How to protect our Nature - Chemistry in TBM tunnelling. From the laboratory to on-site use and muck disposal.

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ABSTRACT: All tunnelling methods need chemical additives - modern tunnel construction without chemicals is utterly impossible. When using chemicals, it is important to investigate not only their efficiency but also their environmental impacts – which mean they shall be carefully selected. Technically perfect products are not necessarily a good choice for the environment.
Health & environmental related chemical impacts like carcinogenicity, toxicity, biodegradation and the use of renewable raw materials will be discussed in detail.

1 INTRODUCTION

In most cases, the chemicals used for TBM tunnelling are in most cases in direct contact with the soil and the groundwater during their application and will remain finally in the soil. Therefore they require a very careful examination regarding their environmental impacts. A couple of questions need to be addressed consequently:
- How do these additives change the soil physically and chemically the soil?
- What are the effects to the water and the organisms living in the water?
- What are the short term and long term effects?
- What is leaching out of the muck?
- Is it better to use chemical or bio-based products?
- What are possible side effects to the environment?

It is important to remember that the environmental pollution caused by inappropriate or wrongly used chemicals may exist but not be directly visible in most cases, with exception of the soil conditioners and corresponding foam formation (figure 1).

Figure 1. Visible water pollution caused by industrial wastewater

Figure 2. Waves producing 'natural foam' with sea proteins – no pollution

2 GENERAL RISK CHARACTERISTICS OF TBM ADDITIVES

In order to minimize the effects of TBM additives during tunnel construction, the general risk characteristics of a product and all its ingredients & impurities need to be evaluated.

2.1 *Mammal toxicity / carcinogenicity / mutagenicity*

All ingredients with the mentioned effects written above shall generally not be used for TBM additives.
One of the best examples of bad / ignorant product choice and on-site use was the application of Polyacrylamide for water sealing injection purposes at the Swedish Hallandsas tunnel project. The hardened polyacrylamide gel itself passed all required tests – the problem here were the unhardened components and their monomer content (with toxic, possible carcinogenic and mutagenic effects) during application.

Lessons learnt:

1. Check the risk characteristics of all ingredients and ban certain chemical components. Don't forget impurities & residual (monomer) contents).
2. No panic when 'Polymers' are used. According to (Wikipedia) definition, a polymer is a large molecule, composed of many repeated subunits. Because of their broad range of properties, both synthetic and natural polymers play an essential and ubiquitous role in everyday life. 'Polymer' is no indication on how good or bad a product is, they can even be bio-produced by bacteria.

2.2 *Risk to air*

All ingredients with a high vapor pressure shall be avoided. No emission for example from the soil conditioning tanks into the air shall take place – and especially for hyperbaric intervention, it is desired to evaporate the lowest possible amount of chemicals into the air.

Lessons learnt:

Modern TBM additives do generally fulfill the above criteria, nevertheless considerable differences during compressed air intervention and related waiting time for chamber ventilation are observed.

2.3 *Persistence / Biodegradation*

Biodegradation is the disintegration of materials by bacteria, fungi, or other biological means. Although often conflated, biodegradable is distinct in meaning from compostable. While biodegradable simply means to be consumed by microorganisms, "compostable" makes the specific demand that the object break down under composting conditions.
Biodegradability is often used in relation to ecology, waste management and the natural environment and is now commonly associated with environmentally friendly products – which is only a part of the real picture. All points listed in chapter 2. have to be judged in order to classify a product as environmentally friendly.
Nevertheless it is generally positive to use chemicals with quick and high biodegradation (if possible: readily biodegradable products). The (OECD 301) tests that can be used to determine the ready biodegradability of organic chemicals include six test methods described in the OECD Test Guidelines No. 301 A-F.
The pass levels for ready biodegradability are 70% removal of dissolved organic content (DOC) and 60% of theoretical oxygen uptake (ThOD) or ThCO2 production for respirometric methods. They are lower in the respirometric methods since, as some of the carbon from the tested chemical is incorporated into new cells, the percentage of CO_2 produced is lower than the percentage of carbon being used. These pass values have to reach a 10-d window within the 28-d test period as illustrated in figure 3.

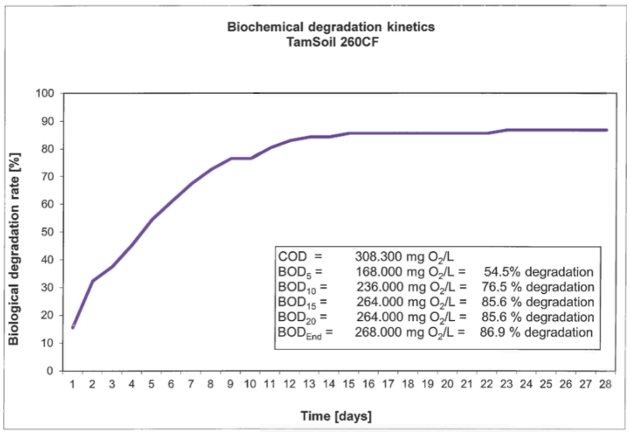


Figure 3.Biochemical degradation kinetics for TamSoil 260CF according to OECD 301F.

Given a positive result in a test of ready biodegradability, it may be assumed that the

chemical will undergo rapid and ultimate biodegradation in the environment (OECD Guideline).
In order to be judged as an environmentally friendly product, these chemicals need to show in addition very low bioaccumulation characteristics as well as low aquatic toxicity – otherwise even excellent biodegradable products have bad effects.
Lessons learnt:
1. Having good biodegradation data is not sufficient to classify a product as environmentally friendly
2. Also persistent products (inert products) can be environmental friendly if bioaccumulation and toxicity are negligible.

2.4 *Bioaccumulation*

Bioaccumulation refers to the accumulation of substances, for example pesticides or other chemicals in an organism. Bioaccumulation occurs when an organism absorbs a - possibly toxic - substance at a rate faster than which the substance is lost by catabolism and excretion. Thus, the longer the biological half-life of a toxic substance the greater the risk of chronic poisoning, even if the environmental levels of the toxin are not very high.

For chemicals used in TBM tunneling, bioaccumulation shall be avoided.

2.5 *Aquatic toxicity*

Aquatic toxicology studies the effects of chemicals on aquatic organisms at various levels of organization, from subcellular through individual organisms to communities and ecosystems.
This field of study generally includes freshwater, marine water and sediment environments. Common tests include standardized acute and chronic toxicity tests lasting 24–96 hours (acute test) to 7 days or more (chronic tests). These tests measure endpoints such as survival, growth, reproduction, that are measured at each concentration in a gradient, along with a control test. Typically, selected organisms with ecologically relevant sensitivity to toxicants and a well-established literature background are selected.

In the case of TBM chemicals, acute aquatic toxicity tests are executed on fish (trout: danio rerio), water flea (daphnia magna) and algue (scenedesmus subspicatus) according to (OECD 203) standard.

The test results will be displayed as follows:

Median Lethal Concentration (LC50) – The chemical concentration that is expected to kill 50% of a group of organisms. Median Effective Concentration (EC50) – The chemical concentration that is expected to have one or more specified effects in 50% of a group of organisms.

No Observed Effect Concentration (NOEC) – The highest test concentration for which no effect is observed relative to a control over a specified exposure time and equal to LC0.

Generally, a chemical additive can be classified as ‘not water hazardous’ if the LC/LD50 values are > 100mg/l – and this is the classification which needs to be achieved when ever possible. The higher a LC/LD50 value, the better for the environment.

The reduction of the acute aquatic toxicity down to a minimum is not a big issue for tail sealants, main bearing greases and soil conditioning polymers if the ingredients are well chosen. Unlike foaming soil conditioners, where low LC/LD50 values are much more difficult to reach.

Standard soil conditioners show LC50 data of around 10-30 mg/l, as indicated in figure 4, (red line).

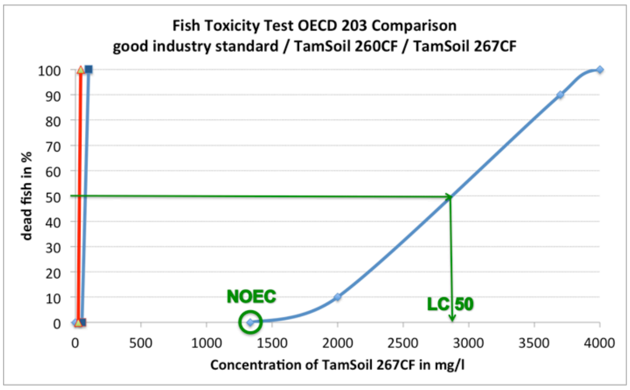


Figure 4. Fish toxicities according to OECD 203 for different soil conditioning foams.

An optimization of the traditional foaming agents can already improve the LC50 already quite well around 2 to 7 times, example TamSoil 260CF: LC50 = 70 mg/l; LC0 = 50mg/l (=NOEC)
→ classification as ‘not water hazardous’ with LC50 between 10-100mg/l and NOEC > 1mg/l according to regulation (EC) no. 1272/2008.

New soil conditioners like the bio-based TamSoil 267CF show 26 times better NOEC and 42 times better LC50 data as indicated in figure 4 (blue line), which describes a step change for environmentally friendly foaming soil conditioners:
TamSoil 267CF: LC50=2'800-3'000 mg/l; LC0=1'333mg/l (=NOEC)
→ classification as 'not water hazardous' with LC50 > 100mg/l and NOEC > 1mg/l according to regulation (EC) no. 1272/2008.

2.6 *Risk to surface water*

Generally the same criteria than for the aquatic toxicity apply here. In some way different to the exposure during excavation are the tunnel run-off water (spillages) and the superficial run-off water from disposal areas. For the later ones it is recommended to install water retention basins before draining into close by streams or rivers as shown in figure 5.

Figure 5. Land modelling with excavated soil & surface water retention basin at Metro Toulouse project, France.

3 HOW DO ADDITIVES CHANGE THE SOIL PHYSICALLY & CHEMICALLY?

3.1 *Excavation*

During excavation, all chemical additives will predominantly be used as per their design: soil conditioners are added to the soil and are immediately captured afterwards together with the soil (working chamber and extraction screw), the same applies for the main bearing greases. The tail sealants remain in a segment concrete / annulus grout sandwich structure with no contact to the surrounding soil or groundwater. Only a very limited amount of chemicals can leach or penetrate into the surrounding ground (generally proposed worst case scenario: 1%).

Consequently, if the chemical additives are well chosen, no effect or only a very limited effect within a couple of meters around the TBM shied shall take place.

3.2 *Disposal*

If the chemical additives are well chosen, the excavated soil does not differ much to the soil in situ. The only changes which can be observed would be the

a. Consistency
b. Total organic content (TOC) and related biological oxygen demand (BOD)

The pH values remains the same, no heavy metals or other undesired products will be added to the soil, nothing will be washed out due to the soil conditioners used. The biodegradation rate is that high within the first days that the TOC drops quite quickly (see figure 3).

Regarding the consistency, the main reason for the soil flowability is the use of foam within the soil. Inside the screw conveyor and during the further transportation process, the foam already starts degrading - generally after 24 hours the excavated soil does not contain any air any more (only the liquid components remain and will start to degrade by biodegradation). The remaining consistency is almost completely driven by the amount of water added during the soil conditioning process and added on the conveyor belt during transportation. This water addition is the most difficult to get rid off in order to achieve a stiffer soil. If a certain soil consistency is desired for disposal, the water addition should be kept at a minimal level by using a higher amount of soil conditioning additives. It is generally not necessary and not desired for environmental reasons to re-work the excavated soil. Only if a very stiff consistency is requested, the addition of water binding polymers or water-reactive chemicals maybe needed.

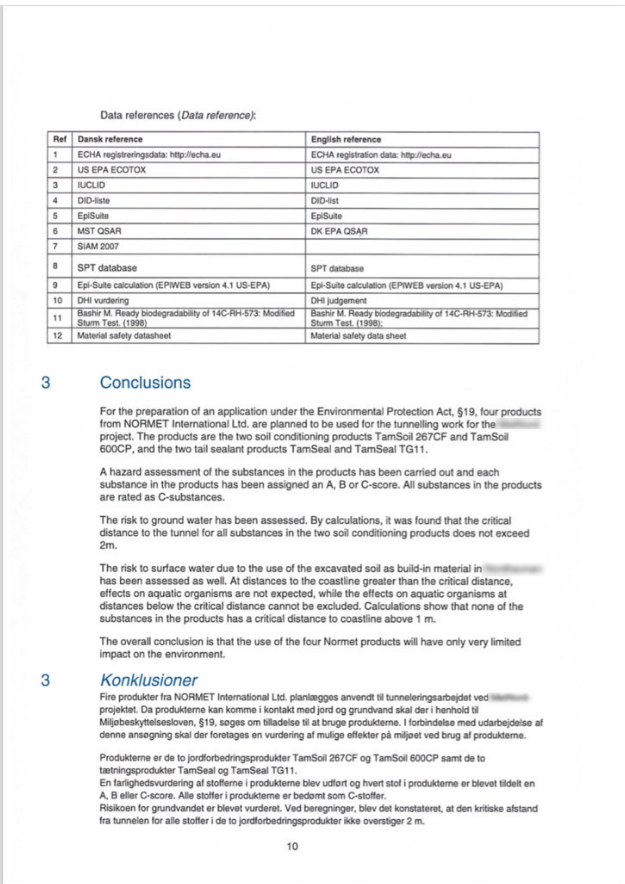
4 SITE EXAMPLES

4.1 *General assessment of chemical substances*

The Scandinavian countries are traditionally very conscious of their environment (and even more as a result of the effects mentioned in chapter 2.1) – their risk assessments are therefore known and dreaded.

Normet took that as inducement for a Metro EPB tunneling project in Scandinavia. Local officials performed a general risk assessment with 3 main areas:

a. Inherent environmental hazardousness (C classification = least hazardous substances)
b. Assessment of potential hazard to groundwater
c. Assessment of potential hazard to surface water



Data references (*Data reference*):

Ref	Dansk reference	English reference
1	ECHA registreringsdata: http://echa.eu	ECHA registration data: http://echa.eu
2	US EPA ECOTOX	US EPA ECOTOX
3	IUCLID	IUCLID
4	DID-liste	DID-list
5	EpiSuite	EpiSuite
6	MST QSAR	DK EPA QSAR
7	SIAM 2007	
8	SPT database	SPT database
9	Epi-Suite calculation (EPIWEB version 4.1 US-EPA)	Epi-Suite calculation (EPIWEB version 4.1 US-EPA)
10	DHI vurdering	DHI judgement
11	Bashir M. Ready biodegradability of 14C-RH-573: Modified Sturm Test. (1998)	Bashir M. Ready biodegradability of 14C-RH-573: Modified Sturm Test. (1998);
12	Material safety datasheet	Material safety data sheet

3 Conclusions

For the preparation of an application under the Environmental Protection Act, §19, four products from NORMET International Ltd. are planned to be used for the tunnelling work for the [illegible] project. The products are the two soil conditioning products TamSoil 267CF and TamSoil 600CP, and the two tail sealant products TamSeal and TamSeal TG11.

A hazard assessment of the substances in the products has been carried out and each substance in the products has been assigned an A, B or C-score. All substances in the products are rated as C-substances.

The risk to ground water has been assessed. By calculations, it was found that the critical distance to the tunnel for all substances in the two soil conditioning products does not exceed 2m.

The risk to surface water due to the use of the excavated soil as build-in material in [illegible] has been assessed as well. At distances to the coastline greater than the critical distance, effects on aquatic organisms are not expected, while the effects on aquatic organisms at distances below the critical distance cannot be excluded. Calculations show that none of the substances in the products has a critical distance to coastline above 1 m.

The overall conclusion is that the use of the four Normet products will have only very limited impact on the environment.

3 *Konklusioner*

Fire produkter fra NORMET International Ltd. planlægges anvendt til tunneleringsarbejdet ved [illegible] projektet. Da produkterne kan komme i kontakt med jord og grundvand skal der i henhold til Miljøbeskyttelsesloven, §19, søges om tilladelse til at bruge produkterne. I forbindelse med udarbejdelse af denne ansøgning skal der foretages en vurdering af mulige effekter på miljøet ved brug af produkterne.

Produkterne er de to jordforbedringsprodukter TamSoil 267CF og TamSoil 600CP samt de to tætningsprodukter TamSeal og TamSeal TG11.
En farlighedsvurdering af stofferne i produkterne blev udført og hvert stof i produkterne er blevet tildelt en A, B eller C-score. Alle stoffer i produkterne er bedømt som C-stoffer.
Risikoen for grundvandet er blevet vurderet. Ved beregninger, blev det konstateret, at den kritiske afstand fra tunnelen for alle stoffer i de to jordforbedringsprodukter ikke overstiger 2 m.

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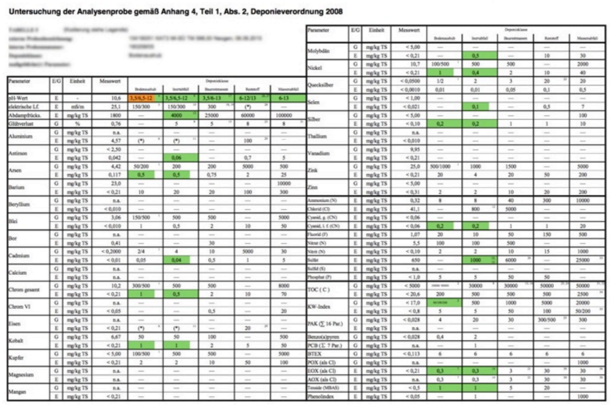
Figure 6. Assessment conclusion sheet, Normet 2016.

As illustrated in figure 6, the effect of TamSoil 267CF soil conditioner, TamSoil 600CP Polymer and TamSeal TG11 and TG12 are rated as having only very limited impact on the environment. None of the products has a critical distance to the coastline above 1m (which is extremely positive).

4.2 *Disposal*

Most important for the disposal classification is the leaching test. A detailed view into the analysis of the excavated soil is given by the example of an EPB TBM tunneling project in Central Europe.

It is of utmost importance to analyze first the virgin soil in order to detect the influences of the chemical additives later. Figure 7 illustrates such test results.



Untersuchung der Analysenprobe gemäß Anhang 4, Teil 1, Abs. 2, Deponieverordnung 2008

Figure 7. Leaching test analysis of a virgin soil, Central Europe.

Once the geogenic characteristics are known, the same soil sample can now be treated as foreseen (or treated as worst case scenario) and then analyzed again.

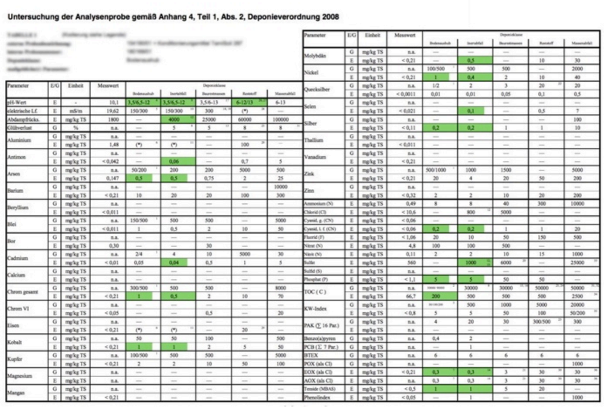


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Figure 8. Leaching test with the same soil as presented inFigure 7. but treated with TamSoil 267CF.

In this case, the comparison of figure 7. & 8. illustrates the environmental effects of the use of TamSoil 267CF in the soil: Nothing else than TOC increase.

5 OUTLOOK & SIDE EFFECTS

The use of highly refined mineral oils or fatty acids derived from crude oil is possible, but needs to be shifted to renewable sources. Rapeseed oils or soya bean oils are excellent technical alternatives. Upside is the plants grow also at moderate climate zones and tropical climate zones are not required. Downside is huge monocultures are necessary to fulfill the quantity demand – with well known influences to the nature. Microbial production can be an alternative.

The base structure of the foaming soil conditioners can be derived from both petrochemical feedstocks as well as from renewable resources (plants and animal oils, micro-organisms). Originally, they were made from renewable resources like fats and oils, whereas today, the majorities are of petrochemical origin (Amaral et al). Some surfactants, known as biosurfactants, are biologically produced by yeasts or bacteria.

5.1 *Better using chemical or bio-based additives?*

As discussed before, in order to develop more environmentally friendly additives, there is a need to move away from mineral oil based raw materials to renewable raw materials based products: lower toxicity and higher biodegradation values as well as low carbon footprint. As described, the product development & use is already moving in this direction.

5.1.1 *Re-newable raw material based*

High efficiency green foaming soil conditioners based on renewable raw materials can be produced by reaction of sugar with fat / fatty acids. The production process involves one step or two step process;

1. Tropical oil (Coconut, Palm oil) → fatty alcohol
2. Corn → starch → Sugar

Green foaming soil conditioners are readily biodegradable; therefore no recycling / further treatment is required. They have high tolerance to salts and other such electrolytes and thus possessing higher efficiency.

Technically this process is well established; enough raw materials are available in order to reach a reasonable pricing structure – still remaining at a higher level than traditional products.

5.1.2 *Chemical or Microbial production*

When using bio-based raw materials – it still remains the question how to produce the end product: Chemical production or microbial production.

The main advantage for microbial production is that microorganisms can use a wide set of carbon sources and energy for growth, including bio-based raw materials or even waste oils.

Figure 9. Example of fermenter, here for pharmaceutical production.

Regarding disadvantages, one of the problems is production cost: remaining at a very high level with 60-70% of the final cost.

5.2 *Possible side effects of bio-based products*

Example: Rapeseed and Soya bean oils: Monocultures in moderate climate zones with all known negative effects on nature: eliminating biological controls (lack of diversity), more synthetic material use (herbicides, insecticides, bactericides, fertilizers with negative effects on for example insects and bees), organism resistance, soil degradation (no natural protection of the soil against erosion due to elimination of ground crops) and water use (high water use due to elimination of ground crops and missing moisture retention of the soil).

Tropical oils are also having a shocking impact on our planet. The production of this palm oil for example is not only responsible for polluting rivers and causing land erosion, but when the plantation workers set fire to the remaining trees, shrubs and debris to make way for the oil palms, it produces immense amount of smoke pollution that is toxic to planet earth. This has been found to be the second biggest contributor to greenhouse gas in the world.

Figure 10. Burnt jungle with new palm plants.

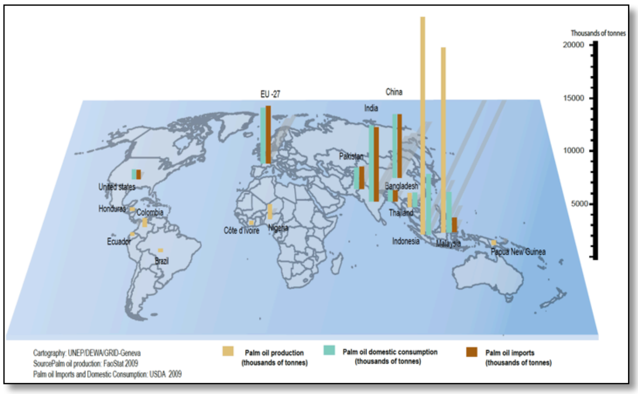
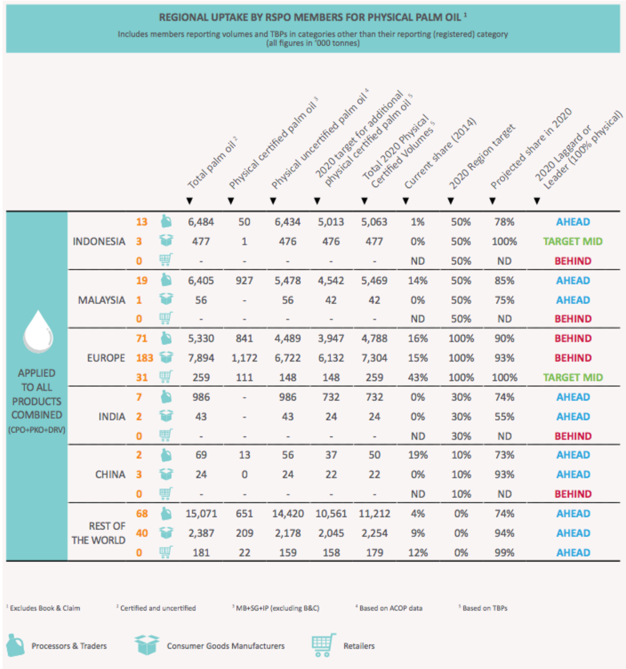


Figure 11. Most important palm oil producers, traders and consumers (RSPO).

Roundtable on Sustainable Palm Oil (RSPO) reports show a growing market share of Certified Sustainable Palm Oil (CSPO), nevertheless still on a quite low level of 1% CSPO in the case of Indonesia (where some big companies lost their RSPO certificates), while it is encouraging in Malaysia with 14%. Both countries together produce more than 85% of the worldwide Palm Oil quantities. More than 70% of the total palm oil production is used for food, less than 20% for technical products according to Palm Oil Investigations Inc. (POI)



REGIONAL UPTAKE BY RSPO MEMBERS FOR PHYSICAL PALM OIL [1]

Includes members reporting volumes and TBPs in categories other than their reporting (registered) category (all figures in '000 tonnes)

	Region	No.	Category	Total palm oil [2]	Physical certified palm oil [3]	Physical uncertified palm oil [4]	2020 target for additional physical certified palm oil [5]	Total 2020 Physical Certified Volumes [5]	Current share (2014)	2020 Region target	Projected share in 2020	2020 Laggard or Leader (100% physical)
APPLIED TO ALL PRODUCTS COMBINED (CPO+PKO+DRV)	INDONESIA	13	Processors & Traders	6,484	50	6,434	5,013	5,063	1%	50%	78%	AHEAD
		3	Consumer Goods Manufacturers	477	1	476	476	477	0%	50%	100%	TARGET MID
		0	Retailers	-	-	-	-	-	ND	50%	ND	BEHIND
	MALAYSIA	19	Processors & Traders	6,405	927	5,478	4,542	5,469	14%	50%	85%	AHEAD
		1	Consumer Goods Manufacturers	56	-	56	42	42	0%	50%	75%	AHEAD
		0	Retailers	-	-	-	-	-	ND	50%	ND	BEHIND
	EUROPE	71	Processors & Traders	5,330	841	4,489	3,947	4,788	16%	100%	90%	BEHIND
		183	Consumer Goods Manufacturers	7,894	1,172	6,722	6,132	7,304	15%	100%	93%	BEHIND
		31	Retailers	259	111	148	148	259	43%	100%	100%	TARGET MID
	INDIA	7	Processors & Traders	986	-	986	732	732	0%	30%	74%	AHEAD
		2	Consumer Goods Manufacturers	43	-	43	24	24	0%	30%	55%	AHEAD
		0	Retailers	-	-	-	-	-	ND	30%	ND	BEHIND
	CHINA	2	Processors & Traders	69	13	56	37	50	19%	10%	73%	AHEAD
		3	Consumer Goods Manufacturers	24	0	24	22	22	0%	10%	93%	AHEAD
		0	Retailers	-	-	-	-	-	ND	10%	ND	BEHIND
	REST OF THE WORLD	68	Processors & Traders	15,071	651	14,420	10,561	11,212	4%	0%	74%	AHEAD
		40	Consumer Goods Manufacturers	2,387	209	2,178	2,045	2,254	9%	0%	94%	AHEAD
		0	Retailers	181	22	159	158	179	12%	0%	99%	AHEAD

[1] Excludes Book & Claim [2] Certified and uncertified [3] MB+SG+IP (excluding B&C) [4] Based on ACOP data [5] Based on TBPs

Processors & Traders Consumer Goods Manufacturers Retailers

Figure 12. Worldwide palm oil production and share of certified & traditional production methods (RSPO).

6 CONCLUSION

Well-selected chemical additives have only a minimum impact on the environment:

- Adapted conditioning of soft ground to increase TBM efficiency and reduce energy & chemical consumption, ensure safe tunnelling almost regardless of the soil type.
- Reduction of (dangerous) dust, (wear) cost and energy is the aim of anti-wear and anti-dust additives.
- Best sealing and lubrication performance of tail sealants and main bearing greases can be combined with lowest environmental impacts when using bio-based raw materials.

High efficiency green foaming soil conditioners are manufactured almost completely from natural, renewable resources. They are notable for their environmental compatibility:

- High biodegradability
- No environmentally harmful intermediates are formed even during mineralization to carbon dioxide and water.

- Sulphate free
- Free of anionic surfactants
- Free of preservatives

But up to now - with only a few exceptions - still the financial effects is the main contributing factor. If we really want to protect our nature (including the tropical regions), then we need a general step change in our mind-set (not only in tunnelling), start using the green technologies being available and stop shifting problems to the 3rd world.

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