



Preliminary Study on the Use of Reverse Osmosis Brine and Mine Tailings as Cement Paste Mixtures for Mine Backfilling Application

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Abstract The processing of low-grade gold ores generates a significant volume of tailings and wastewater that impacts the environment. The treatment of wastewater using reverse osmosis (RO) produces brine as a by-product with high salinity levels. Improper disposal of mine wastes can significantly pollute water bodies and soils. A novel and sustainable method for managing, disposing, and handling these wastes is vital. The use of RO brine and mine tailings to produce cement paste mixtures for backfilling applications has been investigated. Sulfide gold mine tailings and RO brine were characterized, and cement paste backfill (CPB) mixtures were prepared by mixing varying proportions of cement and RO brine. The CPB cubes were cured for a specified number of days, and their physical and mechanical properties were determined. The results indicate a decrease in slump value with increasing cement content, whilst the slump increased with RO brine content. The compressive strength at 28 days increased with binder content reaching a maximum of 1.83 MPa

using 50% RO brine. The CPB cubes produced with 50% RO brine and 12 wt.% cement possessed the required combination of fluidity and strength for mine backfilling applications.

Keywords Reverse osmosis · Brine · Mine tailings · Cement paste backfill · Compressive strength

1 Introduction

Mining industries usually use wastewater treatment facilities to manage their mine effluent. The treated material may subsequently be reused as process water in the mine or discharged as waste into the environment. Generally, mine effluents have high acidity and contain high concentrations of chloride, dissolved metal ions, and sulfates (Araujo et al., 2022; Hatar et al., 2013). Accordingly, untreated or poorly treated mine effluents are toxic and significantly pollute water bodies and soils when discharged, thus degrading the existence of organisms therein. To this effect, strict discharge guidelines, such as the Ghana standards GS 1212 (Owusu-Ansah et al., 2015), are provided by environmental protection agencies to mitigate the likelihood of environmental contamination. Several wastewater treatment techniques, including flotation, coagulation and flocculation, ion exchange, chemical precipitation, and membrane filtration, are available for refining mine effluents (Fu & Wang, 2011; Samaei

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et al., 2020). Among these techniques, the reverse osmosis (RO) membrane separation method is the most widely used technique due to its high efficiency at high feed temperatures during mining (Al-Zoubi et al., 2010). RO water treatment systems utilize a high-pressure selective membrane separation process to remove large molecules and ions from the wastewater, producing an RO permeate and, subsequently, a brine stream characterized by high salinity levels (65,000–85,000 mg/L) as a by-product (Abdul-Wahab & Al-Weshahi, 2009). The salt concentration of the RO brine produced is usually approximately twice that of natural seawater (De Vito et al., 2011). Consequently, it exhibits a high potential to detrimentally impact receiving environments' physicochemical and ecological attributes (Roberts et al., 2010). Thus, researchers continuously explore novel and sustainable methods for managing, disposing, and handling RO brine (Ali, 2021; Panagopoulos et al., 2019; Shanmuganathan et al., 2016).

For instance, in the mining industry, the brine stream is recirculated to the mine process water circuit or transferred to a precipitation reactor where lime and sodium hydroxide are added to produce gypsum (Feng et al., 2000). Although this recycling approach may be beneficial, continuous recirculation of the RO brine stream results in total dissolved solids (TDS) build-up in the mine process water circuit, causing detrimental effects to the water treatment facilities. Alternatively, solar ponds, crystallization, and deep-well injection methods can be employed to manage or dispose of RO brine (Ahmed et al., 2000; Khan & Al-Ghouti, 2021; Greenlee et al., 2009; Pramanik et al., 2017). However, these management options are capital-intensive and environmentally unfriendly. In particular, solar pond management of brine requires a large land size and depends on the climate and regular removal of precipitated salts (Khan & Al-Ghouti, 2021). Additionally, crystallization methods require expensive evaporator units for brine treatment, while the deep-well injection disposal approach is typically considered an opportunistic rather than a generic solution (Mahlaba et al., 2011). Interestingly, an eco-friendly and less expensive brine management option that considers substituting portable water with brine in the preparation of paste backfill material has received much attention recently (Sivakugan et al., 2015). A study by Mahlaba et al. (2011) demonstrated that using chloride

and sulfate-rich industrial brines in cementitious mixtures such as paste and mass concrete produced high-strength properties.

In addition to the RO brine, mining operations generate large volumes of tailings, inconveniently occupying spaces in landfills and causing environmental contamination when improperly disposed of (Qi et al., 2018; Schoenberger, 2016). The composition of mine tailings depends on the nature of the ores being processed and the beneficiation techniques adopted (Araya et al., 2020). Tailings accumulate over the life of the mine and create challenges in terms of storage, stability, safety, and potential adverse impacts on the environment. Consequently, tailing management procedures aim to minimize production and increase tailings' reuse. One emerging alternative for reusing mine tailings is preparing paste backfill for underground mining voids (Hefni et al., 2021; Yilmaz & Yilmaz, 2018). Mine backfilling involves filling voids created during underground excavations to provide ground support to the underground environment. That is, the two main mine-generated waste streams can be repurposed, thus enhancing sustainable mining operations. Against this background, this study explores the potential utilization of RO brine and gold mine tailings to prepare underground paste backfill mixtures. This practical waste management approach is (i) economically friendly as no additional cost is required for materials acquisition and (ii) presents an environmentally safe way of handling these otherwise considered toxic materials, conserving natural resources. The fresh and hardened paste backfills produced in the current work are characterized, and structure–property relationships are discussed. The stabilization effect of cement on tailings was investigated through remobilization tests, and the results were presented.

2 Materials and Methods

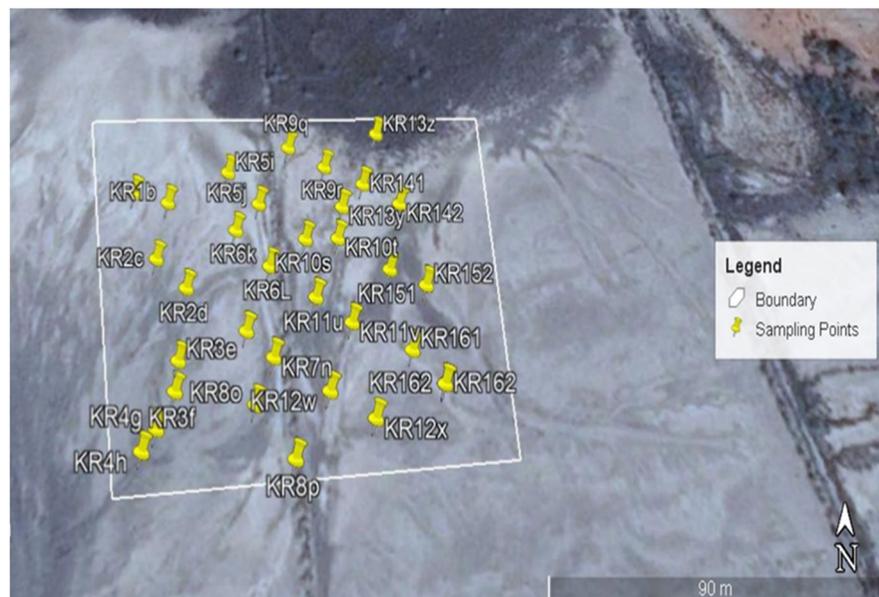
2.1 Sample Collection and Preparation

RO brine and underground (UG) water, used to prepare the paste backfill mixtures, were sourced from a gold mining company in Ghana. Sample bottles were thoroughly washed with 10% nitric acid (HNO_3) solution, rinsed with distilled water, and air-dried before use. The gold mining company operates two RO water treatment plants with different permeate flow rates of 250 m^3/h and

500 m³/h. Eight discrete samples were collected hourly for 8 h from each RO plant and combined to provide a representative sample. Similarly, UG water samples were collected from the different outlet shafts at the mine. The collected RO brine and UG water samples were transported to the laboratory in an ice chest and stored in a refrigerator at 4 ± 2 °C until testing. Furthermore, water samples for metal ion characterization were acidified with a drop of concentrated (>65%) HNO₃ to prevent precipitation of ions and stored at the designated temperature (4 ± 2 °C) before testing. RO brine and UG water samples were brought to room temperature in the laboratory mixing area before preparing the various paste backfill mixtures.

Tailings samples were collected from the decommissioned tailings storage facility (TSF) in the mine. Samples were taken from a 100 m × 100 m² grid. Sixteen different 25 m × 25 m grid cells (sampling sites) were demarcated within the 10,000 m² grid. At each sampling site, soil samples were collected down to a depth of 0.7 m from two different sampling points about 15 m apart using a backhoe and a shovel. The two soil samples within each sub-grid were composited to obtain 16 samples which were put together and homogenized into one composite sample. The bulk composite sample was put into sterile plastic polythene bags and used as fine aggregate in the paste backfill mixtures. Figure 1 shows the tailing sampling points.

Fig. 1 Tailing sampling points within the demarcated area



2.2 Determination of Physical Properties

The pH, electrical conductivity (EC), and total dissolved solids (TDS) of the water samples were measured using a dual calibrated pH meter, an Eu-Tech CON 2700 EC meter, and an Eu-Tech WP COND 610 Bench Top TDS meter, respectively. Likewise, the turbidity of the water samples was measured using a turbidity meter. The total water hardness was calculated from the equation:

$$\text{Hardness} = 2.497(\text{Ca}) + 4.118(\text{Mg}) \quad (1)$$

where Ca and Mg represent mean concentrations of calcium (Ca) and magnesium (Mg) in water samples, respectively. The Ca and Mg concentrations were determined using Agilent 7900 inductively coupled plasma mass spectrometer (ICP MS).

Total suspended solids (TSS) were determined via the direct method. The concentrations of chloride, sulfate, and phosphate anions in tailings were analyzed using the KONELAB 20 Aquakem discrete analyzer. Ten grams of the soil was taken and mixed with deionized water in a soil-to-water ratio of 1:5. The mixture was stirred continuously for 2 h and allowed to settle. The mixture was then filtered through a 0.45-µm filter paper before measurement. The concentration of CN was determined following

the procedure described in APHA 4500 (APHA, 2005) using NaOH, H₃NSO₃ and MgCl₂.

Particle size distribution (PSD) analysis was carried out with an Endecotts EFL 2000 electromagnetic sieve shaker using 0.075- μ m, 0.053- μ m, 0.15- μ m, 0.212- μ m, 0.3- μ m, 0.6- μ m, and 1.18-mm sieve sizes. Sedimentation analyses were also performed on the soil using a hydrometer, according to the protocols outlined in ASTM D7928-17 (ASTM, 2021). The mass percentage of particle sizes was determined using a semi-logarithmic scale.

2.3 Determination of Chemical Properties

An aliquot (5 mL) of RO brine and UG water was taken to evaluate their respective elemental composition according to ASTM D5673-16. The water samples were digested in Teflon vessels for 20 min via the 2-acid digest method using concentrated HNO₃ and HCl in the combination of 2:1. Approximately 3 mL of HCl was used. After acid digestion, the cooled solution was diluted with distilled water to the 50 mL mark on a volumetric flask. The arsenic and metal ion concentrations in the samples were then determined using Agilent 7900 ICP-MS. The KONELAB 20 Aquakem discrete analyzer was also employed to evaluate the concentrations of chloride, sulfate, and phosphate in water samples, per APHA 4500 (APHA, 2005). Blank was prepared for quality control. The chemical analysis of the tailing and cement samples was determined via VMR-Olympus X-ray fluorescence. Type II ordinary Portland cement (OPC), supplied by GHACEM, was selected as the binder for the paste backfill mixtures. The chemical composition of the cement and the tailings used, as determined by XRF, are shown in Table 1.

2.4 Preparation of Cement Paste Backfill Mixtures and Cubes

Table 2 presents the mix design for preparing the CPB mixtures and cubes. A total of 12 mixed formulations were investigated. The pastes were prepared by mixing tailings with varying contents of ordinary Portland Cement (binder) at 8 wt.%, 12 wt.%, and 16 wt.% of the total

weight of the solids in the mix, respectively. RO brine and UG water were used as the mixing water in combinations described in Table 2. A water-to-solid ratio of 0.42 was used for all mixtures. Mixing was carried out using a rotary mixer following ASTM C-305–20 (ASTM, 2020). After mixing, the workability of the paste mixtures was determined via slump tests and the pastes were cast in wooden cube molds of dimensions 100 mm×100 mm×100 mm. Three samples were cast from each paste mix batch described in Table 2. The cast samples were cured in the wooden mold at room temperature for 48 h and de-molded and air-cured for 7, 14, 28, 56, and 77 days, as shown in Fig. 2. Thus, 180 CPB cubes were prepared for unconfined compressive strength (UCS) analysis.

2.5 Characterization Studies

The slump, indicating the workability and transportability of the CPB mixtures, was determined using a standard slump cone on a wetted concrete slab. Slump tests were carried out according to the standardized procedure described in ASTM C143-12 (ASTM, 2012). Elemental and morphological analyses on the fractured surface of CPB cubes were carried out using an energy-dispersive

Table 2 Mixed design for the preparation of cement paste backfill (CPB) mixtures

SN	Water		Solids	
	%UG	%Brine	wt.% Tailings	wt.% Binder
U100B8	100	0	92	8
U50B8	50	50	92	8
U25B8	25	75	92	8
U0B8	0	100	92	8
U100B12	100	0	88	12
U50B12	50	50	88	12
U25B12	25	75	88	12
U0B12	0	100	88	12
U100B16	100	0	84	16
U50B16	50	50	84	16
U25B16	25	75	84	16
U0B16	0	100	84	16

Table 1 Chemical compositions (wt.%) of cement and tailings

Sample	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	CaO	P ₂ O ₅	K ₂ O	TiO ₂	MnO	LOI
OPC	26.15	2.91	1.48	2.97	63.00	0.07	0.42	0.30	0.05	0.46
Tailings (Soil)	64.57	9.41	1.62	6.01	2.08	0.05	1.27	0.57	0.12	14.1

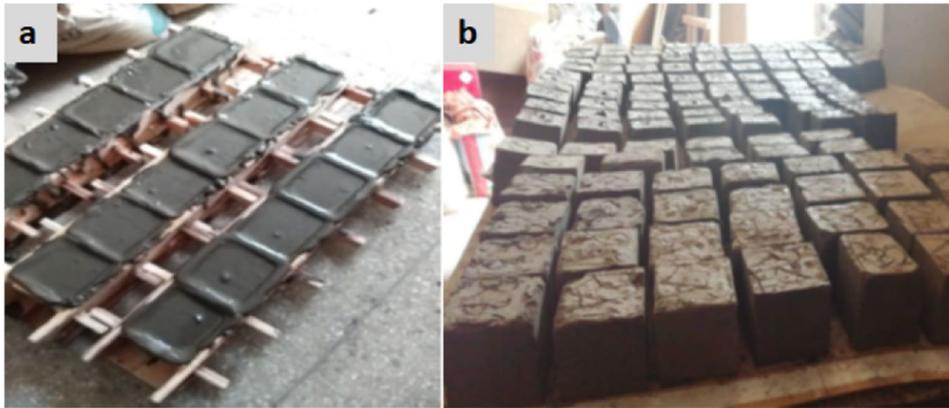


Fig. 2 Curing condition of paste backfill cubes **a** in wooden molds and **b** in air, at room temperature

X-ray spectrometer (EDX) analyzer attached to the scanning electron microscope. Phase identification of the soil and cured samples was conducted at a 2θ range from 5 to 65° via X-ray diffraction techniques (PANalytical Empyrean Series 2), using $\text{Cu K}\alpha_{1,2}$ radiation at 45 kV and 40 mA. Mineral phase identification was achieved using the Jade MDI analysis software package.

The UCS of the hardened CPB cubes at the respective test ages was determined as per BS EN 1015–11 (BSI, 1999). UCS tests were carried out with the PROETI DI CPN2 Universal Tensile Test machine.

2.6 Remobilization Studies

Remobilization studies were carried out on CPB cube samples air-cured for 77 days. A representative from each paste mix batch was placed in a separate leaching basin filled with 300 mL of distilled water. The leaching basins were tightly sealed to minimize evaporation and stored at room temperature for 77 days. Total dissolved solids were determined during storage every 48 h until an equilibrium was reached. At the end of the 77-day test period, ICP-MS analysis was carried out on the leachate solution to determine the concentration of dissolved arsenic and metal ions.

3 Results and Discussion

3.1 Physicochemical Characterization of RO Brine and Underground Water

Table 3 presents the results of the physical and chemical properties of RO brine and underground

(UG) water. A pH range of 7.4–7.7 was observed for the RO brine, whereas the underground water measured a pH range from 7.2 to 7.4. The pH values for brine and UG water samples were within the Ghana standard limit (GS 1212—2019) range of 6–9 for effluent discharge. Both water samples' turbidity and TSS levels were below Ghana's standard requirements. On the other hand, the electrical conductivity (EC) for brine and UG water was 17,900 mg/L and 2290 mg/L, respectively, above the specified minimum concentration of 1500 mg/L. The high EC in both RO brine and UG water suggest that these water bodies have been contaminated by dissolved salts.

Table 3 Physicochemical parameters of RO brine and UG water samples

Component	Unit	Brine	UG	GS 1212
pH	--	7.4–7.7	7.2–7.4	6.0–9.0
EC	$\mu\text{S}/\text{cm}$	17,900	2290	1500
TDS	mg/L	15,525	1740	1000
TSS	mg/L	1.13	5	50
Turbidity	NTU	0.91	3.9	75
Calcium	mg/L	974	152	250
Magnesium	mg/L	1518	244	2
Sodium	mg/L	2550	53.5	200
Potassium	mg/L	168.50	4.9	5
Chloride	mg/L	255	9.4	250
Sulfate	mg/L	12,075	1070	300
Arsenic	mg/L	0.16	0.95	0.1

The brine and UG water TDS exceeded the GS 1212 (2019) limit of 1000 mg/L at 15,525 mg/L and 1740 mg/L, respectively. RO brine indicated a high total hardness level of 9370.15 mg/L, while UG water recorded total hardness of 1561 mg/L. The results are consistent with other research outcomes (Abdul-Wahab & Al-Weshahi, 2009; Mahlaba et al., 2011) and suggest that the RO brine contained higher salt than UG water. The hardness of water is usually an indication of the presence of salts of calcium and magnesium, especially $\text{Ca}(\text{OH})_2$, CaCO_3 , and $\text{Mg}(\text{OH})_2$ (Iyama et al., 2014). High levels of Cl^- , SO_4^{2-} and other ions increase the value of TDS in water (Edori & Kpee, 2016; Mahlaba et al., 2011).

The high SO_4^{2-} content in both water samples (Table 3) can be associated with the mining activities. Arsenic (As) concentration in the UG water (0.95 mg/L) was higher compared to that of RO brine (0.16 mg/L). This observation is credited to the pre-treatment of the RO feed water, reducing the overall arsenic concentration. Nonetheless, the arsenic concentration recorded for both water samples exceeded the Ghana standard GS 1212 (2019) requirement of 0.1 mg/L. The presence of arsenic is linked to the considerable amount of naturally occurring arsenic that is liberated from the arsenic-bearing gold ores (arsenopyrite) during gold extraction (Álvarez-Ayuso & Murciego, 2021; Mesa Espitia & Lapidus, 2021). Hence, these occurrences may account for the high levels of arsenic detected in the untreated UG water samples.

3.2 Physicochemical Characterization of Tailing Samples

The result of the PSD for tailings is shown in Fig. 3a. A particle size range of 0.0015–2.0 mm was obtained. Tailings were found to have approximately 44% sand, 34% silt, and 21% clay fractions. The maximum particle size for paste preparation must be less than 25 mm, and the finer particle concentration must be greater than 40% (Wang et al., 2009). From the PSD results, it is concluded that tailings samples contained more fine particles (55%), hence will be a suitable material for preparing the paste. Figure 3b presents the typical morphology of the tailings used in this study. The particles mainly exhibited sub-rounded

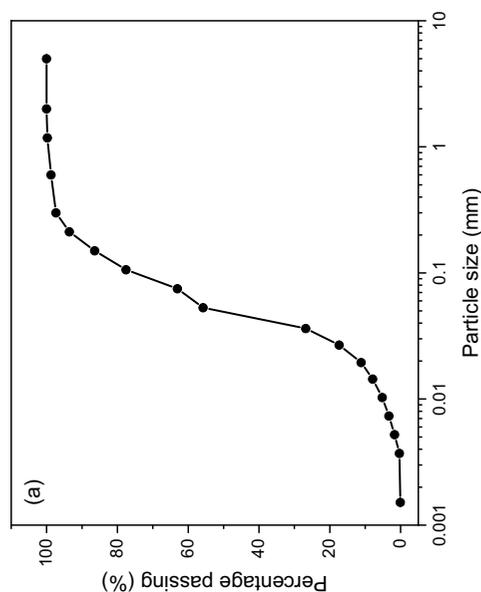
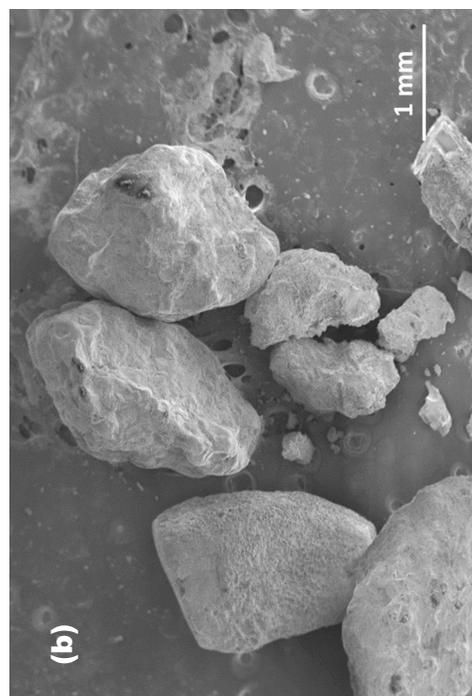


Fig. 3 a Particle size distribution and b morphology of tailing sample

and angular particle shapes. Additionally, some plate-like particles, characteristic of the clay, were also observed.

The chemical composition of the tailings (Table 1) showed that the material predominantly consists of SiO₂ (64.57%) with relatively high Al₂O₃ content (9.41%) and minor fractions of MgO, P₂O₅, SO₃, K₂O, CaO, TiO₂, and MnO. The SiO₂ is the main component of sand, whilst the associated oxides are components of clay. A previous study conducted by other researchers also revealed the primary chemical composition of gold mine tailings as SiO₂, CaO, Al₂O₃, and MgO (Kiventerä et al., 2018, 2019). Among the compounds identified, Al₂O₃, CaO, and MgO reportedly increase the coagulation and strength development of the cemented tailings backfill (Hefni et al., 2021). XRD analysis of the tailings showed a mineralogical composition dominated by quartz (SiO₂), with minor fractions of albite (NaAlSi₃O₈) and iron oxide (Fe₃O₄). No trace of sulfide mineral, such as pyrite, was identified.

A summary of the physicochemical characteristics of the tailings is presented in Table 4. The tailings were alkaline, with pH values ranging from 8.4 to 9.0. The alkaline nature of the tailings may be attributed to the lime used to precipitate arsenic and neutralize acidic liquors during the processing of gold ores. A sulfur and arsenic concentrations of 2101.25 mg/kg and 713 mg/kg found were due to the arsenopyrite (FeAsS) ore used at the mining company where the tailings were sourced.

Table 4 Physicochemical parameters of tailings

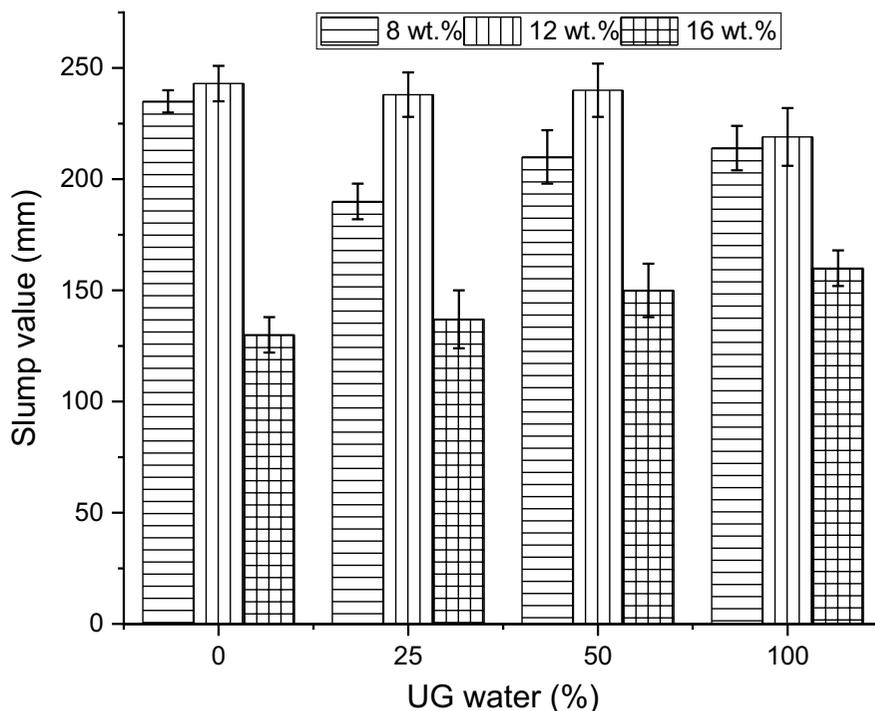
Parameter	Unit	Value
pH	–	8.4–9.0
EC	µS/cm	237.60
Chloride	mg/kg	< 5
Sulfate	mg/kg	329.60
Phosphate	mg/kg	1.45
Calcium	mg/kg	18,000
Magnesium	mg/kg	9368.75
Sodium	mg/kg	82.06
Arsenic	mg/kg	713
Potassium	mg/kg	249.37
Sulphur	mg/kg	2101.25
Cyanide (free)	mg/kg	0.37
Cyanide (total)	mg/kg	0.42

The presence of sulfur-bearing compounds (sulfate) has been reported to deteriorate the quality of cement works (pastes, mortars, and concrete) (Bernier et al., 1999; Santhanam et al., 2001). The tailings also contained minimal chloride concentrations (< 5), below the instrument's detection limit. The free and total cyanide contents resulting from the gold leaching process were 0.37 mg/kg and 0.42 mg/kg, respectively.

3.3 Characterization of Paste Backfill Mixtures

A slump test measures paste consistency to determine the workability or flowability of the paste material. Usually, CPB with high slump property has high pumping ability at the expense of the hardened compressive strength. Meanwhile, high strength with low transportation property is obtained at a low slump value. CPB with low slump may also promote the presence of air voids (Niroshan et al., 2018). The ideal slump for paste mixtures used in backfill applications is typically 200 ± 50 mm (Tikou & Benzaazoua, 2007). Figure 4 illustrates the slump obtained for CPB mixtures produced in this study. The slump values for all the UG water percentages investigated were within the acceptable slump range, except for mixtures containing 16 wt.% binder, which recorded lower slump values of 130–160 mm. In practice, increasing the cement amount while maintaining the water content decreases the slump properties of the mix due to the higher percentage of fine cement particles (increase in the specific surface area), thus the higher water demand (Afshinnia & Rangaraju, 2015; Nochaiya et al., 2010). This was evident in mixtures containing 16 wt.% binder compared to 8 wt. % binder mixtures. However, at 12 wt.% binder content, an increase in the slump was recorded. This can be associated with the decrease in tailing content. Reducing the content of tailings in the mixtures, which potentially have higher water absorption capacity, avails a surplus of free water that acts as a lubricate to increase the flowability of the mixtures (Wang & Huang, 2010). Additionally, another school of thought suggests that increasing very fine particle content induces a filler effect to occupy the voids between sand grains and the total void percentage in the mix; thus, less water is required for improved workability (Ahmad et al., 2021). These

Fig. 4 Effect of UG water on the slump values of paste mixtures



slump results imply that CPB mixtures containing 16 wt.% binders may clog pipelines during transportation, causing challenges in the underground placement of such CPB mixtures (Ouattara et al., 2017).

Table 5 presents the chemical compositions of CPB mixtures after 28 days of curing. The significant oxides, CaO, SiO₂, Al₂O₃, and Fe₂O₃, that facilitate the hydration process of cementitious materials were identified in all samples. It has been reported that Al₂O₃, CaO, and MgO increase the coagulation and strength development of cemented tailings backfill, with MgO possessing early strength development characteristics (Hefni et al., 2021). It can be observed from Table 5 that as the binder content increased, a decrease in SiO₂ and Fe₂O₃ content occurred while CaO (from the cement binder) increased. This outcome is expected since the initial XRF analysis revealed that the tailings (arsenopyrite) contain substantial amounts of SiO₂ and Fe₂O₃. Consequently, as the amount of tailings is decreased with increasing binder content (Table 2), the relative percentages of these components potentially decrease. The results also demonstrate that SiO₂ from the cement had a negligible influence on the paste composition, considering that an increase in binder content did not increase the overall SiO₂

present. It is also worth noting that at all the binder percentages investigated, the amount of sulfur (SO₃) in the paste increased with increasing RO brine water content in the makeup mix water. This is attributed to the high sulfate content (12,075 mg/L) in the RO brine water, as seen in Table 3. A similar observation can be made for K₂O; however, due to the potassium released from the cement binder during hydration (Chen & Brouwers, 2010), this occurrence becomes prominent as the binder content increases.

XRD analysis was carried out on the CPB mixtures after 28 days of curing. All the samples, regardless of their composition, indicated similar primary hydration phases identified as ettringite (Ett), portlandite (CH), calcium silicate hydrate (CSH), and quartz (S). These phases are consistent with findings reported in previous studies (Yan et al., 2019; Zhou et al., 2020). The XRD spectra of CPB containing 16 wt.% binder with 100% RO brine water (U0B16) and 100% UG water (U100B16) are shown in Fig. 5a.

It could be observed that the hydration phases identified were the same in both samples. The XRD spectra also exhibited quartz peaks representing the high SiO₂ content from the tailings. The high sulfate content of the RO brine did not influence the

Table 5 Chemical composition of paste backfill mixtures after 28 days of curing

	8 wt.% Binder				12 wt.% Binder				16 wt.% Binder			
	100% UG	50% brine	75% brine	100% brine	100% UG	50% brine	75% brine	100% brine	100% UG	50% brine	75% brine	100% brine
MgO	1.06	0.82	0.96	1.57	1.02	0.96	0.74	1.09	1.07	0.75	1.33	1.30
Al ₂ O ₃	8.45	8.44	8.82	7.46	8.24	7.93	7.32	8.56	8.28	7.76	8.13	8.12
SiO ₂	54.02	53.71	55.53	59.35	51.91	53.14	56.09	52.14	50.43	53.35	50.43	49.62
P ₂ O ₅	0.04	0.04	0.04	0.04	0.05	0.05	0.04	0.06	0.05	0.03	0.04	0.05
SO ₃	0.53	0.76	0.76	0.68	0.59	0.66	0.73	0.96	0.89	0.77	1.01	1.16
K ₂ O	1.17	1.17	1.21	0.99	1.12	1.02	0.96	1.18	1.10	1.034	1.11	1.11
CaO	6.30	6.38	6.55	5.76	8.35	7.95	7.70	8.44	9.36	8.93	9.29	9.58
TiO ₂	0.54	0.49	0.49	0.49	0.49	0.51	0.47	0.49	0.48	0.45	0.44	0.43
MnO	0.10	0.10	0.11	0.11	0.10	0.11	0.11	0.10	0.10	0.10	0.09	0.10
Fe ₂ O ₃	5.56	5.52	5.65	6.33	5.46	5.39	6.06	5.19	5.30	5.83	5.29	5.11

ettringite formation, as varying the mixed water content did not reflect the intensities of the peaks representing the hydration phases. However, the high sulfate content was detected during XRF analysis (Table 6); thus, further quantitative diffraction analysis may be required to elucidate such phase changes.

Subsequent high-magnification SEM–EDX analysis was carried out to identify the hydration phases in the CPB samples. A typical example of the microstructure of a fractured CPB cube is shown in Fig. 5b. A needle-like microstructure characteristic of ettringite was observed with cloud-like C–S–H gels and the typical plate-like features of portlandite. At low magnification (Fig. 6a), the SEM micrographs revealed the presence of tailings on the fractured surface, identified as isolated quartz via EDX (Fig. 6b).

The unconfined compressive strength (UCS) is regarded as the most helpful measure for comparing the relative strengths of cemented backfills (Wang et al., 2019). This paper presents only compressive strength values at 28, 56, and 77 days. In several scenarios, the suitable UCS for a typical backfill material for mining activities is 0.7–2.0 MPa (Brackebusch, 1995). It must be mentioned that in this study, the 7-day UCS values obtained were greater than 0.3 MPa for all mixtures investigated. Figure 7a–c presents the UCS of CPB cubes cured at different ages for mixtures containing various binder percentages. Figure 7d illustrates the effect of the makeup water on the 28-day UCS at the respective binder contents. Generally, the UCS of the CPB was observed to increase with increasing binder content. Maximum UCS values were recorded for samples containing 16 wt.% binders. The increase in strength can be associated with better compaction due to the higher density of this mixed batch and improved particle packing owed to the finer cement particles (Ke et al., 2015; Kwan & Wong, 2008; Niroshan et al., 2018). This is demonstrated by the lower slump observed for mixtures with 16 wt.% binder content (Fig. 4).

Kesimal and Ercikdi further exhibited in their work that a substantial difference in strength can be obtained with a 1-in. change in the slump (Kesimal et al., 2004). Additionally, higher cement content relates to an increase in the proportion of the cementitious CSH formed, which is the major contributor to the compressive strength of cement works (Juenger & Siddique, 2015; Sun et al., 2020).

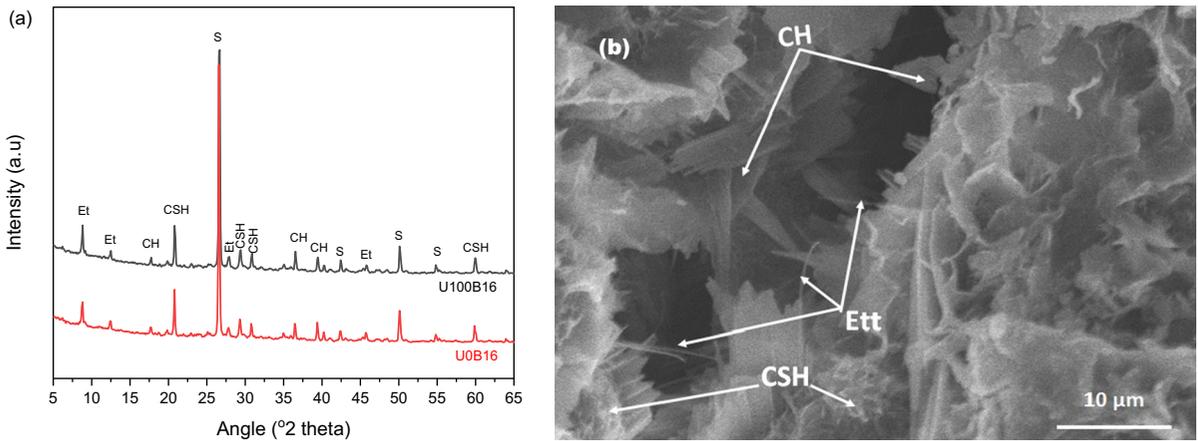


Fig. 5 **a** XRD patterns of cement paste backfill cubes after 28 days of curing and **b** microstructure of fractured cement paste backfill showing hydration phases in sample U100B16

Table 6 Metal concentration (mg/L) in leachate for 12 wt.% binder at varying UG water content

UG water	As	Ca	Na	K	Mg	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻
0%	1.6	167	400	124	1.7	53.3	4.77	1400
25%	1.5	178	312	118	2.7	43.7	6.29	947
50%	1.1	157	240	112	3.4	32.2	7.87	924
100%	1.1	92	29.1	44.9	1.5	4.5	10.8	379
GH-EPA	0.1	250	200	5	2	250	50	300

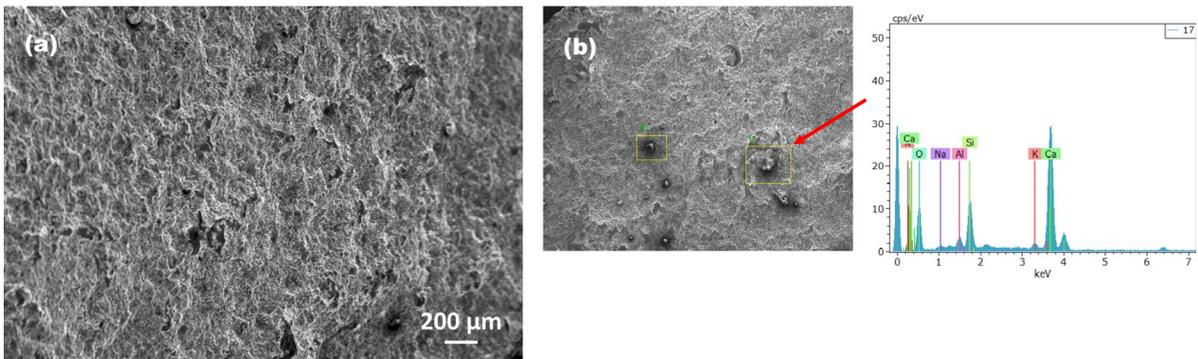


Fig. 6 **a** Low magnification of fractured cement past backfill cube cured after 28 days and **b** EDX of the selected area

The effect of curing age on the strength of CPB was inconsistent with increasing binder content and the mixed water composition. For example, at 8 wt.% binder content (Fig. 7a), the UCS of CPB increased with UG water content and curing age, reaching a maximum value of 0.64 MPa after 77 days for samples containing 100% UG water. Meanwhile, when

the binder content was increased to 12 wt.% (Fig. 7b), the UCS generally decreased with UG water content and curing age, with the highest UCS of 0.69 MPa measured for CPB with 50% UG water after 56 days. Nonetheless, the extent of strength reduction as a function of age appears to depend on the percentage of UG water in the makeup water. Considering that

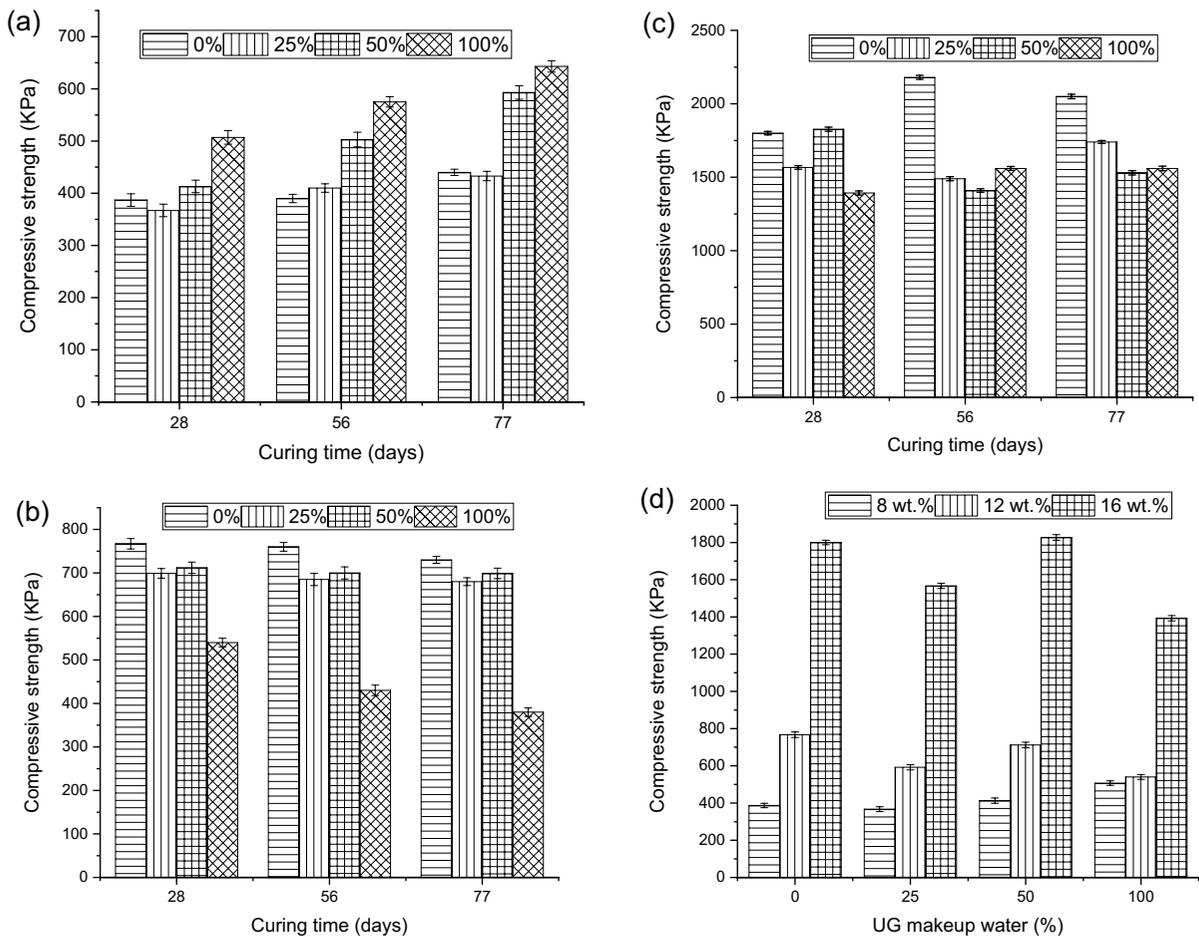


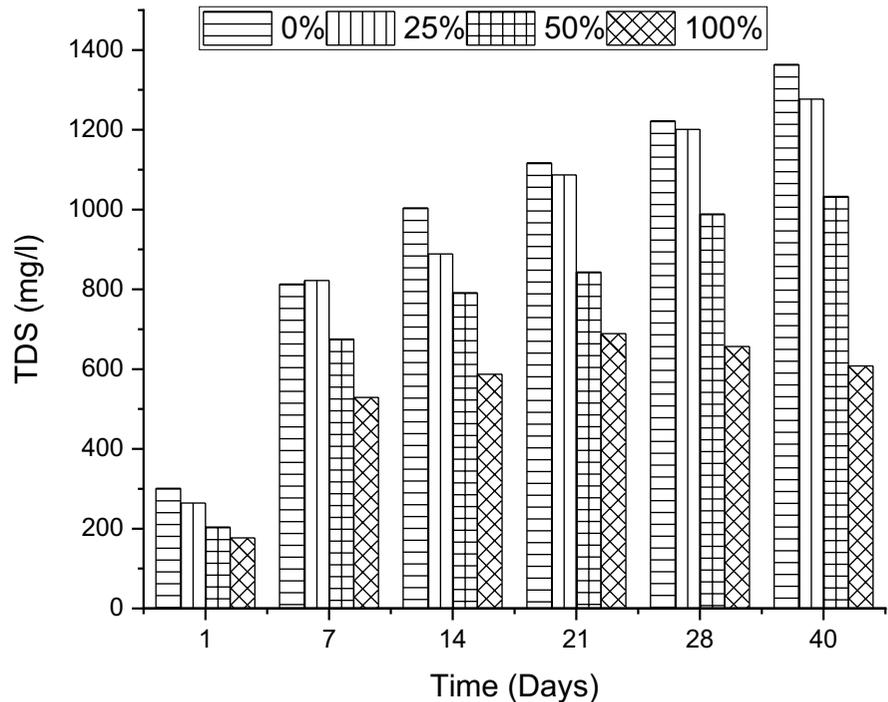
Fig. 7 Compressive strength of paste backfill cubes with varying makeup water at **a** 8 wt.%, **b** 12 wt.%, and **c** 16 wt.% cement contents. **d** The effect of makeup water on compressive strength at 28 days for the different cement contents

this observed trend was peculiar to the 12 wt.% binder sample set, it can be concluded that the decline in strength with age is caused by the combined effect of the chemical composition of the makeup water (RO brine water+UG water) and the binder content in the CPB. Similar outcomes have been reported elsewhere (Mahlaba et al., 2011). From Fig. 7c, a more incoherent UCS trend with age and makeup water can be observed. These results allude to reactions between the components of the makeup water and the cement constituents, leading to the formation of varying proportions (amounts) of the primary hydration phases as well as other potential phases such as layered double hydroxalites (LDHs) (Sun et al., 2020) in the respective CPB mix compositions that contributed to the strength properties observed for the individual

CPB mix sets. While the XRF analysis of the pastes provides adequate information to corroborate this claim, this conclusion is arguable based on the results obtained in the XRD analysis; thus, further confirmatory studies may be required.

The influence of the makeup water on the UCS at the various binder content levels after 28 days of curing (Fig. 7d) further demonstrated that the compressive strength increased significantly with binder addition, regardless of the makeup water. In particular, at 100% RO brine water (i.e., 0% UG water), an increase of about 98% was observed when the binder content increased from 8 wt.% (0.39 MPa) to 12 wt.% (0.77 MPa). A further increase of approximately 134% was observed when binder content was increased from 12 (0.77 MPa) to 16 wt.% (1.8 MPa).

Fig. 8 TDS of cement paste backfill cubes with 12 wt.% binder content at varying UG water content



Similarly, at 50% RO brine water content (50% UG), increasing UCS values of 0.413 MPa, 0.712 MPa, and 1.827 MPa were recorded for CPB containing 8 wt.%, 12 wt.%, and 16 wt.% binder content, respectively. However, the UCS increase for CPB containing 100% UG water was lower than samples prepared with 100% RO brine water. This trend is notable for CPB compositions with higher binder content (12 wt.% and 16 wt.%). Studies investigating the potential use of seawater, which essentially contains chloride, calcium, sodium, and sulfate as the significant components found that the resulting cement product was more workable and has higher strength than the control, which was prepared with potable water (Akinkulere et al., 2007; Mahlaba & Pretorius, 2006). From Table 3, RO brine water contains high concentrations of these elements, and thus, a strong correlation between seawater and RO brine water can be made. Moreover, the practice of adding chloride-bearing additives to improve the mechanical properties of cement works (paste, mortar, and concrete) has been well established (Taylor & Kuwairi, 1978). Chloride influences cement hydration by increasing setting time and accelerating the formation of CSH and some aluminosilicate hydrates (Juenger et al., 2005). Furthermore,

sulfate, found in high concentrations in RO brine water, reacts with tricalcium aluminate (C_3A) in the cement binder to form ettringite which is also beneficial for early age strength gain (Santhanam et al., 2001). Therefore, it can be concluded that CPB mixes containing increasing RO brine water potentially have more CSH and ettringite phases, resulting in the higher UCS values observed. Similar findings from Kishar et al. agree well with this conclusion (Kishar et al., 2013). From Fig. 7d, it can also be observed that the contribution of RO brine water in strength development is exacerbated with increasing binder content due to the increase in C_3A from the cement.

Indeed, high sulfate and chloride concentrations in cement pore solution typically engender sulfate attack and aggressive chemical reactions such as an alkali-silica reaction that can degrade the long-term mechanical properties (Islam & Akhtar, 2013; Santhanam et al., 2001). The harmful effects of these constituents have been discussed in previous studies wherein a threshold of 8000 mg/L of sulfate (Santhanam et al., 2001) and 0.2–0.5 wt.% chloride for regular concrete and 2.1–2.5 wt.% for submerges applications (Glass & Buenfeld, 1997; Gowripalan et al., 2000) has been identified. Below

these thresholds, the deleterious effects of sulfate and chloride are unlikely to occur. The continuous increase in UCS for CPB with RO brine water proposes that these threshold limits were not reached; thus, the favorable effects of sulfate and chloride were manifested. Currently, the recommended compressive strength for CPB at 28 days is specified in the range of 700–2000 kPa (Ercikdi et al., 2013). Considering that one of the driving factors for CPB material selection is the pumping ability of the slurry, CPB mixtures prepared with 50% RO brine water and 12 wt.% cement binder provided a balance that optimizes both the compressive strength and flow properties for practical backfill applications.

3.4 Remobilization of Cemented Paste Backfill Mixtures

Figure 8 shows the results of remobilization for CPB with 12 wt.% binder content. The results indicate that salt remobilization increased with age for all the makeup water compositions studied. After 40 days, CPB with 100% RO brine water content recorded the highest TDS of 1364 mg/L, whereas a TDS concentration of 607 mg/L was measured for samples prepared with 100% UG water. This observation can be attributed to the relatively low salt levels in the UG water samples, as seen in Table 3. As per the Ghanaian standard (GS 1212; 2019), the limit for TDS is 1000 mg/L. However, the results presented in Fig. 8 indicate that the TDS levels for all the CPB mixtures exceeded the permissible limit, except for makeup water compositions containing 50% and 100% UG water.

Additional immersion studies to determine CPB's metal ion leaching potential were carried out in distilled water for CPB cubes containing 12 wt.% binder content. The metal ion concentration in the respective leachate solutions is presented in Table 6. The concentrations of leached metal ions were higher in CPB cubes containing RO brine water than those with 100% UG water. The high levels of sulfates (SO_4^{2-}) in all leachate samples are due to the high sulfide content of the tailings. Sodium (Na) was also leached mainly from CPB samples prepared with RO brine water credited to the high concentration of Na in the RO brine water (Table 3). The concentration of leached calcium (Ca) was below the GS 1212 (2019) limit for all the CPB samples.

4 Conclusion

This study compares the use of underground (UG) water and reverse osmosis (RO) brine water as partial mixing water for cemented paste backfill (CPB) using gold mine tailings as fine aggregate.

CPB mixtures were prepared with makeup water composed of varying percentages of UG and RO brine and cement content of 8 wt.%, 12 wt.%, and 16 wt.%, to determine the fresh and hardened properties of the CPB. The results show a decrease in slump value with increasing binder content. The compressive strength at 28-day increased with binder content, reaching a maximum of 1.83 MPa with 50% RO brine. The results also showed that the sulfate and chloride concentration levels in the RO brine, although relatively high compared to UG water, were below the threshold at which these elements could cause deleterious effects. Further remobilization studies established that at 12 wt.% binder additions, the TDS values are within acceptable limits. The CPB cubes produced with 50% RO brine and 12 wt.% binder exhibited the desired flowability (slump) and compressive strength for potential paste backfill applications.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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