Investigation of Technologies for Road Tunnel Wash Water Treatment

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Summary

Road tunnels are regularly cleaned to improve the road safety and to increase its lifespan. Challenging climate and landscape with fjords and mountains have increased the use of road tunnels in Norway. The country has approximately 1 150 road tunnels with a total length of 800 km. In tunnels with high traffic loading, particles from tyres, asphalt, road paint, brakes etc. are deposited on roads, walls and ceiling. Frequency of cleaning depends on type of tunnel and traffic loading. Norwegian tunnels are cleaned on a regular basis, from 2 to 12 times a year, using approximately 60-100 l water with 0.5-1% detergents per one-meter tunnel. This results in a significant amount of polluted tunnel wash water (TWW), which needs to be properly treated before releasing it to the environment. Sedimentation ponds are the most common treatment applied to treat TWW. Many pollutants can be removed by sedimentation, but some heavy metals and micropollutants were not removed successfully. This paper presents and discusses the results of a series of experiments conducted to find improved treatment alternatives for copper and zinc removal of TWW from the Nordby tunnel on E6. Project goal was to achieve the effluent limits of 10 µg Cu/l and 50 µg Zn/l. Samples were collected from cleaning the tunnel in a summer and a winter situation. Testing of many different water treatment techniques were carried out in laboratory scale with the two water qualities collected. The Norwegian Public Road Administration (NPRA) was looking for a low-tech treatment solution, which is robust, cheap and easy to operate. The results from this work is presently used by local authorities in Norway for designing new tunnel wash water treatment plants. Operational experience is yet not available.

Sammendrag

Undersøkelse av behandlingsteknologier som er egnet for behandling av vaskevann fra veituneller: Vasking av vegtunneler er viktig for veisikkerhet og for å øke levetiden for tunneler. Utfordrende klima og landskap med fjorder og fjell har økt bruken av vegtunneler i Norge. Landet har ca. 1 150 vegtunneler med en total lengde på ca. 800 km. I tunneler med høy trafikkbelastning, blir partikler fra dekk, asfalt, veilmaling, bremser etc. deponert på vei, vegger og tak. Norske tunneler rengjøres regelmessig, fra 2 til 12 ganger i

året, ved bruk av ca. 60-100 liter vann med 0,5-1% vaskemidler per meter tunnel. Dette resulterer i en betydelig mengde forurenset vann, som må behandles godt før det slippes ut i miljøet. Sedimentasjonsdammer utenfor tunnelene er mest brukte rensemetode for å behandle dette vannet. Undersøkelser viser at noen tungmetaller og prioriterte miljøgifter er vanskelig å fjerne bare med sedimentering. Dette dokumentet diskuterer resultat fra en rekke forsøk gjennomført i laboratorieskala for å undersøke ulike rensealternativer for fjerne kobber- og sink fra tunnelvaskevann (TVV) fra Nordbytunnelen i Norge. Målet for prosjektet var å finne egnet vannbehandling for å nå utslippsgrensene på 10 µg Cu /l og 50 µg Zn /l. Vannprøver ble samlet fra rengjøring av tunnelen i en sommer- og en vintersituasjon. Testing av mange ulike reseprosesser ble gjennomført i laboratorieskala med de to vannkvalitetene. Statens Vegvesen ønsket en lav-teknologi løsning, som var robust, billig og enkel i drift. Resultatet fra det arbeidet som er beskrevet i denne artikkelen benyttes i dag som designgrunnlag for nye renseanlegg for tunnelvaskevann både av Statens Vegvesen og Nye Veiler. Driftserfaring med metoden er enda ikke tilgjengelig.

Introduction

Challenging climate and the landscape with fjords and mountains are increasing the use of road tunnels in Norway. The country has about 1 150 road tunnels with a total length approximately 800 km. In tunnels with high traffic loading, fine particles from abrasion of break wears, tyres, road pavement and exhaust fumes are deposited on the tunnel roads, walls, ceilings, road marking, road signs and signalling systems. Cleaning of road tunnels is an important maintenance practice for maintaining traffic safety and increasing lifespan of the tunnels. The frequency of the cleaning process depends on the annual daily traffic (ADT) loading of the tunnel. In general, Norwegian tunnels are washed on a regular basis, normally performed from 2 to 12 times a year (Paruch and Roseth, 2008).

Road signs, lights, walls and roads inside the tunnel are cleaned using high pressurised water jets and detergents. Approximately 60-100 l water mixed with 0.5-1% detergent is used for a full cleaning of one-meter tunnel (Meland et al., 2010a; Meland, 2012). This results in a significant amount of polluted wash water, which unless properly treated will be a source of contamination to the receiving environment. Wash-water contains a mix of organic and inorganic pollutants originating from the vehicle-exhaust particles, tyres and breaks wear, tunnel construction materials, asphalt and surfactants (Meland et al., 2010a; Paruch and Roseth, 2008; Councell et al., 2004; Roseth et al., 2003). The Norwegian Public Road Administration (NPRA)'s R&D Programme NORWAT (Norwegian Road Water) focussed on finding low-tech feasible and robust technologies with low need for operation and maintenance.

Until recently, road runoff water (RRW) during construction of new roads and road tunnel wash water (TWW) have been collected in outdoor retention ponds for treatment. Effluents from the retention ponds were discharged to the nearest water recipient. Open sedimentation ponds were mostly built outside tunnels (Meland, 2012). Removal of pollutants in the sedimentation ponds is expected by long term sedimentation and microbial degradation. The removal rates are, however, depending on the retention time in ponds and chemical and physical characteristics of the TWW (Meland et al., 2010b; Meland, 2012). Effluents from existing sedimentation basins have been reported toxic to aquatic organisms and requires improved treatment.

Pollutants include contaminants such as trace heavy metals, organic micropollutants like aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), and road salt (Paruch and Roseth, 2008) besides the detergents used during washing. Studies have shown that detergents used for tunnel washing mobilize and dissolve the heavy metals in water (Aasum, 2013). Particulate contaminants can be removed through sedimentation, but the dissolved

pollutants will still pass through the treatment process (Meland et al., 2010b). Several of these pollutants have been shown to give adverse effects to fish, both in the laboratory and in field studies (Heier et al., 2009; Grung, 2016; Petersen, 2016). Therefore, concentrations of toxic metals in surface waters are restricted by standards (European Commission, 2006; USEPA, 2006) and efficient treatment of tunnel wash water is required.

Both physio-chemical and biological treatment methods are effectively used for heavy metal removal from different types of wastewater. Chemical precipitation of metal hydroxides and coagulation-flocculation are well-known methods for the removal of heavy metals. Many heavy metals are amphoteric and thus their solubility changes with pH, giving an optimum pH range for the process to occur. This range is different for different heavy metals (EPA, 1983; Tang et al., 2014). Different precipitation chemicals also work better at different pH ranges. Therefore, the heavy metal removal by chemical precipitation in different pH ranges was studied.

Biological treatments are environmentally friendly and effective methods for wastewater treatment. Biological heavy metal removal is explained in two mechanisms. Active biological heavy metal removal can occur by different mechanisms like intracellular accumulation, extracellular precipitation and chemical transformations, such as oxidation, reduction, methylation, demethylation, catalysed by microorganisms. Passive mechanisms of metal binding are extracellular complexation of metal by substances excreted by cells and biosorption - binding of heavy metals to active groups of chemical compounds of cell walls and membranes (Kulbat et al., 2003). Anaerobic and aerobic microorganism use different mechanisms in different conditions. Both aerobic and anaerobic treatments were evaluated during the present study.

This paper presents and discusses the research and results of work conducted, on behalf of NPRA, to find the best available and most cost/efficient low-tech tunnel wash water techniques for reducing the copper (Cu) and zinc (Zn) content in the wash water from the Nordby-tunnel in Norway. Our goal was to achieve sufficient removal of Cu and Zn to meet the effluent quality < 10 and 50 µg/l, respectively. These levels were established to avoid toxic levels from occurring in the local river during low flow conditions. The details are described in a Project report prepared by Garshol et al. (2015).

Materials and Methods

Wash water used in this study was collected from the Nordby-tunnel, which is located on Interstate Highway E6, south of Oslo, Norway. The tunnel is 3.84 km long and has two separate 10 m wide concrete tubes. The ADT is > 45 000 vehicles. About 14 % of the ADT is heavy vehicles over 3500 kg weight and the average vehicle speed in the tunnel is about 89 km/h.

The tunnel is washed 4 to 6 times per year. The wash water is routed through sand traps, where the largest fractions of the solids are removed, and is then collected in a sedimentation pond outside the tunnel. Treated water after sedimentation is discharged into river Årungselva (Meland et al., 2010a).

The TWW sample was collected during the full tunnel wash in August 2014 (summer situation), and March 2015 (winter situation). A total of 500 l representative flow proportional wash water sample was collected after the sand traps before entering the sedimentation tank. Due to the high solids content in the wash water, careful handling of the sample was important to get representative samples for both investigations.

Following treatment alternatives were investigated in laboratory scale to find different treatment alternatives or combinations, could meet the treated water requirement of < 10 µg Cu/l and < 50 µg Zn/l.

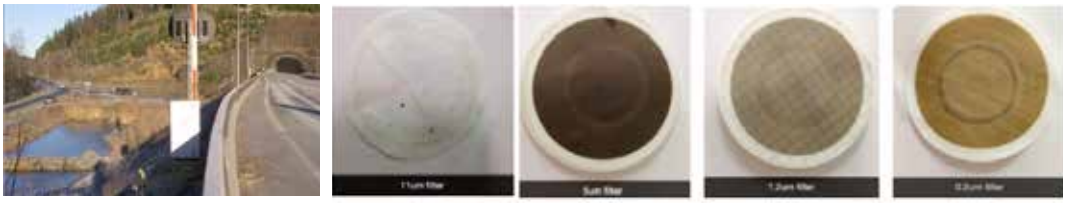
- Filtration
- Sedimentation
- Chemical precipitation
- Aerobic biological treatment
- Anoxic/anaerobic biological treatment

Figure 1 shows pictures of the test set-up used.

Filtration: Raw water was filtered through 1.2 µm Whatman® grade GF/C glass-fibre filter papers and the Cu and Zn concentrations were measured. Then sequential filtration (11; 5;1;2 and 0,2 µm) was conducted before Cu and Zn was measured.

Sedimentation: Sedimentation is the most often treatment practiced for TWW. Three sedimentation tests were conducted. The two first were performed in triplicate with 1 l samples in Imhoff cones, conducted at room temperature (20 °C) and at 4 °C. Samples of 10 ml were taken on days 1,2,3,4 and 7 to measure the turbidity and particle size distribution (PSD). The third trial was conducted with a 15 l sample volume at room temperature (20 ± 2 °C) for a period of 37 days. Samples of the supernatant were withdrawn along the whole period for analyses of heavy metals.

Biological degradation trials: Biological degradation of wash-water was studied in three different tests. Sediments from the existing TWW sedimentation tank of the Nordby-tunnel was



a) The sedimentation ponds at the Nordby-tunnel shown in the left picture; b) Sequential filtration tests.

c) The sedimentation lab-test with Imhoff glass (left picture); d) Aerobic biodegradation (right picture).

e) Two aerobic and one anaerobic test vessels (left picture); f) Chemical precipitation tests using Jar-tests (right picture).

Figure 1. Treatment technologies investigated for tunnel wash water treatment: a) The full-scale outdoor sedimentation pond for the Nordby-tunnel; b) to f) Laboratory tests technologies described in this paper.

used to inoculate the biological treatment process applied during the experiment. The anoxic trial was conducted in a 10 l container of TWW and inoculated with sediment bacteria. The container was sealed to ensure no oxygen was provided. One anoxic trial was run in a 35 l container filled with TWW and inoculated with sediment bacteria. The other aeration treatment had the same volume and same conditions but was not inoculated with sediments. An extra supplement of nutrients (NH_4-N and PO_4-P) was added to all three biological trials.

Chemical precipitation: Heavy metal co-precipitation by employing iron (Fe) and aluminium (Al) based coagulants was assessed using poly-aluminium chloride (PAX18 and PAX-xl60) and ferric sulphate (PIX 318 and PIX 313) based coagulants from Kemira co. ltd.

A series of screening tests, using 100 ml TWW in a 150 ml Erlenmeyer flask with a magnetic stirrer was run for selecting coagulants. Tests were conducted also in three different initial pHs. Raw TWW pH was adjusted by adding 1 molar NaOH. After the screening tests, Jar tests were performed on 1 l samples, with the selected coagulant.

All the testing and sample analyses were done in well-equipped laboratories. Determinations of pH, dissolved oxygen, redox potential, turbidity, total and suspended volatile solids were measured according to standard methods (APHA, 1995). Cu, Zn, nitrogen-based analyses, (Tot-N, NH_4-N), phosphorus analyses (Tot-P, PO_4-P), Total organic carbon (TOC) and Chemical oxygen demand (COD) were measured with HACH test cell kits and a HACH DR 5000 UV/VIS spectrophotometer. Polyethersulfone membrane filters with 0.45 µm pore size were used to filter samples for analysis of the dissolved fractions. Particle size distribution (PSD) analyses were performed using laser diffraction analyses by Malvern Mastersizer 3000 (Malvern, UK).

Table 1. Tunnel wash water quality of the Nordby-tunnel in a summer and a winter situation compared with Good Environmental Quality Standards (EQS) for Norwegian freshwater and acceptable discharge quality defined by the municipality of Oslo for discharging into the sewer system.

Water quality		Wash water Nordby-tunnel summer	Wash water Nordy-tunnel winter	Norwegian EQS fresh water	Acceptable discharge to Oslo's sewer system
Zn	µg/l	2400	44000	11[1)]	500
Cu	µg/l	350	4400	7.8[1)]	200
Cr	µg/l	44	1100	3.4[1)]	50
Pb	µg/l	20	500	1.3[1)]	50
Hg	µg/l	0,02	0.3	0.05[1)]	2
Cd	µg/l	0.4	53	0.08[1)]	2
NI	µg/l	33	660	1.7[1)]	50
OiW*	mg/l	3.2	27	0.07*	20
PAH	µg/l	5	120	11.3[2)]	n.a.
Tot-P	mg/l	5.6	9	11[2)]	10
Tot-N	mg/l	11.5	35	0.4[2)]	60
NH4-N	mg/l	0.1	0.7		
TOC	mg/l	155	654	3.5[2)]	200
TSS	mg/l	544	28000	3[2)]	400
TU		5	2	0.01[3)]	

* OiW = Oil-in-water; EQS =OSPAR PNEC value for marine systems [1)] Heavy metals; EQS freshwater in Weideborg et al (2013) [2)] Organic matter, phosphorous, nitrogen, solids from SFT's Guidelines, 1997. [3)] Toxicity Unit =TU, TU in receiving water is based on a safety factor of 100 to account for chronical effects, (SFT 1750/2000).

Results and Discussion

Water Quality

Table 1 shows the characteristics of TWW of the Nordby-tunnel in a summer and a winter situation and compares to Good Environmental Quality Standard (EQS) of Norwegian freshwater and the acceptable discharge levels to Oslo's sewer system. Proving the need for pre-treatment, raw TWW sample was highly polluted compared to an average inland fresh waterbody. Even though many of the parameters are lower than the expected limits for discharging it to the Oslo sewer system, concentrations of Zn and Cu were substantially higher in TWW.

Filtration

Filtration of the raw TWW through 1.2 µm filter removed only 29 and 60 % of the total Zn and Cu, respectively while 71 and 40 % of the Zn and Cu content in the TWW still was dissolved or present as particles < 1.2 µm. The residual after filtration was 1704 µg Zn/l and 140 µg Cu/l. Sequential filtration (see Figure 1) did not improve removal of Zn and Cu significantly.

Chemical treatment

Table 2 presents the results from screening tests with increasing pH and performing chemical precipitation with four different coagulant types and three different initial pH of TWW. TWW pH was 8.5 and it was increased to 10.9 and 11.9 by adding NaOH. Precipitate formation was clearly visible when adding NaOH to the TWW. This is caused by the metal hydroxide precipitation taking place with increased pH. The table shows that the metal precipitation when increasing pH to 11 and 12 was still not sufficient to achieve the treated water goals.

Hydroxide co-precipitation by coagulation and flocculation with metal salts is one of the most efficient methods for heavy metal removal from water. Four different commercial coagulants were tested for co-precipitation of metal salts. All four coagulants performed equal for Zn removal, but Fe based PIX performed better for Cu removal. Both Fe based coagulants removed 99 % Zn and 86 % Cu with initial pH 12. But it required considerably high (68 mg Fe/l and 98 mg Fe/l) coagulant doses and still, it did not reach

*Table 2. Results of pH adjustment of TWW followed by chemical precipitation trials with PIX and PAX coagulants. Zn and Cu were analyzed after 30 minutes sedimentation. * L= low pH, M= medium pH, H= high pH*

Coagulant or chemical	Metal	pH*	Metal dose	Turbidity	Treated water conc.		% Removal	
			mg Me/l	NTU	Zn (µg/l)	Cu (µg/l)	Zn	Cu
NaOH	-	L (8.5)	-	381	2400	350	-	-
NaOH	-	M (11)	-	120	1500	230	37	34
NaOH	-	H (12.1)	-	24	200	220	92	37
PIX313	Fe	L (8.5)	62	6.0	1200	138	51	61
PIX313	Fe	M (10.9)	87	1.5	60		98	
PIX313	Fe	H (11.9)	68	1.1	20	50	99	86
PIX318	Fe	L (8.5)	61	5.0	2700			
PIX318	Fe	M (10.9)	104	2.1	60		98	
PIX318	Fe	H (11.9)	96	1.9	20	50	99	86
PAX 18	Al	L (8.5)	55	1.1	1760		29	
PAX 18	Al	M (10.9)	31	3.8	40		98	
PAX 18	Al	H (11.9)	38	2.0	10	75	99	79
PAX xl60	Al	L (8.5)	47	2.5	1760		29	
PAX xl60	Al	M (10.9)	43	3.0	70		97	
PAX xl60	Al	H (11.9)	37	3.9	20	84	99	76

the aimed limits for final Cu content. Previously, researches have reported that compared to Al-based coagulants, the Fe based coagulants have better performance for heavy metal removal due to their wide optimum pH range and large surface area of the resulting flocs (Tang et al., 2015). Using these results, we selected Fe based coagulant, PIX313 for further testing.

Sedimentation

The impact of sedimentation of TWW at two ambient temperatures 4 and 20 °C in three replicates over a sedimentation period of 7 days is shown in Figure 2 and Figure 3. The small sized particles in TWW (Figure 3) makes the sedimentation very slow. Figure 2 shows that it took about 48 hours to reduce the initial turbidity of

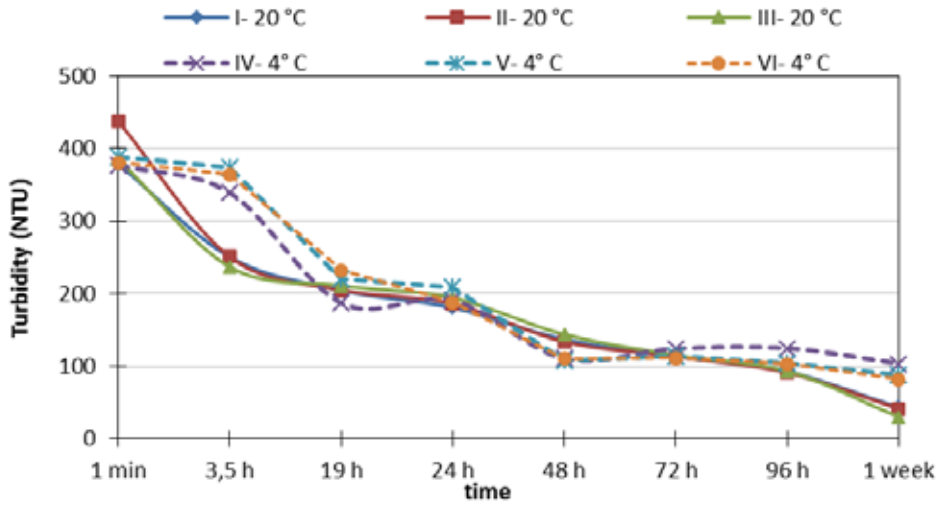


Figure 2. Sedimentation profile for the trials at 20 °C (I, II and III) and the trials at 4 °C (IV, V, VI).

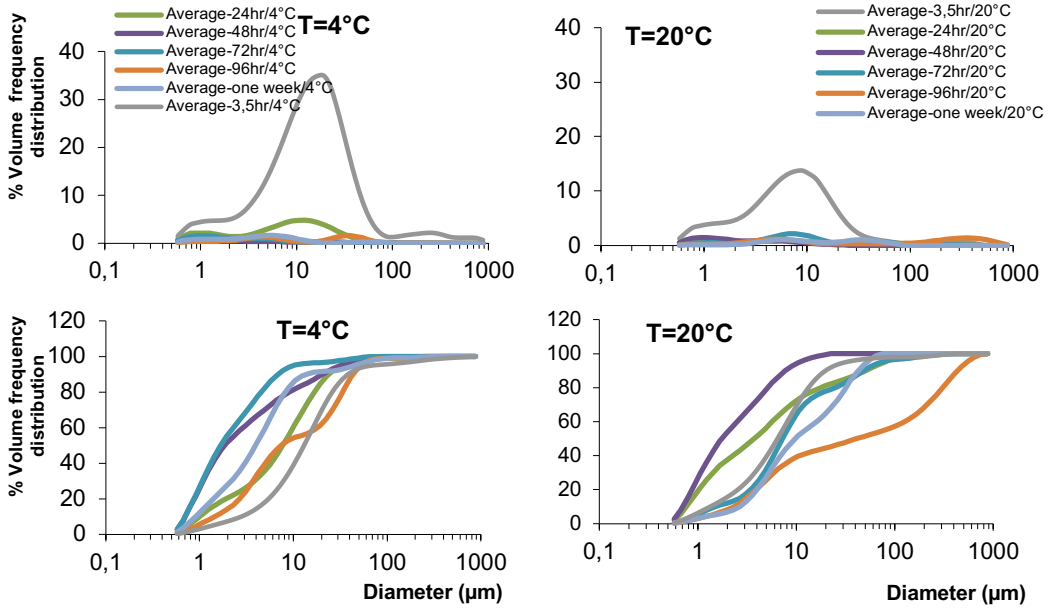


Figure 3. Particle size distribution analysis after sedimentation trial.

381 NTU to 100 NTU, and still a substantial amount of fines are left in the water.

Sedimentation at 4 °C is slower than at 20 °C. After 7 days, the turbidity of the sample at 20 °C was reduced to ~ 30 Nephelometric Turbidity Units (NTU) and at 4 °C to 82 NTU. Figure 3 shows the PSD profiles for the sedimentation trials, which is visualizing the difference in sedimentation rate between the two temperatures over 24 hours. After 24 hours, 50 % of particles were <8 µm at 4 °C and <4 µm at 20 °C. This can be explained by the viscosity at different temperatures. Viscosity increases with decreasing temperature and it reduces the sedimentation rate of the bigger particles at the first hours of sedimentation. Influence of the water viscosity for smaller particles is smaller and thus the turbidity of the sample in two temperatures follows each other.

Figure 4 shows the change in Cu and Zn concentrations of the TWW with sedimentation time at 20 °C. Both Cu and Zn concentrations was reduced exponentially with time. Treated TWW was very clear after 37 days of sedimentation, and the total Cu and Zn concentrations of the supernatant was reduced to 9.5 µg/l and 120 µg/l, respectively.

Chemical treatment of sedimented water

Total Zn and Cu of the samples after 7 days sedimentation at 20 °C were 1000 and 99 µg/l, respectively. This water was used in chemical

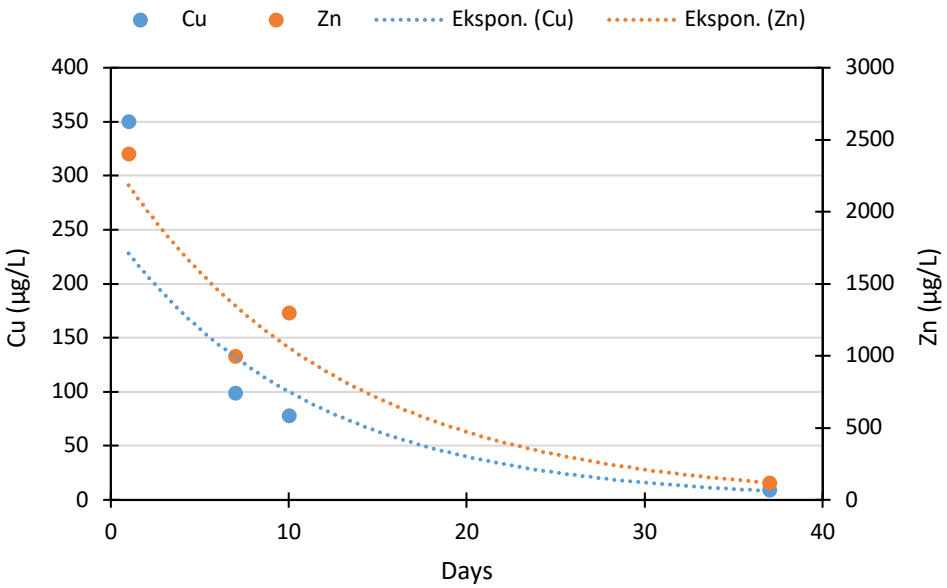


Figure 4. Profile of total Cu and total Zn levels during 37 days of sedimentation

Table 3. Results of chemical precipitation with PIX 313 on Nordby-tunnel wash water samples after 7- and 37-days sedimentation at 20 °C.

TWW type Sedimentation time	Initial pH	Reaction pH	Metal dose	Turbidity	Treated water		% removal	
			mg Al/l	NTU	µg Zn /l	µg Cu/l	Zn	Cu
7 days	7.6	4.7	78	3.1	160	9.9	93	97
7 days	10.4	8.9	19	3.4	760	5.3	68	98
7 days	12.9	11.4	19	2.2	43	5.0	98	99
37 days	12.9	11.3	19	2.8	48	5.1	98	99

precipitation tests with PIX313. Table 3 shows the results after coagulation of water after 7- and 37-days sedimentation. As expected, the Zn and Cu removal is increasing with increasing initial pH of TWW. The coagulant dose needed to obtain the best performance was 19 mg Fe/l, which is significantly lower than what was needed for untreated TWW. The poor Zn removal obtained in the test with initial pH 10.4 is suspected to be an analytical error. Other than that, both tests with high pH (12.9) resulted 95 % Cu and 96 % Zn removal. Removal efficiencies for total Cu and Zn at start-pH of 12.9 achieved the targeted concentrations and resulted in 43 µg Zn/l and 5 µg Cu/l in treated water. Due to limited volume of water available, only one jar test (at pH 12.9) was carried out with water after 37 days sedimentation. Though the initial Zn and Cu concentrations were lower after 37 days sedimentation, treated water concentrations obtained were the same as after 7 days sedimentation.

Biological treatment

Three biological treatment trials with different conditions were conducted. To provide sufficient nutrients, NH_4-N and PO_4-P were added to all three biological test units before starting. Other necessary micronutrients, such as nickel, zinc, sulphur and copper, were sufficiently available in TWW.

Results of the biological treatment are presented in Figure 5. There was no significant difference between inoculated and not inoculated aerobic treatment tests. Turbidity, COD and Cu concentration changes of both aerated trials showed similar results. Zn concentration of the not inoculated test was reduced fast during the first weeks and then both tests reached the same levels.

Turbidity and COD concentrations in both aerated tests (Figure 5 (a) and (b)) were reduced rapidly during the first week of the tests. COD was reduced from 772 mg/l to 120 mg/l and turbidity from 381 to 42 NTU during the first week

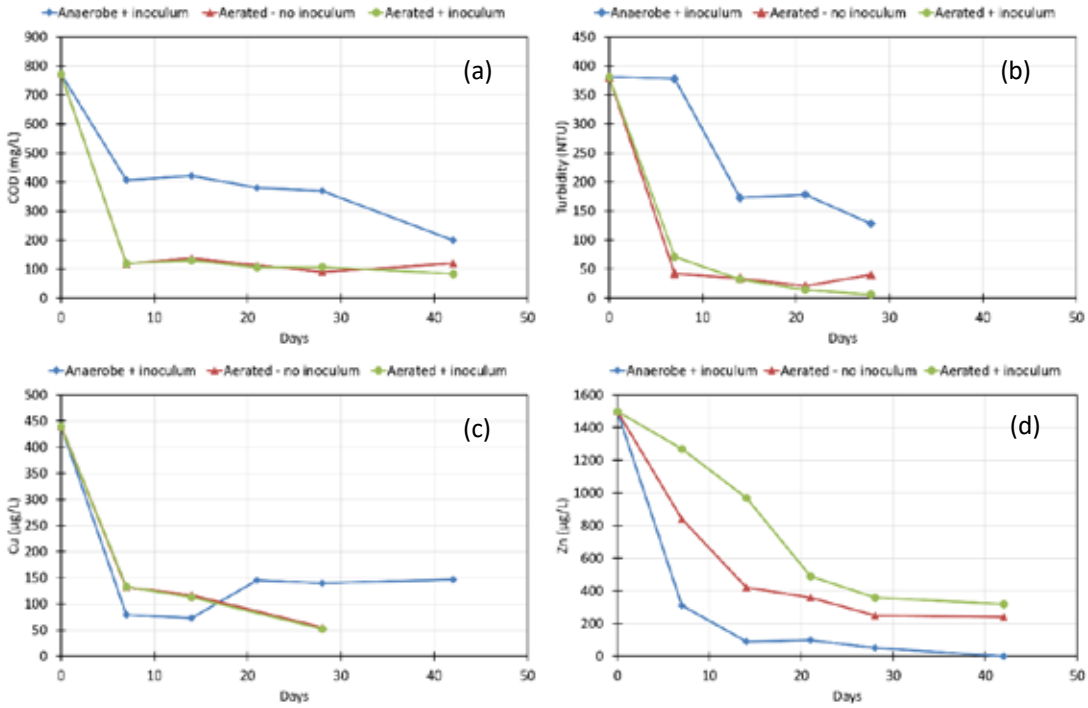


Figure 5. COD (mg/l), turbidity (NTU), filtered Cu and Zn (µg/l) profiles for the anaerobic, aeration and aerobic trials.

of aeration, and was reduced only to 407 mg COD/l and 380 NTU in the anaerobic test. The reason for this is the rapid consumption of COD for aerobic bacteria. Organic carbon degradation under anaerobic condition is slower.

Anaerobic treatment performed comparatively better than the two aerobic treatments with respect to Zn and Cu removal (Figure 5 (c) and (d)). Zn concentration was after 42 days of anaerobic degradation <0.5 µg/l (detection limit), while aerated samples with and without inoculum was 240 and 320 µg/l, respectively. Cu concentration in the anaerobic tests decreased to ~70 µg/l during the first 14 days and then it increased to ~150 µg/l. This is probably due to remobilization of Cu under anaerobic conditions. Cu concentration after 14 days in both aerobic degradation tests was reduced to around 113 µg/l and was measured 52 µg/l after 28 days (4 weeks).

Detergents used for tunnel washing mobilize and dissolve heavy metals in water (Aasum, 2013). One of the objectives of the biological treatment studies was to reduce this impact by biological degradation of the detergents.

In sulphate rich, anaerobic environments, Sulphate-Reducing Bacteria (SRB) and Sulphate Reducing Prokaryotes (SRP) use sulphur as the electron donor and reduces it to sulphide (Chen et al., 2008). Sulphide efficiently precipitates metal ions as metal sulphides. Phosphate concentration in anaerobic water was higher than in the aerated water during the tests (2.6 mg/l compared to 1-1.2 mg/l respectively). Phosphate also has the capability to precipitate metals as metal phosphate. Sulphide precipitation and phosphate precipitation could be the explanation for more rapid reduction of Zn and Cu levels obtained in the anaerobic reactor.

Precipitated metal oxides, sulphides and phosphates are small particles. Therefore, separation by sedimentation may take a longer time. Coagulation and flocculation followed by sedimentation improved the removal of heavy metals from the anaerobic treated TWW. Table 4 presents the results after coagulation of the biologically treated water. Water pH was not adjusted in any of the tests and only 20 mg Al/l was needed. The anaerobe treated samples gave the best removal and could achieve the experiment goals.

Conclusions

Filtration through 1.2 µm filters showed only 29% Zn and 60 % Cu removal from the TWW, and did not meet the target concentrations.

Heavy metal precipitation happens with increasing pH, but the increasing pH by adding NaOH alone was insufficient to meet the treated water quality goals. Co-precipitation by metal salts improved the removal of heavy metals from TWW. Four commercial coagulants were tested with raw TWW. Though both Al- and Fe-based coagulants were equally performing for Zn and Cu removal, the needed Fe based coagulant dose was lower. However, the treated water goals for Cu and Zn (10 and 50 µg/l, respectively) were not reached by co-precipitation of TWW.

Sedimentation reduced both Zn and Cu concentration significantly with time. Sedimentation followed by chemical precipitation with the iron based coagulant PIX 313 at high pH (11-12) improved the removal of Cu and Zn significantly.

Biological treatment under anaerobic conditions showed better performance than biological

Table 4. Jar test results of the biologically treated water. Water pH was not changed. PIX 313 (20 mg Fe /l) was used in all three tests.

Treatment	Cu			Zn		
	Start (µg/l)	PIX (µg/l)	Removal (%)	Start (µg/l)	PIX (µg/l)	Removal (%)
Aerated -no inoculum	66	46	30.3	280	24	91.4
Aerated + inoculum	60	36	40.0	360	35	90.3
Anaerobe + inoculum	147	35	76.2	50	10	98.0

degradation under aerobic conditions. There was no significant improvement by inoculating the aerobic cultures with bacteria from the sedimentation ponds at the Nordby-tunnel. The target limits could be achieved by chemical precipitation of the anaerobically pre-treated water, while the chemical precipitation of aerobically treated water failed to achieve the target.

The treatment solution needed to meet both targets of 10 and 50 µg/l Cu and Zn, respectively, was challenging, but it is likely to be met by using a combination of anaerobic degradation and sedimentation as the secondary treatment after sand traps, and a filtering process as the tertiary treatment to ensure sufficient solids removal. The anaerobic degradation and sedimentation process with 4-5 weeks hydraulic retention time (HRT) has been proposed to the NPRA based on test results achieved in the work carried out by Vik *et al* (2017).

The TWW quality is likely to vary from tunnel to tunnel and with the time of the year. More extensive studies are needed to document and improve the design basis for a sustainable treatment process meeting different environmental requirements.

Acknowledgment

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