DRILLING FLUID FOR USING SBM ON LAND AND REUSING CONTAMINATED CUTTINGS WITH ZERO WASTE

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ABSTRACT

With the use of invert emulsion fluids, environmental responsibility has increased the cost and liability associated with the disposal of contaminated drill cuttings. In environmentally sensitive areas it is unlikely that any discharges of contaminated cuttings will be permitted and responsible treatment methods must be found to minimize future liability.

Development of an invert emulsion drilling fluid designed for both the high performance drilling and optimized treatment of contaminated cuttings has been a key in minimizing environmental impact. Developing efficient treatment techniques for the local environment has been equally as important. True environmental responsibility has been achieved by combining chemistry and treatments to produce an end product which can be beneficially re-used in the local environment.

The Authors will discuss the drilling fluid chemistry and treatment techniques, show the field performance of these fluids, and will review the potential for beneficial reuse of contaminated cuttings in this context.

INTRODUCTION

Historically, drilling fluids having a continuous, hydrocarbon-based phase have shown superior drilling performance when compared to water-based drilling fluids. The impact of discharging cuttings contaminated with such fluids into the marine environment has been a subject of concern and study for many years. Initially, this led to the use of low-toxicity, low-aromatic mineral oils, then later to the use of synthetic-based fluids. The design of these novel drilling fluid systems has primarily focused on the technological and environmental challenges of operating and discharging in the offshore environment. The same fluid systems can be used to drill wells on land, however significantly less study had been undertaken to categorize the effects of the discharge of contaminated cuttings in this environment. While some work has been conducted on the type and amount of salts used in fluids for land operations, their environmental profile has never been fully optimized. It is generally accepted that, while it is possible to apply various techniques such as thermal desorption and cuttings re-injection to the destruction and removal of hydrocarbons, it is not always as easy to remediate and negate the environmental problems caused by persistent hydrocarbons and the salts used in the brine phase.

Disposal of hydrocarbon-contaminated cuttings can be a major issue for drilling operations on land, particularly in remote areas. In most countries, regulatory limits on the electrical conductivity of water run-off, total oil and grease, and heavy metals make the effective remediation of cuttings to regulatory approved levels a slow and complex process. Such disposal issues are compounded by the drive towards zero discharge in the offshore environment, necessitating transportation of contaminated cuttings and fluids to land for treatment and disposal.

The high-performance, synthetic-based, invert emulsion drilling fluid described in this paper is specifically engineered with materials chosen for their enhanced biodegradation, low-toxicity and soil enhancing characteristics. The fluid is designed for cost-effective drilling and delivers all the performance benefits of these types of fluids. In addition, the system has been specifically designed to degrade using land-based bioremediation techniques such as landfarming, composting, vermidigestion, bioreactors, and biopiles with minimal organic and inorganic residues.

In addition to the drilling fluid chemical design, a careful study has also been made of the treatment design, such that the end result of treating drilling-fluid-contaminated cuttings is the generation of either a usable, enriched top soil or a valuable organic-type fertilizer that can be utilized to enhance plant growth and improve poor soils.

DRILLING FLUID DESIGN

The original aim was to design a drilling fluid system that does not negatively impact the soil when contaminated cuttings are spread on land. The fluid also should readily and rapidly degrade leaving minimal organic residues, and for the brine phase should not rely on salts that could create toxicity or plant growth problems when deposited in soil. It was further intended that the treated fluid and cuttings could actively enhance soil quality and subsequent plant growth.[1,2] Environmental tests were carried out at the University of Calgary on various potential base fluids, internal phase salts, and aged drilling fluids. Based on this data, the technical performance of the drilling fluids was evaluated and optimized. Six base fluid types, five emulsifier packages, seven internal phase materials, two viscosifying organophilic clays, three fluid-loss-control agents, and three weighting materials were evaluated. Environmental tests were also carried out on several fully-formulated drilling fluids and a few samples of contaminated cuttings before and after treatment in a bioreactor. The environmental evaluation (conducted at the University of Calgary) consisted of tests for biodegradability, phytotoxicity, earthworm survival, springtail survival and Microtox (LC_{50} on bacterium).

LABORATORY RESULTS

Base Fluid. Environmental data on the six base fluid candidates of similar carbon chain length are shown in Tables 1 and 2. The base fluids were chosen with the understanding that their viscosity characteristics would be suitable for optimized drilling fluid design.

The biodegradability test results indicate that diesel and the branched paraffin are considerably more resistant to rapid biodegradation than the other four fluids. The isomerized olefin (IO) is intermediate in biodegradability, while the linear alpha olefin (LAO), linear paraffin (LP), and the ester exhibit the highest biodegradability.

The toxicity data in Table 2 clearly shows that the diesel and the ester are considerably more toxic than the branched paraffin, LP's or olefins in all five tests. The Microtox test also showed some differentiation between the $C_{12\text{-}13}$ LP, olefins and branched paraffin. This is to be expected, because higher–molecular-weight branched fluids tend to exhibit lower acute toxicity in tests that focus on water-column toxicity. On the basis of the combined biodegradability and toxicity results, the $C_{11\text{-}14}$ linear paraffin was chosen as the base fluid for the remainder of the studies.

Weighting Material. Hematite was chosen over barite and calcium carbonate based on standard fluid properties and environmental effects. Barite was not selected as the preferred weight material, because it was not seen to provide any benefit to the final product. Hematite is an attractive choice as the toxicity of dissolved iron is considered low for most forms of life, and hematite contains exceptionally low levels of bio-available heavy metals. In addition, hematite has the potential to provide iron to iron-poor soils and fits the model for product selection for improving soil quality.

Internal Phase. Various candidate salts and organics were tested before two suitable candidates were identified. One version of the internal phase is a nitrate brine.[4] A second uses an acetate brine as the internal phase. A third version of the internal phase is a blend of the nitrate and acetate brines. The blend of acetate and nitrate salts was found to be particularly suited for direct land treatment of contaminated cuttings, as the acetate is intrinsically biodegradable while the nitrate accelerates the overall biodegradation process.

Emulsifier Package. The performance of emulsifiers in invert fluids is affected by the nature of the base fluid, the type of organophilic clay, and the nature of the internal phase. A biodegradable emulsifier was developed that could provide good drilling fluid properties up to at least 250°F. A blend of conventional emulsifiers was also found to be suitable, and it was tested up to 450°F.

DRILLING FLUID COMPARISON

Standard drilling fluid properties of three 13-lb/gal, 70/30 (synthetic/water ratio) formulations, one with an acetate brine (Formulation A), one with a nitrate/acetate blended brine (Formulation NA) and one with a nitrate brine (Formulation N) are shown in Table 3.

Biodegradability and toxicity of Formulations A and N are compared with those of a typical diesel/$CaCl_2$/barite fluid in Table 4.

These results show clearly that muds A and N both are consistently more biodegradable and much less toxic than the diesel mud. In comparing Formulation A with a similar formulation weighted with barite (instead of hematite), biodegradability and toxicity appear to be similar for both fluids. However, a soil-enhancing iron source is considered desirable for its long-term potential benefits.

Formulation A showed lower overall toxicity than Formulation N. This trend appears to correlate with the trend in electrical conductivity (EC) measured after the biodegradation tests, i.e. after 65 days. Thus, a mud with a higher EC generally gives a higher toxicity, which is to be expected, (toxicity increasing with increasing ionic strength). The toxicity data for the fluid formulations in Table 4 indicate that the percent root elongation observed for Formulation A is nearly 50% greater than for the control. This suggests that Formulation A enhances some aspects of the quality of the soil.

FIELD TRIAL RESULTS

Early Field Trials. The initial field trial of the novel synthetic-based drilling fluid was conducted in New Zealand using a linear paraffin as the base fluid, calcium ammonium nitrate as the internal phase and barite as the weight material. Barite was chosen from an economic and logistical standpoint. The fluid was introduced in a field where high–weight, water-based mud ranging from 16 – 19 lb/gal was traditionally used at depths around 1000 m with many hole problems experienced, including but not limited to:

Extremely reactive plastic clays
Significant borehole ballooning
High background gas and gas kicks
Numerous hole pack offs due to tectonics
Narrow equivalent circulating density (ECD) window
Fluid rheology problems at high weights
Induced fractures due to high ECD
Water flows
No logs successfully run
Difficulty in running casing
Resultant fluid cost contributed to 30% of the AFE total well budget.

Eleven wells had previously been drilled in the area with these fluids and all experienced extensive hole problems. Alternative systems were considered and the newly engineered “bioremediation-friendly” synthetic-based mud was chosen based on the selection criteria discussed previously.

The results of the bioremediation-friendly synthetic mud system surpassed expectations. A depth of 2544 m was achieved in only 34 days. No drilling problems were experienced and torque and drag was reduced. The hole was successfully logged with the calliper indicating gauge hole, and hole integrity was maintained during a five-day, openhole testing program. Additional wells have since been drilled in this area using the same fluid and with minimal hole problems and lower overall drilling fluid costs as compared to the previous WBM wells. Drilling such wells is still challenging but the combination of experience, good drilling practices, and the bioremediation-friendly synthetic mud system has contributed to a successful ongoing drilling program.

For these field trials the use of worm-driven technology to remediate the contaminated drill cuttings was introduced along with the bioremediation-friendly synthetic mud system. This remediation technique utilized the existing biotechnology infrastructure to treat the drill cuttings as outlined below.

Later Field Trials. The novel synthetic-based drilling fluid was later used in the US Rocky Mountain region using a linear olefin as the base fluid and calcium carbonate as bridging material. The fluid was introduced in an area where minimum-weight, water-based mud was traditionally used with many hole problems experienced, including but not limited to:

Reactive plastic clays
Numerous hole packoffs
Narrow ECD window
Induced fractures due to high ECD
Significant lost circulation
No logs successfully run
Difficulty in running casing
High fluid cost

Alternative invert emulsion and oil-based systems were considered and the bioremediation-friendly synthetic based fluid was chosen based on the selection criteria discussed previously. The new synthetic fluid was used to successfully drill the next well, with no hole problems being experienced, no drilling fluid losses incurred, and the drilling fluid used being recovered for use on future wells.

For these field trials the use of co-composting technology to remediate the contaminated drill cuttings was introduced. This remediation technique utilized local materials to treat the drill cuttings as outlined below.

WORM-DRIVEN REMEDIATION

Drill cuttings were mixed with sawdust (45% w/w) to facilitate transport to an existing vermiculture site where they were blended with paunch waste (undigested grass) before being fed to the worm beds. The drill cuttings were blended and mixed with the paunch material at variable ratios and combined with water giving a 50:50 v/v water:solids slurry that could be evenly distributed along the beds. Once the blended material was prepared, it was loaded into a feed-out wagon for application as feedstock for the worms to process in windrows of 290-ft long by 9-ft wide. The blended material was applied to the centre/top of the windrows, usually once a week, at an average depth of 1 to 2 inches. The exact application rate depends upon climatic conditions and is higher in summer than winter. The worms "work" the top 3 to 4 inches of each windrow, consuming the applied material over a five- to seven-day period.

Successful degradation of organic materials by worms is dependent upon maintaining optimal environmental conditions for the worms, the most important parameters being the carbon/nitrogen ratio (25:1) and moisture content (75%). Each of the windrows is covered completely by a polypropylene-backed felt mat to exclude light from the worm bed. Although semi-permeable to water, the polypropylene deflects heavy rainfall away from the surface of the bed and prevents the windrow from becoming waterlogged, maintaining an optimal aerobic environment. The process is illustrated in Figures 1a-f. Once the worms have degraded the waste and converted the applied material into vermicastings, the vermicast organic fertilizer is harvested using an industrial digger and is then packaged for distribution and use on agricultural and horticultural land as a beneficial fertilizer and soil conditioner.

Vermiculture Field Tests. Controlled field tests were performed to evaluate the effect of worm farming on the remediation of drill cuttings, and to evaluate the effect of cuttings addition to the vermiculture process. Initial testing demonstrated a decrease in hydrocarbon concentration in samples taken from a worm bed to which drill cuttings had been applied, while later testing studied the effect of different cuttings application rates on the process. In addition to monitoring hydrocarbon concentrations within the worm beds, a wide variety of soil chemistry parameters were also measured. As the barite weight material contains a number of heavy metals and earthworms are known to be liable to bioaccumulate such materials,[7-8] it was also decided to evaluate the fate of the heavy metals from the drilling fluid in the worm beds.

Test Results. In the initial test the hydrocarbon concentrations decreased from and initial 4600 mg/kg to less than 100 mg/kg in under 28 days following a fairly typical exponential-type degradation curve. The bulk of the hydrocarbons detected comprised $C_{10} – C_{14}$ aliphatic hydrocarbons, which is in good agreement with the carbon-chain-length distribution of the $C_{12} – C_{17}$ linear paraffin blend used in the drilling fluid, thereby indicating there were no external sources of contaminating hydrocarbons.

There was no detectable excess mortality among the worms that were fed the drill cuttings and there appeared to be a definite preference among the worms for the area where the cuttings and paunch feed had been applied. It was also noted that there was complete physical degradation of the cuttings by the vermidigestion process and none of the original intact cuttings could be found, the original cuttings size being 5 –10 mm in diameter. It was also apparent that the applied drill cuttings mix caused the worms to actively seek out the clumps of material containing drill cuttings. Figure 2 shows the hydrocarbon degradation results from various cuttings loadings applied to the worm beds. Due to the way in which the cuttings were applied to the worm bed, some of the initial samples taken were variable, however taken overall, a number of general trends can be seen.

The hydrocarbons in the cuttings applied at 30% w/w decreased from an average of 2900 mg/kg to less than 60 mg/kg within 45 days. The hydrocarbons in the cuttings applied at 50% w/w decreased from an average of 4600 mg/kg to the detection limit within 45 days. The hydrocarbons in the cuttings applied at 70% w/w showed quite a clear trend and decreased from an average of 20,000 mg/kg to 1500 mg/kg within 45 days. The hydrocarbons in the cuttings applied at 100% w/w (i.e. without any paunch amendments) did not show any obvious degradation throughout the course of the experiment (60 days). It is thought that this is because the consistency of the cuttings (mixed with sawdust to facilitate transport) combined with lack of paunch material makes the un-amended mixture of cuttings and sawdust very "unappealing" to the worms.

A third field trial carried out over the summer showed the advantages of favourable environmental conditions, specifically the effect of the temperature in the worm beds which was considerably lower in the New Zealand winter. The 30 and 50% application rates showed significant degradation of hydrocarbons to background levels within 30 days during the summer test.

CO-COMPOSTING REMEDIATION

Co-composting drill cuttings was first validated in the laboratory with various lab-scale compost piles. With these studies a different approach was taken to the traditional composting. The design was to make quality soil that could be used to re-vegetate the drillsite, choosing the correct co-composting amendments to achieve this goal. This process started with an evaluation of the site soil quality, and an evaluation of the anticipated drill cuttings geology, tying these together and determining the correct quantity and type of amendments that would be required to generate an end product beneficial to plant life. The simple triangle diagram shown in Figure 3 aids adjustment of soil properties towards the "loam" area which was the optimal target.

To achieve the optimal co-composting results, the compost piles require management. As well as mineralogical composition, this includes the control of the nitrogen and moisture levels as well as particle size, porosity and bulk density. These parameters are required to be optimized to increase the rate of reduction in the total petroleum hydrocarbons (TPH) and to optimize final soil properties. Compost pile isolation and containment to prevent excessive moisture, as well as regular "turning" of the pile to optimize aeration and bacterial distribution, are required; Figure 5 shows the application of a blender/shaker which accomplishes many of these functions by turning the compost pile on an average twice-weekly basis.

Co-composting Field Tests. Following an analysis of local soil properties and evaluation of the well geology, the amendments that were chosen for co-compost treatments of the first field trial well were peat for the organic portion and bulking agent, sand for the texture, top soil for the microorganisms, and agricultural fertilizer for the nitrogen. In the initial pre-trial laboratory experiments, the compost piles were able to reduce the TPH from 7.4-10.6% down to 1% or less in 49 days. Figure 5 shows the reduction in TPH versus time in three of the studies. In these studies a 50% loading of "cuttings" with respect to total compost pile content was used. The knowledge achieved in these studies was utilized to compost the cuttings from a well drilled in the Rocky Mountains region. Figure 6 shows the reduction in TPH versus time in the field test. The degradation rate was significantly slower in the field due to the test being carried out over the winter months where ambient temperatures were below freezing and the cuttings/compost pile was covered with snow.

The field results generally match the trends seen in the laboratory studies, however the rate of degradation was slower than that seen in the laboratory. In the laboratory it is easy to optimize the parameters needed to have a rapid decrease in TPH. On the field level it is more difficult to optimize these parameters because of the size of the pile and lack of control on certain parameters. The degradation of the hydrocarbons in the pile assists in maintaining a high pile temperature. In the field trial it was possible to maintain a pile temperature of 90 – 110° by efficient management, compared to an ambient temperature of 25 – 45°F. The key control parameters maintained as: an efficient moisture level (25 – 30%), sufficient nitrate levels for bacterial activity (~500 ppm as free ammonia), and a good, homogeneous, aerated soil mixture (straw being used as additional bulking agent to ensure clay cuttings do not coagulate).

CONCLUSIONS

The bioremediation-friendly invert emulsion drilling fluid described in this paper possesses the excellent drilling properties of conventional invert drilling fluids.

Contaminated drilled cuttings generated from the use of this invert emulsion fluid can be used to provide the basis of a soil-enhancing product when combined with the correct bioremediation techniques – in the field test cases given, vermiculture and co-composting were the remediation methods of choice based on local infrastructure.

The combination of a bioremediation-friendly fluid design and a designed and controlled bioremediation technique can reduce overall drilling costs and minimize waste disposal liabilities.

REFERENCES

1. Whitfill, D. L. and Boyd, P. A.: "Soil Farming of Oil Mud Drill Cuttings," SPE 16099, SPE/IADC Drilling Conference, New Orleans, Mar 15-18, 1987.
2. Bleckmann, C. A., Gawel, L. J., Whitfill, D. L. and Swindoll, C. M.: "Land Treatment of Oil-Based Drill Cuttings," SPE 18685, SPE/IADC Drilling Conference, New Orleans, LA, Feb 28-Mar 3, 1989.
3. Mackey, R. R.: "ENVIROVERT – The Calcium Chloride Invert Alternative," CADE/CAODC Spring Drilling Conference, Calgary, Apr 19-21, 1995.
4. Atiyeh, R.M., Subler, S., and Edwards, C.S.: "Growth of Tomato Plants in Horticultural Potting Media Amended with Vermicompost," *Pedobiologia,* v. 43 (1999) 1.

5. Edwards, C. & Burrows I.: "The Potential of Earthworm Composts as Plant Growth Media," In: *Earthworms in Waste and Environmental Management,"* by Edwards, C.A. and Neuhausen, E.F.; SPB Academic Publishing, The Hague (1998).

6. Norman, M., Ross, S., McEwen, G. and Getliff, J.: "Minimizing Environmental Impacts and Maximizing Hole Stability; Significance of Drilling with Synthetic Fluids in NZ," New Zealand Petroleum Conference, Auckland, New Zealand, Feb 24-27, 2002.

7. Buchanan, M.A.: "Chemical Characterisation and Nitrogen Mineralisation Potentials of Vermicomposts," In: *Earthworms in Waste and Environmental Management,"* by Edwards, C.A. and Neuhausen, E.F.; SPB Academic Publishing, The Hague (1998).

8. Corp, N. and Morgan, A. J. "Accumulation of Heavy Metals from Polluted Soils by the Earthworm *Lumbricus rubellus*," *Environmental Pollution,* v. 74 (1991) 39.

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Table 1
Biodegradability of Various Base Fluids

Treatment	% Reduction of Hydrocarbons	Biodegradability Rank
C_{11-14} LP	97	1
C_{12-13} LP	94	2
Ester	91	3
C_{14} Linear alpha olefin (LAO)	90	4
Isomerized olefin C_{14} (IO)	83	5
Diesel	61	6
Branched paraffin	43	7

Table 2
Toxicity of Various Base Fluids*

Treatment	**Water Toxicity**	**Animal Toxicity**	**Alfalfa Phytotoxicity***		**Toxicity Rank**
	Microtox IC_{50}	**% Earthworm Survival**	**% Seed Emergence**	**% Root Elongation**	
Branched Paraffin	106	100	95	107	1
C_{11-14} LP	98.5	100	96	134	2
C_{12-13} LP	65.9	100	95	120	3
C_{14} Linear olefin (LAO)	62.3	100	97	115	4
Isomerized C_{14} IO	61.7	100	101	144	5
Diesel	10.3	0	7	2	6
Ester	5.9	0	0	0	7

* Seed Emergence and Root Elongation test results are normalized to Control test values of 100.

Table 3
Standard Properties of three Paraffin-Based Fluids

Component (g)	Formulation A		Formulation NA		Formulation N	
Linear Paraffin	144		144		144	
Organophilic Clay	5		5		5	
Lime	3		3		3	
Fluid Loss Reducing Agent	5		5		5	
Emulsifier #1	8		8		8	
Emulsifier #2	2		2		2	
Acetate Brine	97		-		-	
Nitrate/Acetate Brine	-		115		-	
Nitrate Brine	-		-		113	
Hematite	283		267		264	
Rheology at 150°F	**Initial**	**Hot-Rolled***	**Initial**	**Hot-Rolled***	**Initial**	**Hot-Rolled***
PV (cP)	24	22	22	21	22	19
YP (lb/100 ft^2)	7	6	17	9	8	4
Gel S (lb/100 ft^2)	6/9	6/7	8/10	6/6	6/6	5/5
Electrical Stability (v)	171	199	320	263	314	242
Internal Phase Aw	0.86		0.76		0.77	
HTHP at 250°F (mL)	-	1.8	-	2.0	-	0.8
Filtrate Water (mL)		trace		Nil		Nil

* Hot-Rolled for 16 hr at 250°F

Table 4
Biodegradability , Toxicity & Electrical Conductivity of Formulations and Treated Cuttings
6% w/w Loading on Topsoil from Southern Alberta Grassland

	Biodegradability (65 days)	**Animal Toxicity**		**Alfalfa Phytotoxicity***			**Relative Electrical Conductivity (after 65 days)**
System	**% Loss of Extractable Hydrocarbons**	**% Springtail Survival**	**% Earthworm Survival**	**% Seed Emergence**	**% Root Elongation**	**% Shoot Mass**	
Formulation A	98	80	100	100	149	97	1.0
Formulation N	98	87	93	4	11	47	4.0
Diesel / CaCl$_2$ / Barite	68	0	0	3	8	25	4.9
Form. A with Barite	99	90	100	100	108	105	0.8
Treated Cuttings, Formulation NA	-	93	100	109	134	129	-
Treated Cuttings, Formulation N	-	73	100	113	116	121	3.9

*Animal Toxicity and Phytotoxicity test results are normalized to Control test values of 100.

a) Collecting drill cuttings **b) Drill cuttings + sawdust** **c) Blend of cuttings with paunch**

d) Blending final feed mixture **e) Feeding the windrows** **f) Vermiculture windrows**

Figure 1 – The Cuttings Collection and Vermiculture Treatment Process

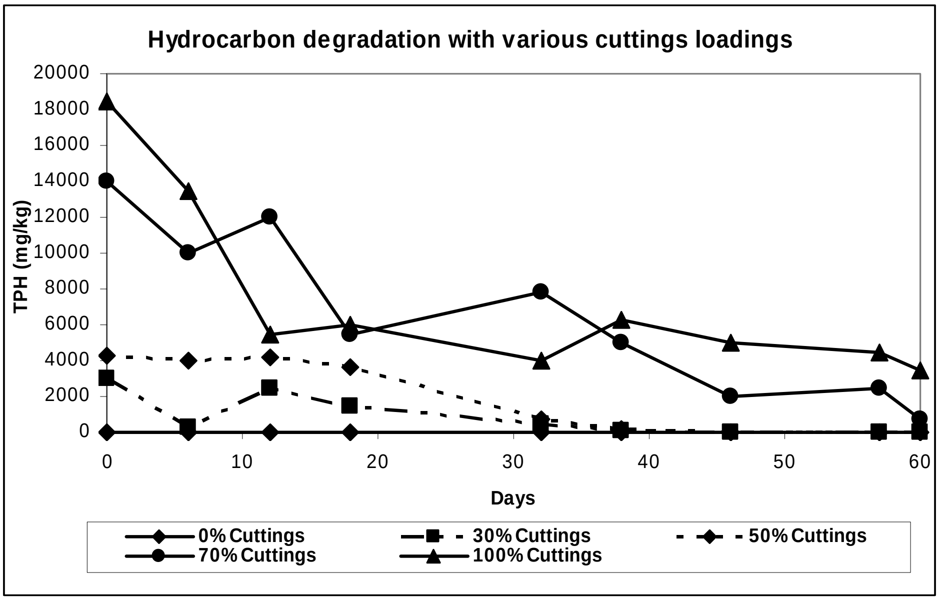

Figure 2 – Degradation Rates vs Cuttings Loading

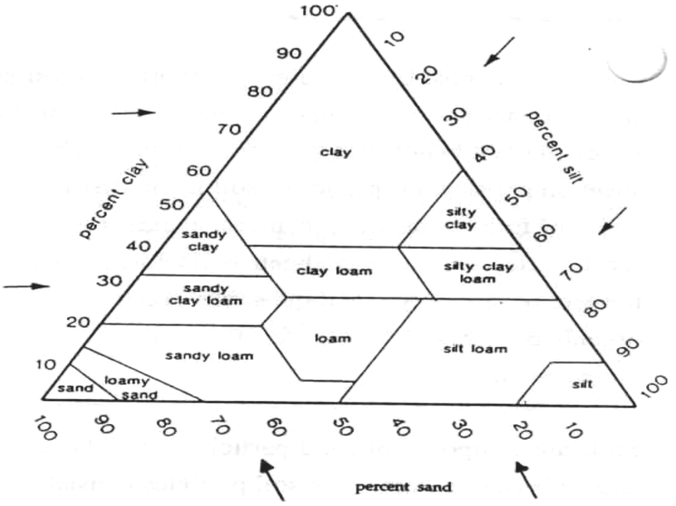

Figure 3 – Adjustment of Soil Properties to Achieve Optimal Target

a) contained compost pile **b) tractor mounted blender** **c) Turning the compost pile**

Figure 4 – The Compost Containment and Treatment Process

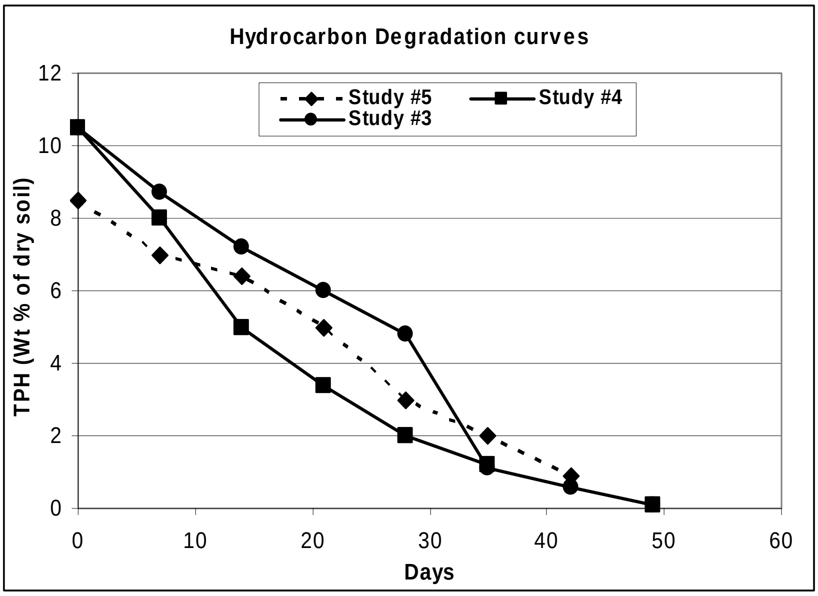

Figure 5 – Degradation Rates from Lab Studies

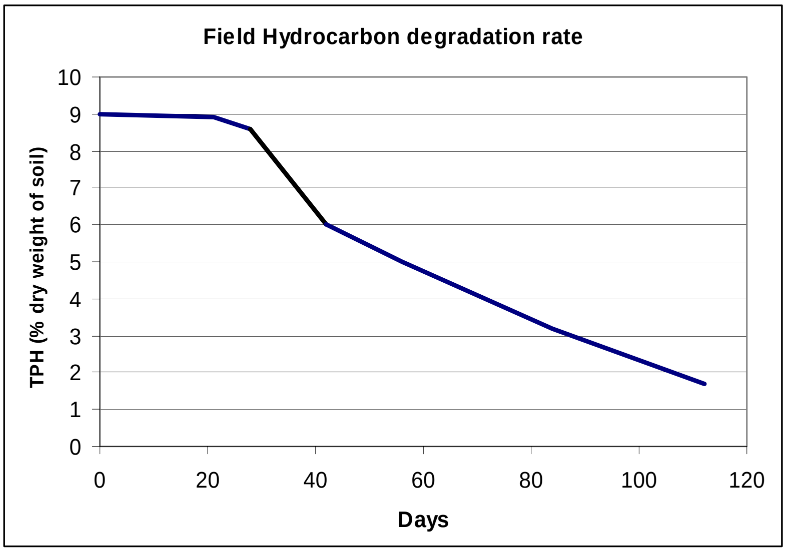

Figure 6 – Degradation Rates from Field Test