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THE EFFECT OF TEMPERATURE ON THE LEACHING OF Cr, Cu, Fe, Ni AND Zn FROM TAILINGS, BALLANGEN DEPOSIT, NORWAY

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ABSTRACT

In this study, the effect of temperature on the leaching of Cr, Cu, Fe, Ni and Zn from oxidized tailings, Ballangen deposit, Norway, was investigated by a laboratory batch leaching experiment. The leaching was conducted at four different temperatures 5°C, 10°C, 15°C and 20°C and 2 precipitation rates of 8 mm/week and 20 mm/week. The leachates from six leaching cycles were collected, and the concentrations of Cr, Cu, Fe, Ni and Zn were tested. The results showed that at a precipitation rate of 20 mm/week, the leached amount of Cr, Fe, Cu was highest at a leaching temperature of 20°C and the lowest leached amount for Cr was observed at 10°C. 10°C seems to be a threshold temperature for the leaching of Cr. However, at a precipitation rate of 8 mm/week, the highest leached amount of Cr, Fe and Cu was observed at 5°C and the lowest leached amount for Cr and Fe was observed at 20°C. The relationship between the accumulated leached amount of Cr, Cu, Fe, Ni and Zn and leaching water volume was approximated by a logarithmic function at different temperatures. If the factor of precipitation is ignored, only the accumulated leached amount at different temperatures is considered. The accumulated leached amount of Cr, Fe and Cu is highest at a leaching temperature of 20°C, which is significantly higher than that at other leaching temperatures by the established statistical model. The accumulated leached amount of Ni at 15°C and 20°C is significantly higher than that at 5°C and 10°C. The accumulated leached amount of Zn was highest at a leaching temperature of 10°C, which was significantly higher than that at 15°C and 20°C by the statistical model. Zn tends to be leached out at low temperatures.
Keywords: temperature, precipitation, batch leaching, contaminants, tailings.

1 INTRODUCTION

Mining activity is well known for its deleterious effects on the surrounding environment, due to the deposition of large volumes of wastes and subsequent leaching of contaminants to the surrounding environment [1]. Acid mine drainage (AMD) from mine waste and the contamination of water and soils with heavy metals are considered major problems in mining areas [2]. Mobility of heavy metals from tailings deposit to the surrounding environment has been studied extensively [3–6]. The leaching of contaminants will significantly degrade the environment, and the contaminants will further transport from the environmental medium to the ecosystem and the human beings living in the area in the long-term [7–10].

Immobilization behaviour of heavy metals is influenced by many factors such as the variation in composition and nature of heavy metals, the pH of the leachant, temperature, the duration of leaching and the type of leachant, liquid–solid ratio, sorbent nature, concentration of organic and inorganic ligands, redox reactions etc. [11–15], among which temperature is one important parameter. Increased temperature will affect chemical reaction kinetics [16]. Any step along the transport and redistribution pathways is influenced by temperature because chemical reactivity, adsorption and accumulation are temperature dependent [16]. Temperature is one of the most important parameters of global climate change. Climate change has great impact on the process of contaminant transport and concentrating process in the environment [17]. Climate change is expected to alter the environmental distribution of contaminants and their bioaccumulation due to changes in transport, partitioning and bioaccumulation

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process [18]. The climate change in the Nordic region is expected to be more drastic than that in other regions [19]. It is estimated that the rate of climate change in the Nordic region is two times faster than the global average [20]. Therefore it is of great importance to investigate the effect of temperature, one of the most important parameters linked to climate change, on the leaching of contaminants from waste deposit in the Nordic region.

A batch leaching test is a rapid and inexpensive way to evaluate the potential hazardousness of a waste disposed to land [21]. Batch leaching methods have been used for several decades to estimate the potential release of contaminants from soils [22]. However, the environmental conditions of the batch leaching experiments in previous studies vary a lot. There are limited amount of studies focusing on the effect of temperature [23], especially the effect of temperature on the leaching of contaminants from waste deposits in the Nordic region has been rarely investigated. In this study, the effect of temperature on the leaching of Cr, Cu, Fe, Ni and Zn from a tailings deposit in the Nordic region, Ballangen tailings deposit, in Norland County, northern Norway, was investigated by a laboratory batch leaching experiment.

2 STUDY AREA

The nickel mine "Nickel and Olivine AS" in Ballangen municipality in Nordland county, Norway, was in operation during the period 1988–2002 [16]. The sulphidic nickel ore contains about 0.5% Ni [24]. The tailings from the ore dressing plant were deposited in two deposits near the Ballangen fjord, the Fornes deposit and the Ballangsleira deposit as shown in Fig. 1 [24]. According to the data from the closest official weather station near Ballangsleira deposit, the lowest and highest average monthly temperature during the last 13 months has been –5.2°C and 15.8°C, respectively [25]. Precipitation has significant variations throughout the year. It was lowest in May, with an average of 46 mm, and highest in October, with an average of 127 mm [26].

At Ballangsleira deposit, the tailings from the Nickel and Olivine AS covered over the old sulphide-containing tailings from the closed Bjørkåsen mine as shown in Fig. 1 [27]. After the tailings deposition ceased, the tailings were covered with a thin layer cover with 10–20 cm of soil. The soil was seeded and fed fertilizer afterwards in order to establish a vegetation layer on the soil to avoid erosion of soils [28]. However, the thin soil layer is not effective in preventing the oxidation of the underlying tailings [16, 29]. Previous investigation on the tailings in the settling pond showed that the sulphides in the tailings are oxidizing under the soil cover and concentration of Ni was relatively high in the water leachate [29]. Leakages of metals from the deposits in the fjord are moderate [28]. Therefore, Ballangsleira deposit is chosen as our study area to investigate the leaching of contaminants from tailings.

3 METHODS

3.1 Tailings sampling and analysis

Both unoxidized and oxidized tailings were collected from Ballangsleira deposit into several polyethylene plastic bags with plastic spade in July 2016. The samples were sent to ALS Laboratory Group AS for elemental analysis. The Environmental Protection Agency (EPA) modified methods 200.7 and 200.8 were used for elemental analysis. The dried samples were digested according to the ASTM 3682 and the concentrations of elements were analysed with Inductively coupled plasma atomic emission spectroscopy (ICP-AES) and Inductively coupled plasma mass spectrometry (ICP-MS) [16]. Samples were grounded to a fine powder for mineralogical characterization by X-ray diffraction (XRD) measurement using a Rigaku Smartlab diffractometer with a Co lamp (40 kV, 135 mA).

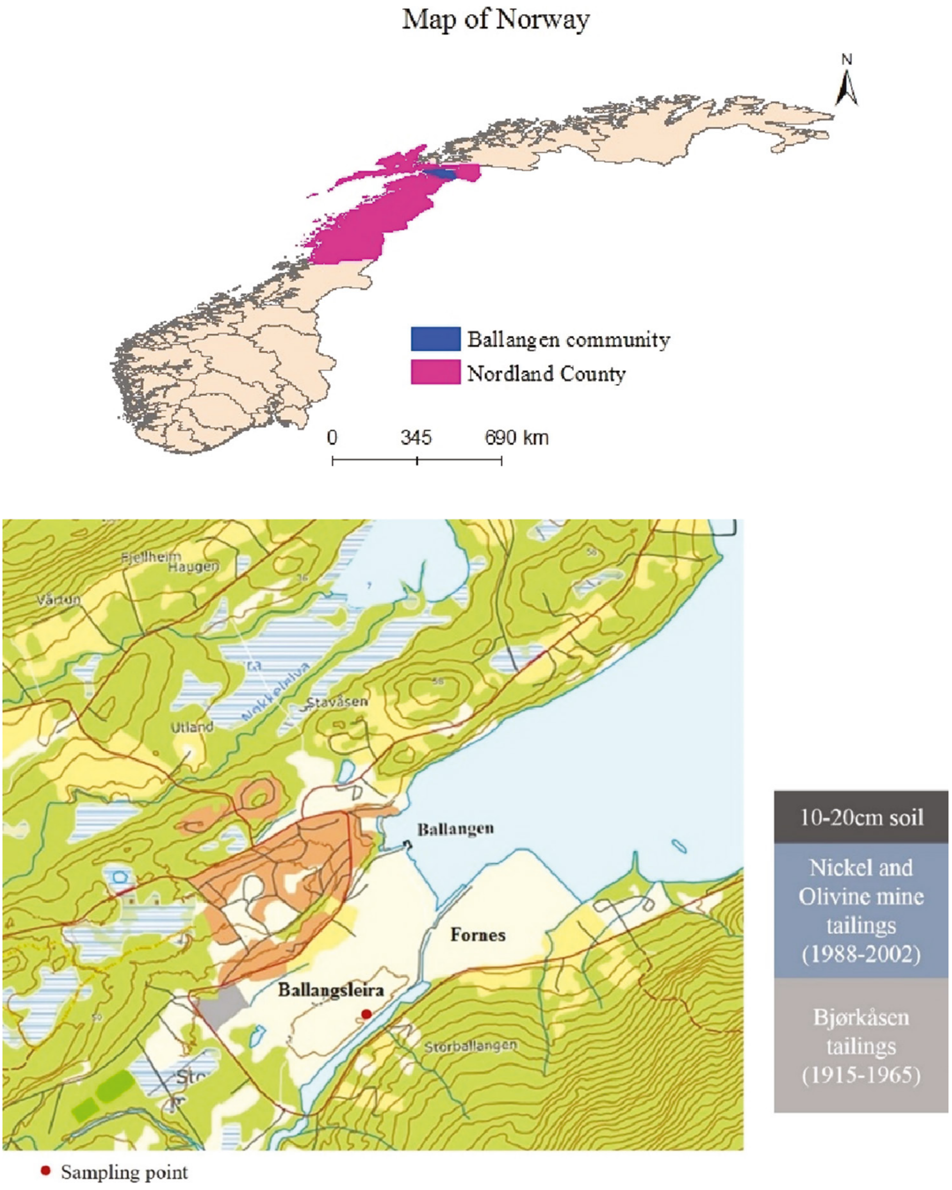

Figure 1: Tailings deposits and sampling location.

3.2 Laboratory batch leaching experiment

To investigate the leaching of contaminants from tailings at different precipitation rates and different temperatures, a small-scale laboratory batch leaching experiment was performed on the oxidized tailings. Ten grams of tailings was put into a 50 ml centrifuge tube. Four and ten milliliters of deionized water was added to the tubes and capped. The addition of water was based on the lowest and highest precipitation rate of 8 mm/week and 20 mm/week. Therefore, every two leaching cycles are equal to one week's leaching in reality. It would be best to use the real rainwater to simulate precipitation instead of deionized water. However, the rainwater composition is not stable throughout the test period. It varies from time to time. To add some chemical to the deionized water to simulate rainwater is not a good solution since the chemical may react with the tailings and thus affect the leaching results. These options will add additional uncertainty on the results. Therefore, the deionized water was used in the experiment. The tubes were put into four different incubators, which were set at temperature of 5°C, 10°C, 15°C and 20°C, respectively. There are eight tubes in total in the experiment. The leachate was collected after every one leaching cycle (10 ml) or two leaching cycles (4 ml), and the concentrations of Cr, Cu, Fe, Ni and Zn were analysed with ICP-AES according to the EPA methods 200.7 [16].

3.3 Statistical test model

The concentration level comparisons are pairwise. Suppose at precipitation levels $t_1, t_2, \ldots., t_n$, the respective observations at two temperatures are

$$y_1, y_2, \ldots., y_n ; z_1, z_2, \ldots., z_n \tag{1}$$

For each temperature level, a regression model can be developed as

$$y = \alpha t + b + \varepsilon_1 ; z = \beta t + c + \varepsilon_2 \tag{2}$$

where ε_1 and ε_1 are noise parameters assumed to have a normal distribution. They represent the random experimental error. If the observed y at temperature level 1 is always higher than z at temperature level 2, the difference $y - z$ is therefore always larger than 0, and mathematically, the difference between the two concentrations given by Equation (2) remains linear regression as

$$y - z = (\alpha - \beta)t + b - c + \varepsilon_1 - \varepsilon_2 \tag{3}$$

For simplicity, Equation (3) is rewritten as

$$x = \gamma t + d + \varepsilon \tag{4}$$

where $x = y - z$, $d = b - c$, $\varepsilon = \varepsilon_1 - \varepsilon_2$ for simplicity. In order to test if $y > z$ or $y < z$ significantly, we can test the significance of $y - z$ deviating from 0. Statistically, given a certain precipitation level $\boldsymbol{t_0}$, the observed γt_0 is normal distributed with a mean of the true $\boldsymbol{\gamma t_0}$ with variance $\sigma^2 t_0'(t't)^{-1}t_0$. The σ is the standard deviation of $\varepsilon = \varepsilon_1 - \varepsilon_2$. Let $s = \hat{\varepsilon}'\hat{\varepsilon}/(n-2)$. The $\hat{\varepsilon}$ is the residual from (4). The s^2/σ^2 follows Chi-squared distribution. Then the $\frac{t_0\hat{\gamma} - t_0\gamma}{\sqrt{s^2 t_0'(t't)^{-1}t_0}}$ follows Student distribution with degree of freedom $n - 2$ [30], i.e.

$$\frac{t_0\hat{\gamma} - t_0\gamma}{\sqrt{s^2 t_0'(\boldsymbol{t't})^{-1}t_0}} \sim t_{n-2} \tag{5}$$

In this study, 0.95 was chosen as significance level. If temperature 1 is significantly different with temperature 2, the statistics will locate at the extreme of the student distribution t_{n-2}, i.e. the value of $\frac{t_0\hat{\gamma} - t_0\gamma}{\sqrt{s^2 t_0'(\boldsymbol{t't})^{-1}t_0}}$ will be located in the two tails of the student distribution t_{n-2}.

More specifically, if the values are located in the extremes, it implies that at precipitation level t_0, the concentration level is significant different for the two temperatures. In this paper, the mean of observed t is chosen as the t_0 for the comparison of concentration levels.

4 RESULTS

4.1 Characteristics of tailings

XRD analysis showed that major minerals in the tailings were forsterite (ferroan) and enstatite, while minerals from amphibole and serpentine groups were also identified. The elemental compositions of the unoxidized and oxidized tailings are shown in Table 1. The concentrations of Co, Cr and Ni are much higher in the oxidized tailings than in the unoxidized tailings. However the concentrations of Al, Ca, K are higher in the unoxidized tailings. This indicates that the oxidation of tailings will lead to the leaching of Co, Cr and Ni to the surrounding environment, which is correlated to the high concentration of Co and Ni in the grass from tailings deposit compared to that from the reference area without tailings deposit [16]. As the tailings oxidize, the buffering minerals are consumed by the generated acid, which leads to the lower concentration of elements originating from buffering minerals (such as Al, Ca and K) in the oxidized tailings. The results show that the tailings were rich in heavy metals such as Fe, followed by Mn, Cr, Cu, Zn, Ni and Co.

4.2 Effects of temperature on the leaching of elements

The accumulated leached amount of Cr, Cu, Fe, Ni and Zn at different temperatures under the different precipitation rates of 8 mm/week and 20 mm/week were plotted and the results are shown in Figs. 2–4. The accumulated leached amounts of Cr, Cu, Fe, Ni and Zn after 1, 2

Table 1: Elemental compositions of the tailings [16, 31].

Element	Unit	Unoxidized tailings	Oxidized tailings
Total solid	%	81.5	88.2
SiO_2	% TS	39.5	40.1
Al_2O_3	% TS	4.47	3.95
CaO	% TS	3.18	2.22
Fe_2O_3	% TS	17.3	14.2
K_2O	% TS	0.417	0.211
MgO	% TS	27	31.3
MnO	% TS	0.165	0.149
Co	mg/kg TS	38	83.1
Cr	mg/kg TS	820	1,410
Ni	mg/kg TS	77.8	476
Cu	mg/kg TS	144	81.3
Zn	mg/kg TS	144	60.1

and 3 weeks' precipitation under different leaching temperatures were compared. The effect of temperature on the amount of elements leached out from the tailings is discussed in the following section.

4.2.1 The effect of temperature on the leaching of Fe

Generally, the leached amount of Fe is highest at a leaching temperature of 20°C when the precipitation rate is 20 mm/week (Fig. 2). The difference in leached amount becomes more pronounced as leaching goes on. However, at a precipitation rate of 8 mm/week, the accumulated leached amount was lowest at a leaching temperature of 20°C and highest at a leaching temperature of 5°C after 2 and 3 weeks' precipitation. The highest leached amount of Fe was found after 3 weeks' precipitation at a leaching temperature of 20°C and a precipitation rate of 20 mm/week. This showed that a combined high leaching temperature and high precipitation can lead to high leaching of Fe from tailings.

4.2.2 The effect of temperature on the leaching of Cr

Under a precipitation rate of 8 mm/week, the leached amount of Cr was highest at a leaching temperature of 5°C and lowest at a leaching temperature of 20°C (Fig. 3). The leached amount decreased with increasing leaching temperature. However, under a precipitation rate of 20 mm/week, the leaching was different. The highest and lowest leached amount was observed at a leaching temperature of 20°C and 10°C, respectively, after 2 and 3 weeks' precipitation. It seems that 10°C is a threshold temperature for the leaching of Cr under a precipitation rate of 20 mm/week. As with Fe, the highest leached amount was observed at a leaching temperature of 20°C and a precipitation rate of 20 mm/week, which showed that a combined high temperature and high precipitation will lead to high leaching of Cr also.

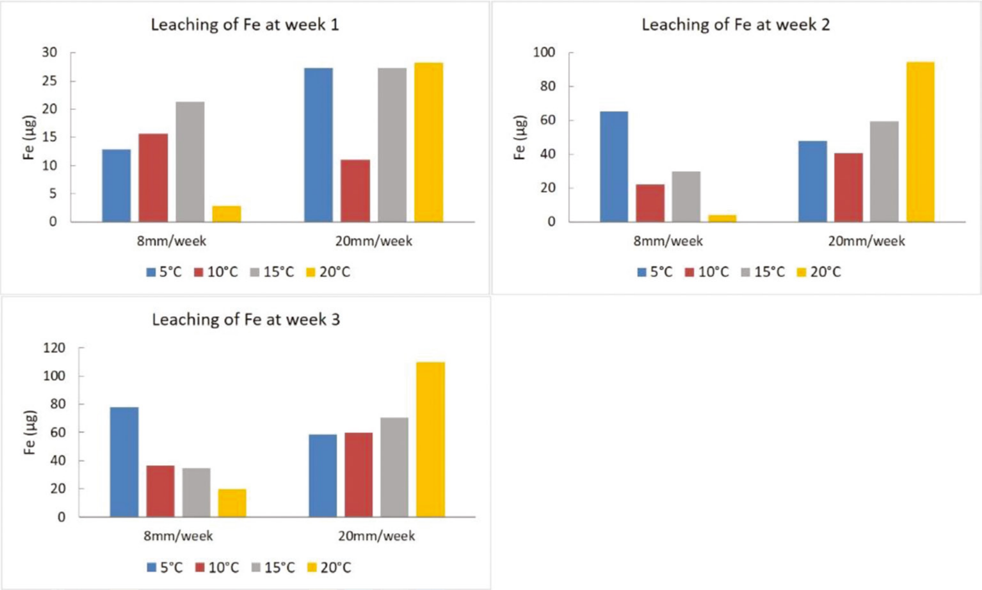

Figure 2: Accumulated leached amount of Fe at different temperatures.

4.2.3 The effect of temperature on the leaching of Cu

The accumulated leached amounts of Cu after 1, 2 and 3 weeks' precipitation were compared at different leaching temperatures and the result is shown in Fig. 3. Under a precipitation rate of 8 mm/week, the leached amount of Cu was highest at a leaching temperature of 5°C after 2 and 3 weeks' precipitation. However, under a precipitation rate of 20 mm/week, the leached amount of Cu was highest at a leaching temperature of 20°C after 2 and 3 weeks' precipitation. As with Fe and Cr, the highest leached amount was observed at a leaching temperature of 20°C and a precipitation rate of 20 mm/week, which indicates a combined effect of temperature and precipitation.

4.2.4 The effect of temperature on the leaching of Ni

The accumulated leached amounts of Ni after 1, 2 and 3 weeks' precipitation are shown in Fig. 4. In contrast to the leaching of Fe, Cr and Cu, the leached amount of Ni was highest at a leaching temperature of 20°C under both precipitation rates of 8 mm/week and 20 mm/week. The highest leaching was observed at a leaching temperature of 20°C and a precipitation rate

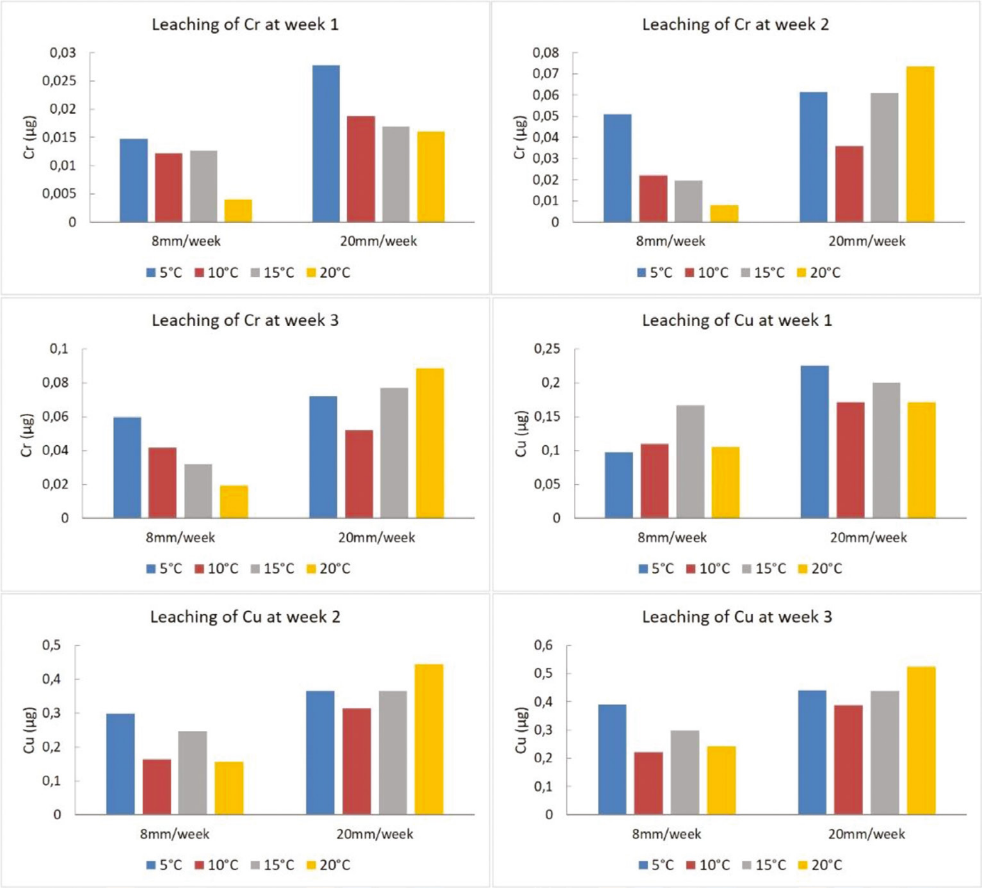

Figure 3: Accumulated leached amount of Cr and Cu at different temperatures.

of 8 mm/week. The leached amount does not have a significant difference between leaching temperature of 5°C and 10°C and leaching temperature of 15°C and 20°C.

4.2.5 The effect of temperature on the leaching of Zn

The accumulated leached amounts of Zn after 1, 2 and 3 weeks' precipitation were compared at different leaching temperatures, and the result is shown in Fig. 4. Under a precipitation rate of 20 mm/week, the leached amount of Zn was highest at a leaching temperature of 10°C. There is no significant difference in the leached amount at leaching temperatures of 5°C, 15°C and 20°C. Under a precipitation rate of 8 mm/week, the leached amount of Zn was highest at a leaching temperature of 5°C. There is no significant difference in the leached amount at leaching temperatures of 10°C, 15°C and 20°C. Compared with other elements, it seems that Zn tends to leach out from tailings more easily at low temperatures.

4.3 The accumulated leached amount of Cr, Cu, Fe, Ni and Zn at different temperatures

The accumulated leached amount of Cr, Cu, Fe, Ni and Zn with increasing leaching water volume was analysed, and the results are shown in Figs. 5–9. Generally, the accumulated

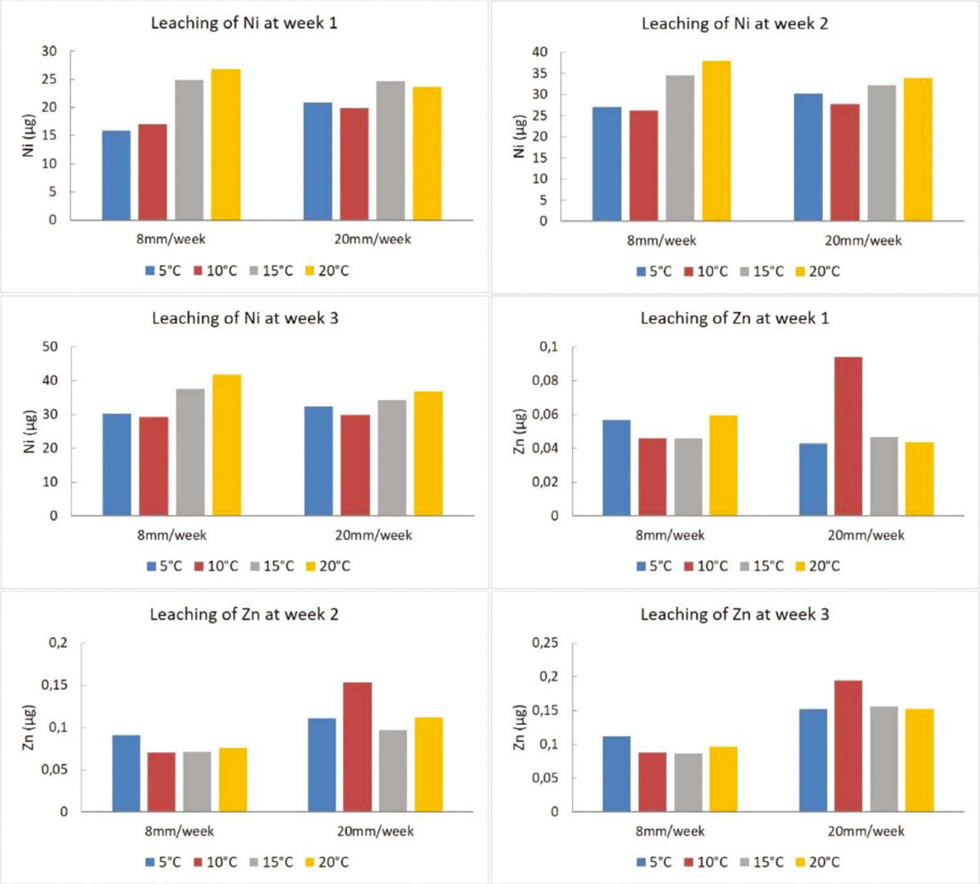

Figure 4: Accumulated leached amount of Ni and Zn at different temperatures.

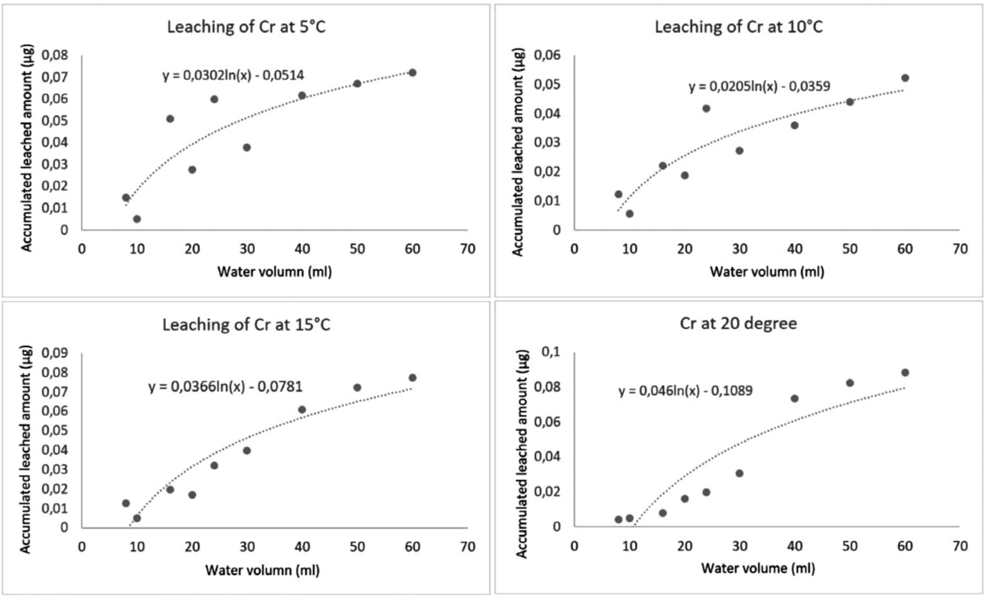

Figure 5: The accumulated leached amount of Cr with water volume.

leached amount of these elements increases with increasing leaching water volume. Their relationship can be approximated by logarithmic functions.

4.3.1 The accumulated leached amount of Cr at different temperatures

The relationship between the accumulated leached amount of Cr and leaching water volume is shown in Fig. 5. Model (5) described in Section 3.3 was used to test if the concentrations are significantly different at two temperature levels. If the value of model (5) locates in the extreme of the student distribution, the difference is then significant. The results show, at significant level 0.95, that the accumulated leached amount of Cr at a leaching temperature of 20°C is significantly higher than that at leaching temperature of 5°C and 10°C. There was 0.08848 µg of Cr leached out at 20°C when the leaching water volume was 60 ml, which is much higher than an accumulated leached amount of 0.072 µg at 5°C and 0.05226 µg at 10°C.

4.3.2 The accumulated leached amount of Cu at different temperatures

The relationship between the accumulated leached amount of Cu and leaching water volume is shown in Figure 6. Using model (5) from Section 3.3 to test if the concentrations are significantly different at two temperature levels, the results show that the accumulated leached amount of Cu at a leaching temperature of 20°C is significantly higher than that at leaching temperatures of 10°C and 15°C. There was 0.5233 µg of Cu leached out at 20°C when the leaching water volume was 60 ml, which was 19% and 35% higher than the accumulated leached amount at 15°C and 10°C, respectively. The accumulated leached amounts of Cu at 15°C and 10°C were 0.44 µg and 0.3871 µg, respectively.

4.3.3 The accumulated leached amount of Fe at different temperatures

The relationship between the accumulated leached amount of Fe and leaching water volume is shown in Fig. 7. Using model (5) from Section 3.3 to test if the concentrations are significant

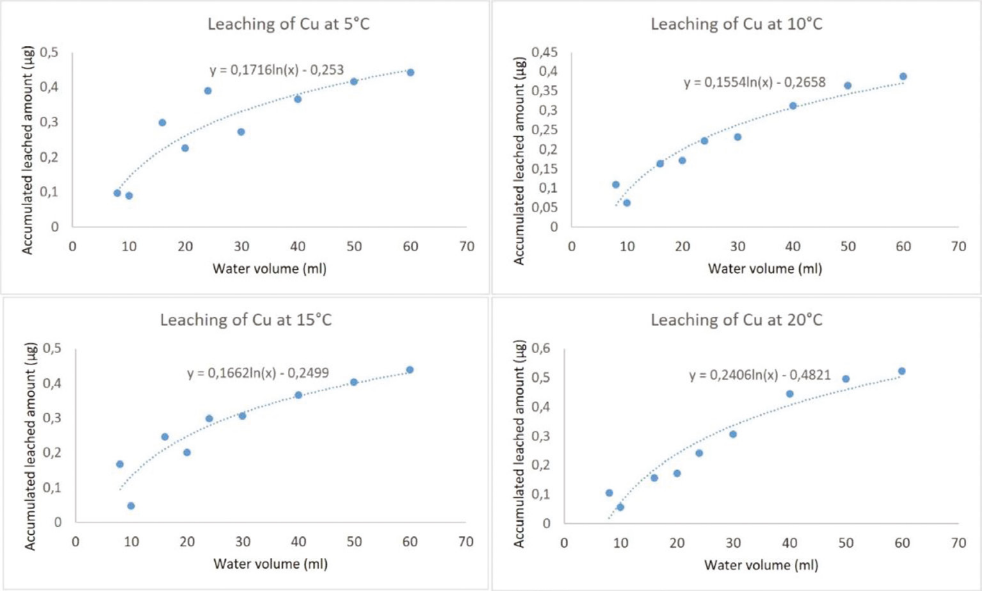

Figure 6: The accumulated leached amount of Cu with water volume.

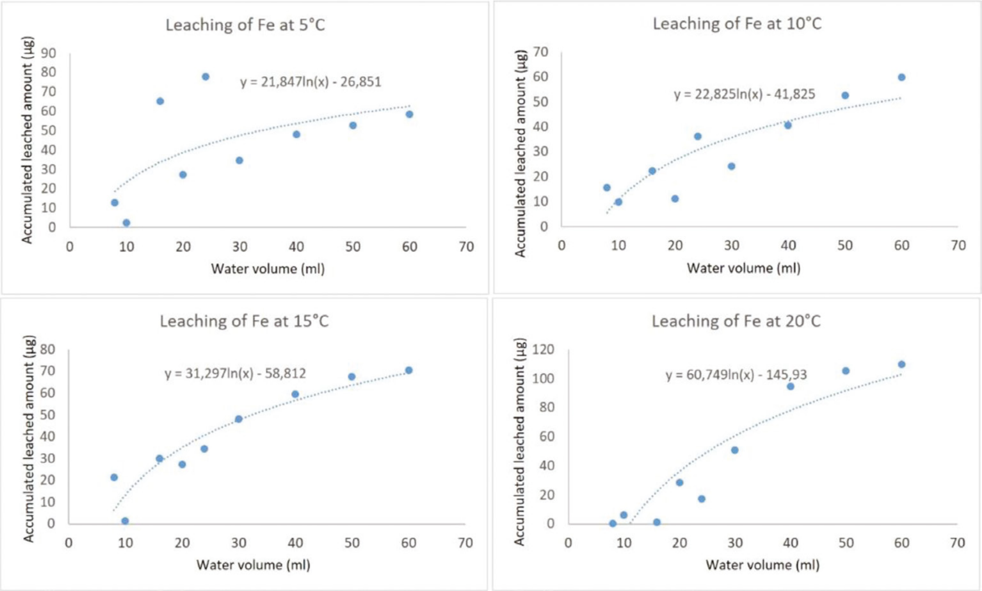

Figure 7: The accumulated leached amount of Fe with water volume.

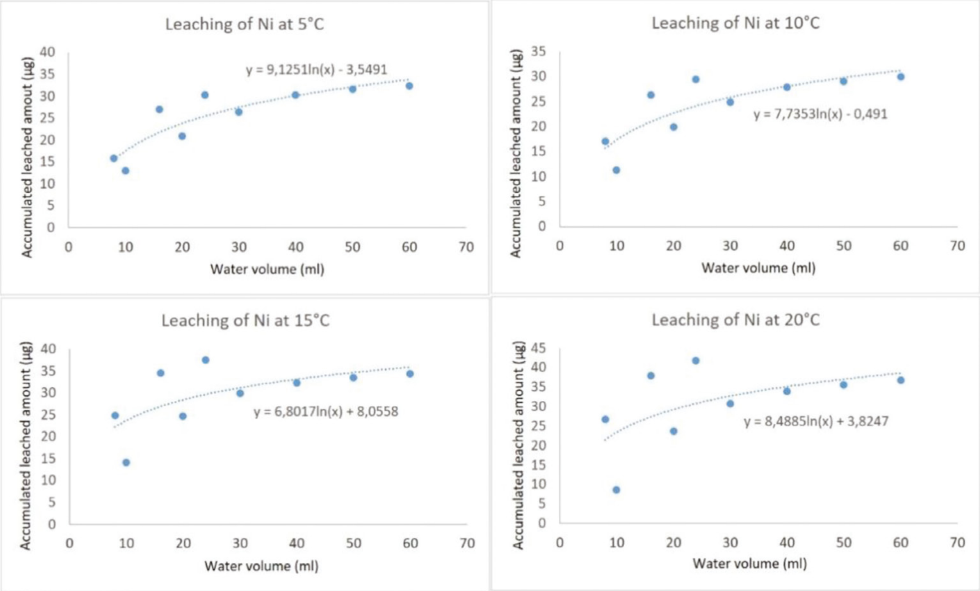

Figure 8: The accumulated leached amount of Fe with water volume.

at two temperature levels, the results show that the accumulated leached amount of Fe at a leaching temperature of 20°C is highest, which is significantly higher than that at leaching temperatures of 10°C and 15°C. There was 109.68 µg of Fe leached out at 20°C when the leaching water volume was 60 ml, which was 83% and 87% higher than the accumulated leached amount at 10°C and 15°C, respectively. The accumulated leached amounts of Cu at 10°C and 15°C were 59.81 µg and 70.66 µg, respectively. The difference in accumulated leached amount for Fe is much higher than that for Cr and Cu.

4.3.4 The accumulated leached amount of Ni at different temperatures

The relationship between the accumulated leached amount of Ni and leaching water volume is shown in Fig. 8. Compared with other elements, the increase of accumulated leached amount of Ni with leaching water volume is not so obvious. Ni just showed a slight increase with increasing water volume.

Using model (5) from Section 3.3 to test if the concentrations are significantly different at two temperature levels, the results show that the accumulated leached amount of Ni at leaching temperature of 15°C and 20°C was significantly higher than that at leaching temperatures of 5°C and 10°C. The difference in accumulated leached amounts between 15°C and 20°C and 5°C and 10°C is not statistically significant.

4.3.5 The accumulated leached amount of Zn at different temperatures

The relationship between the accumulated leached amount of Zn and leaching water volume is shown in Fig. 9. The accumulated leached amounts at different temperatures were compared and the significance of the difference has been tested using the t-test in Model (5) of Section 3.3. The results show that the accumulated leached amount of Zn was highest at a leaching temperature of 10°C, which was significantly higher than that at leaching temperatures of

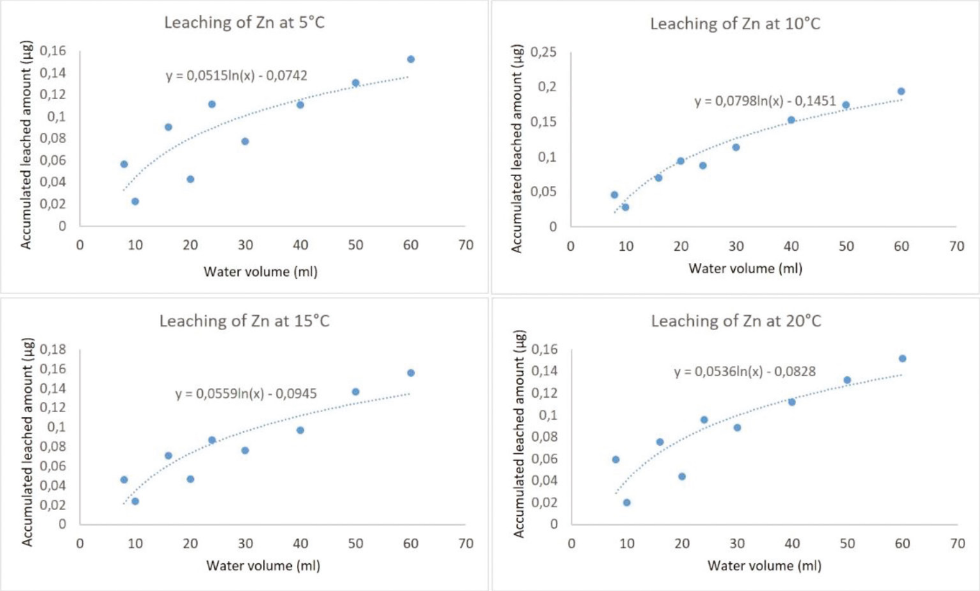

Figure 9: The accumulated leached amount of Zn with water volume.

15°C and 20°C. The leaching of Zn with temperature is different compared with other elements. There was 0.1945 μg of Zn leached out at 10°C when the leaching water volume is 60 ml, which was 24.5%, and 28% higher than the accumulated leached amount at 15°C and 20°C, respectively. The accumulated leached amounts of Zn at 15°C and 20°C were 0.1562 μg and 0.1519 μg, respectively.

5 DISCUSSIONS

5.1 The effect of temperature on the weathering of tailings

The effect of temperature on the oxidation rates of sulphides in tailings has been discussed in many studies [32]. A significant increase in the oxidation rate of pyrite and pyrrhotite with increasing temperature has been observed [32, 33]. The effect of temperature is reported to be more significant than that of pH with the reaction rate doubling between 25°C and 35°C or increasing by 3–5 times for a 20°C increase with oxygen as oxidant and by 2–11 times for 30°C increase with ferric iron as oxidant [33]. The oxidation process follows Arrhenius equation [32, 33]. An increase in temperature can enhance the rate of O_2 diffusion and therefore the formation of ferric oxide and ferric sulphate products [33]. The rate of acid production is controlled by the availability of oxygen at the sulphide surface [34]. A steady oxygen supply to the surface of pyrite grains is a prerequisite for oxidation in both frozen and unfrozen mine tailings [32].

5.2 The effect of temperature on the leaching of contaminants from tailings

The accumulated leached amount of Cr, Cu, Fe was observed at a leaching temperature of 20°C and a precipitation rate of 20 mm/week (10 ml leaching). Ignoring the precipitation factor, the accumulated leached amount of Cr, Cu and Fe is significantly higher at a leaching temperature of 20°C than at other leaching temperatures. There are other studies, which also showed the increased leaching of elements with temperature. The temperature effects on the leaching and recovery of Zn and Cu from brass slag by sulfuric acid were investigated, and the results showed that the leaching of Zn and Cu increases with leaching temperature for Zn up to 35°C and for Cu up to 70°C [35]. The effect of temperature on the leaching of heavy metals from sewage sludge was investigated, and the results showed that the optimal temperature range for bioleaching bacteria growth was 20°C-30°C [36]. The optimum temperature for ferrous iron and sulfide oxidation by T. ferrooxidans is between 28°C and 30°C, and at lower temperatures a decrease in metal extraction will occur [37]. The released amounts of Cu, Fe, Mn, Ni and Zn from the pyrite tailings at Sichuan province, China, at a temperature range of 15–45°C were investigated in a laboratory batch experiment and showed the released amount of each metal had an increasing trend as temperature increases [38]. The release characteristic caused by temperature is related to the solubility product constant K_{sp}, which is positively correlated with temperature [38].

Our results showed that the accumulated leached amount of Zn at a leaching temperature of 10°C is significantly higher than that at other leaching temperatures. Zn tends to be leached out at low temperatures. Another study result from a test work also concluded that the solubility of Zn is greater at low temperatures and Zn leaching increases as the temperature falls [39].

5.3 Environmental impact of Cr, Cu, Fe, Ni and Zn leaching

The contamination of leachate from the deposit with Cr, Cu, Fe, Ni and Zn will have a significant environmental impact. Heavy metal pollution in surface water sources can result in considerable pollution of local soil [40, 41]. When the soils are polluted by heavy metals, the heavy metals can further transport from soil to the grass that are grown on the soil. Contamination of grass in the deposit area by As, Co, Cu and Ni has been reported earlier [16]. Animals that graze on contaminated grass, as well as marine lives that breed in heavy metal polluted waters, will accumulate the metals in their tissues [40]. The milk products that are produced from the cows grazing in the area can also be contaminated with the metals [40]. Humans at last can be exposed to heavy metals by consuming contaminated animal meat and milk. Therefore, the leaching of Cr, Cu, Fe, Ni and Zn from the tailings deposit constitute a serious threat to the local environment and health of people living in the area.

6 CONCLUSIONS

In this study, the effect of temperature on the leaching of Cr, Cu, Fe, Ni and Zn from oxidized tailings, in the Ballangen deposit, Norway, was investigated by a laboratory batch leaching experiment. The relationship between the accumulated leached amount of elements and leaching water volume was approximated by a logarithmic function at different temperatures. At a precipitation rate of 20 mm/week, the leached amount of Cr, Fe and Cu was highest at a leaching temperature of 20°C and the lowest leached amount for Cr was observed at 10°C. 10°C seems to be the threshold temperature for the leaching of Cr. However, at a precipitation rate of 8 mm/week, the highest leached amount of Cr, Fe and Cu was observed at 5°C and the lowest leached amount for Cr and Fe was observed at 20°C. The accumulated leached amount of Cr, Cu and Fe is highest at a leaching temperature of 20°C, which is significantly higher than that at other leaching temperatures as found by the established statistical model. The accumulated leached amount of Ni at 15°C and 20°C is significantly higher than that at

5°C and 10°C. The accumulated leached amount of Zn was highest at a leaching temperature of 10°C, which was significantly higher than that at 15°C and 20°C as found by the statistical model. Zn tends to be leached out at low temperatures. The results of threshold leaching temperature for Cr and Zn at 10°C are important information for environmental protection agencies and environmental management officers when it comes to environmental pollution management. When decision is made on management strategies regarding the leaching of contaminants, temperature should be taken into consideration as an important parameter, especially in the Nordic region, where the temperature change is more intense under the global climate change context compared with other regions.

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