in the long term after the initial curing periods of 56 days when OPC is used in the binder phase. The incorporation of pozzolanic wastes; FA, GBFS and SF into the binder phase appeared to mitigate the strength losses in the long term although the initial rate of development of strength of CPB samples tended to slow down with increasing the dosage of these pozzolanic wastes in the binder phase. However, the addition of WG (10–30 wt%) was observed to lead to the strength losses even more severe than those noted for the CPB samples of OPC only. Despite their beneficial effect on the long-term performance for stability, CPB samples containing FA (at 10–30 wt%) and GBFS (at >20 wt%) did not sustain the strengths above the threshold level of 0.7 MPa over 360 days. The partial replacement of OPC with SF (up to 15 wt%) allowed CPB samples to maintain consistently higher strengths (>0.7 MPa) after 56 days than those samples of OPC only. The deterioration in the long-term stability of CPB samples can be attributed to the interactions of hydration products with the sulphate and acid that form as a result of oxidation of sulphide

moiety of the tailings under the curing conditions. The formation of expansive phases such as gypsum was already confirmed by SEM studies.

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