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The degradation of plastic litter in rivers: implications for beaches

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Abstract. Polythene sheeting is a major litter component on estuarine beaches and river banks. Sanitary towel backing strips, which are one of the commonest items of sewage related debris found on beaches, enter the riverine system via combined sewer overflows. Investigations on these items, positioned at natural riverine stranding levels, showed that after an initial rapid breakdown little further loss of tensile strength occurred. Experiments carried out on backing strips, buried in the bank, suspended from a tree and tethered to the bank, showed significant change. Buried samples retained the greatest tensile strength retention, dropping no lower than 90 %, the other samples showed similar retention rates at 80 %. The difference is probably due to photodegradation as biodegradation effects were minimal. Probably, the longevity of such plastics is a major reason for their abundance and widespread distribution both on river banks and beaches.

Keywords: Biodegradation; Photodegradation; Sanitary towel; Tensile strength.

Introduction

Coastal conservation bodies such as Friends of the Earth, frequently spend days picking up beach litter (Anon. 1992a) and Councils spend large sums of money in beach litter cleanups. For instance, Kent County Council, UK, spend some $15 million to clean their beaches (Gilbert pers. comm.), and another $150 000 is required to clean up the beach in summer at Weston Super Mare, UK. This encourages volunteers but is often a waste of time as within days an equivalent amount of litter will have returned (Simmons & Williams 1993). Plastic litter is very common on many beaches, as has been described in numerous publications (e.g. Scott 1972; Lentz 1987; Pruter 1987, Laist 1987; Anon. 1992a-c; Nash 1992; Simmons et al. 1993; Simmons & Williams 1993, 1994). The present paper describes plastics, derived in the main from fly tipping sites or combined sewer overflows that enter the river system and end up on a beach. Marine litter research is some 25 years old; research on riverine litter is in its infancy, yet some 80 % of the litter on the estuarine beaches of South Wales, UK, comes from this source (Anon. 1992b, c; Williams et al. 1993a, b; Simmons & Williams, 1994; Williams & Simmons 1995). Any region with large rivers entering the sea will input large amounts of litter into the coastal system from source but quantification remains to be resolved. One particular aspect of riverine litter which appears to cause great aesthetic offence, resulting in many public complaints, is the stranding of plastics along the length of rivers (Anon. 1991; Anon. 1992d). This study quantifies plastic degradation in the river Taff in South Wales, UK. which enters the sea at Cardiff. The ‘flashy’ nature of rivers in South Wales and resultant flow fluctuations, allow litter items to be transported considerable distances until they are filtered by suitable obstructions, often vegetation. Physical characteristics of some litter items allow them to become entangled in the vegetation and be stranded when the water level recedes resulting in a ‘Christmas tree’ adornment. This is more conspicuous when water levels have fallen and during winter months when lack of foliage offers less camouflage (Fig. 1). The materials move down stream in an episodic fashion and accumulate at the beach area.

One particular polyethylene product commonly found along river banks and beaches, the sanitary towel backing strip, was deemed appropriate for investigation. Not only does this product contribute to the overall aesthetic nuisance of litter, but also impinges upon broader issues such as health and safety. The sanitary towel market is expanding and by 1990 the sanitary protection split between towels and tampons was 56 % to 44 % (Anon. 1990a; Howarth pers. comm.). With the recent introduction of daily use panty-liners, contributing 28 % of the market (Howarth pers. comm.), towels obviously constitute a waste disposal problem. Smith and Nephew Products Ltd. estimated that 72 % of all towels are flushed (Howarth pers. comm.) and with the still largely archaic and ineffective screening in UK sewerage systems, their contribution to riverine plastic as a whole could be fairly substantial. In light of these facts, panty-liner backing strip degradation trials were initiated.

Plastics

"Plastics can be defined as organic materials containing molecules of high molecular weight (i.e. between 10^4 and 10^7) which can be moulded to shape by the application of pressure at moderately high temperatures. Once moulded they may retain their plasticity in the manner of polyethylene or nylon (thermoplastics) or they may become permanently hard and brittle like bakelite (thermosetting plastics)" (Higgins 1988, p. 243). Until the beginning of the twentieth century emphasis was placed on the destruction of complex organic compounds to produce larger numbers of simpler materials. It was only then that chemists learnt to rebuild some of the products of destructive processes to produce substances which did not occur naturally. Of major importance amongst such substances produced were the super-polymers (plastics).

"Two general mechanisms are usually considered for degradable plastics, namely photodegradation and biodegradation. Unfortunately, care is not taken to define which mechanism is involved in a particular process with a degradable plastic and the two have come to be used almost interchangeably. There is frequently a tendency to presume that plastics degrade virtually completely by biodegradation. However, in most instances photodegradation is the major process involved" (Klemchuk 1990, p. 188). Photodegradation is the process by which ultra-violet light (in sunlight) reduces the molecular weight of polymers, causing the plastic to become brittle and disintegrate. In contrast, biodegradation may be defined as the "breakdown of the physical and chemical properties of a structure by the action of living organisms - typically fungi and bacteria" (Lloyd 1987, p. 20). Many studies have been undertaken to explore the biodegradation of plastics (Nykvist 1974; Klemchuk 1990; Lloyd 1987). Klemchuk (1990, p. 183) made the interesting observation "that all commercial packaging plastics are not biodegradable, because their molecular weights are too high and their structures are too rigid for assimilation by organisms".

An important study by Potts et al. (1972) found most commercial thermoplastics to be immune to fungal attack. Although polyethylene film initially supported growth, it was apparently due to additives. Longer term studies (two and eight years) of soil burial, showed that

Fig. 1. The'Christmas tree' effect.

polymer losses of between 1% and 3% were the most that could be expected. Seal (1988) considered that after exposure to UV-light, biodegradation of the remaining polymer was not enhanced, but that small molecules produced by photo-oxidation were the only biodegradable element which could decompose to give the overall polymer loss. The lack of naturally occurring biodegradation of plastics has stimulated intensive research with a view to producing truly biodegradable polymers. Although polyethylene plastic has been manufactured which exhibits increased photochemical oxidation and therefore fragments more quickly, the packaging cannot be considered truly degradable until fragments undergo further decomposition to components which may recycle in nature.

Onions & Rees (1992), in an investigation of photodegradable Hi-Cone carriers (4/6 pack holders) in the South Wales beach environment, demonstrated that use of photodegradable plastic resulted in earlier embrittlement and fragmentation. Tensile testing was carried out on samples of conventional and photodegradable Hi-Cone carriers after various exposure trials. Ultimate embrittlement (reduction to 5% elongation) of the photodegradable samples was reached after only 74 days on a UK beach (Merthyr Mawr, Mid-Glamorgan), whilst no reduction in elongation was recorded for the conventional carriers. Tensile testing, as a measure of degradability, produced conclusive results in the Hi-Cone study. The benefits of this uncomplicated test procedure and its application to environmental trials led to its adoption for use in this research as a measure of polyethylene degradation in riverine environments pre deposition on a beach.

The river and beaches

The Severn estuary and Bristol Channel system is an aggressive morphogenic environment with macro-tides (14.8 m at Avonmouth) and is subject to frequent storms, especially in the SW direction. Many rivers discharge into the Channel with estimated sediment inputs varying from 0.7×10^5 tonnes per year (Brookes 1974) to 1.8×10^6 tonnes per year (Shaw 1977). Selected sites were established in rivers and assessed for baseline surveys by the authors. To ensure optimum litter deposition conditions (Dixon & Dixon 1981) low energy, preferably sandy, beaches with wide reach zones and multiple strandlines were chosen (West Aberthaw, Llantwit Major, Southerndown, Merthyr Mawr). Similarly, 50 riverbank sites were analyzed for litter over one year on the River Taff, South Wales. Some 22 % of the river Taff's litter is made up of feminine hygiene products, litter items averaging 584 items per kilometre of bank (Simmons & Williams 1994).

The Irish Sea Study Group (Anon. 1990b, p. 52) concluded from numerous beach surveys that "approximately 50% of plastic containers were believed to originate from ships discharges, and the remainder from land-based sources, primarily holiday makers". This does *not* appear to be the case in the South Wales region. High numbers of beverage, dairy product and DIY-related containers indicates greater contribution from land-based sources, either by beach users or riverine inputs. This result is not surprising considering the Bristol Channel's estuarine nature, the comparative lack of shipping and the unlikely occurrence of major oceanic inputs. Analysis of container origins indicated ship discards were less prominent in the Bristol Channel survey areas, the geographical origin being 92 % British. By number, 82 % of containers reported in this paper on these estuarine beaches were plastic, 17 % metal and 1 % glass. Many of these plastics were felt likely to have originated from riverine fly-tipping sites. Widespread illegal dumping of all types of waste, but in particular that of household origin, has led to the establishment of numerous fly-tipping sites along the banks of the River Taff. During high-flow conditions, mobile objects such as containers were often observed being carried from such sites in the river flow, but no increases were recorded at riverine survey sites when water levels receded, suggesting transportation to the sea. Plastic containers considered to be DIY-related, for example interior paints, herbicides and carpet cleaners were thought unlikely to have originated from either shipping vessels or beach-users and thus were likely to be of riverine origin. For non-containers, 58% of the beach litter was plastic in origin.

A summary of results obtained from a 5-m wide transect at Merthyr Mawr beach, Wales, on December 16, 1994 showed the following:

- of 118 metal items, 94 were aluminium cans;
- 25 glass items were bottles (mainly wine);
- sweet wrappers/crisp packets constituted 240 items out of 272 paper items found;
- out of 97 sanitary items counted, 65 were sanitary towel backing strips;
- out of 455 plastic items, 114 were plastic sheeting and 96 were bottles.

These are extremely high figures that have been borne out by many surveys in this area. The NUC (Anon. 1995) study of beach strand lines in South Wales found that sanitary items averaged 11 per km; metal cans 115 per km and plastics bottles 128 per km. These items are essentially riverine in origin and surveys carried out by the authors on the same estuarine beaches gave quite different result (Williams & Simmons in press).

At Merthyr Mawr beach, South Wales, December 16, 1994, survey records revealed:
- sanitary items: 75 per km;
- metal cans: 210 per km;
- plastic bottles: 550 per km (340 plastic, 210 polyethylene).

On December 6, 1995, 2856 containers were counted along the same 1 km stretch of strand line. This beach is a litter sink *par excellence*. The NUC (Anon. 1995) study also indicated that about half of Britain's coastline is polluted, with an average of 20 sanitary items, 17 metal cans and 22 plastic bottles occurring per km of coast.

The unusually high quantities of plastic found within the Bristol Channel are a threat to fishermen's livelihoods (Anon. 1992b, c; Williams et al. 1993b). Circulation patterns and slow flushing times within the Bristol Channel are likely to result in long residence times before this material is released into the open sea. The Channel may therefore act as an eventual sink for plastic sheeting and other mobile materials. If inputs of such material continue, a build-up within the Bristol Channel may occur.

Test material

The test material used was a brand of panty-liner marketed as a daily use towel. Panty-liners generally consist of a (non woven polypropylene/polyethylene/rayon) cover enclosing cotton pulp which is backed by a polyethylene shield. A strip along the shield is coated with pressure-sensitive adhesive and covered with a silicone-coated release tape. The release tape is removed upon initial application and generally the remaining product is flushed intact after use. The towel is then transported by the sewerage system to a sewage treatment works, where appropriate treatment is carried out. Final effluent may be discharged to inland waters or sea and the sludge to the land, sea or atmosphere. Unfortunately, during the sewage treatment process there is a tendency for the plastic backing strip to become dissociated from the cotton pulp. In this form the strips constitute a major screening problem. "Certain types of plastics and cotton bud sticks appear to align themselves so that they give least resistance to flow and as a result a higher proportion get past the screens than would be expected" (Huntingdon 1990, p. 3). Even under optimum conditions, sanitary towel backing strips often find their way into watercourses. This problem is exacerbated during periods of heavy rainfall as flows during storm conditions have to be discharged after only coarse screening (often 12 - 25 mm bar screens) unless suitable storage facilities exist. Concurrently, under the same conditions, Storm Water Overflows also operate, commonly discharging completely unscreened effluent into receiving waters. Once present in the watercourse, it is generally only the plastic backing strip of a sanitary towel which persists and ends on a beach. As such, tensile testing of just the backing strips was felt to be appropriate.

Methodology

Control samples were required in order to develop appropriate methods for test piece preparation and optimum test parameters. To obtain the test pieces, release tapes were first removed from each of the panty-liners. The panty-liners were then submerged in water for 1-2 days until separation of the backing strip from the cotton pulp could be achieved without damaging or stretching the test material.

Guidelines exist regarding standard tensile testing procedures for plastic sheeting (ASTM D882-83, Anon. 1983a, b; BSI 2782, Anon. 1986). A 19-mm strip was cut from the centre of the specimen; this width conforms with the standard testing procedure. A steel rule was used as a template and using a scalpel, clean parallel edges were cut along the length of the backing strip (150 mm). Following BSI 2782 (1986) recommendations, tensile testing was carried out at a variety of speeds, initial gauge lengths (distance between grips), grip types and loads. Due to the unique nature of the test piece, a trade off was required between these factors in order to produce the most consistent results. After several trials and discussions with materials experts (Wild pers. comm.) the test parameters were finally set. Under these constant conditions, twenty control specimens were tested with which samples could be compared after exposure.

Test procedure

A JJM30K tensile testing instrument was used for the degradation analyses. The instrument's standard gnurled grips were unsuitable for the test material as they caused tear failure at the grip interface. This was overcome by lining the grips with rubber. The digital displays were programmed to the chosen settings (maximum load 0.1 KN, maximum extension 500 mm, grip separation speed 25 mm/min) and the plotter linked to produce a graphical printout. The grips were set to the initial gauge length (90 mm) and specimens marked to ensure the test was carried out using the centre of the test piece. Once the specimen was properly aligned and both the tensile instrument and plotter zeroed, the test was initiated. The grips pulled apart at a constant rate of 25 mm/min whilst the digital displays monitored the

Fig. 2. Panty-liner degradation trial samples.

increase in load and extension. When specimen failure occurred, digital outputs for maximum load and extension were recorded, along with the extension at yield point (“first point on the force-extension curve at which an extension occurs without an increase in force”; BSI 2782, Anon. 1986, p. 2). This procedure was repeated for the ten specimens in the sample and for each subsequent sample of ten test pieces.

Field testing

Panty-liner degradation trials were initiated on a weekly/monthly sampling programme, using ten test pieces to be measured per unit time, a number felt to be suitable based on BSI 2782 (Anon. 1986) recommendations of a minimum five test pieces per sample. Having separated the backing strips from the remainder of the towel, these were secured to hardboard exposure plates in sets of ten, using carefully placed drawing pins. River bank attachment height for exposure plates was governed by the level of indigenous litter stranding, i.e. the previous flood level. Three exposure plates were secured to the bank, three were buried and the remainder attached to nearby tree branches. As all strips were positioned at a natural stranding level they were exposed to equivalent environmental conditions as those stranded naturally (Fig. 2).

Results and Discussion

Beneficial properties of plastic products such as durability and strength have led to their widespread use in society. Plastics are expected to retain these properties throughout their service lifetime in order to fulfil their required function. Specific mechanical properties may be measured to predict material durability, aiding determination of potential applications, and may also act as a reference with which to monitor the breakdown of plastics. Tensile testing of materials to record load/ extension measurements, allow mechanical properties such as tensile strength and elongation to be calculated. Tensile strength is “the maximum tensile stress which the test piece is capable of supporting” (BSI 2782, Anon. 1986, p. 3) and may be calculated using the equation:

$$\sigma = \frac{F}{A} \tag{1}$$

Where: σ = maximum tensile strength (MPa);
F = maximum force (N);
A = Initial mean cross-sectional area (mm).

Elongation is “the elongation produced in the gauge length of the test piece at break” (BSI 2782, Anon. 1986, p. 2) and is expressed as a percentage of the original gauge length. Elongation at break may be calculated using the equation:

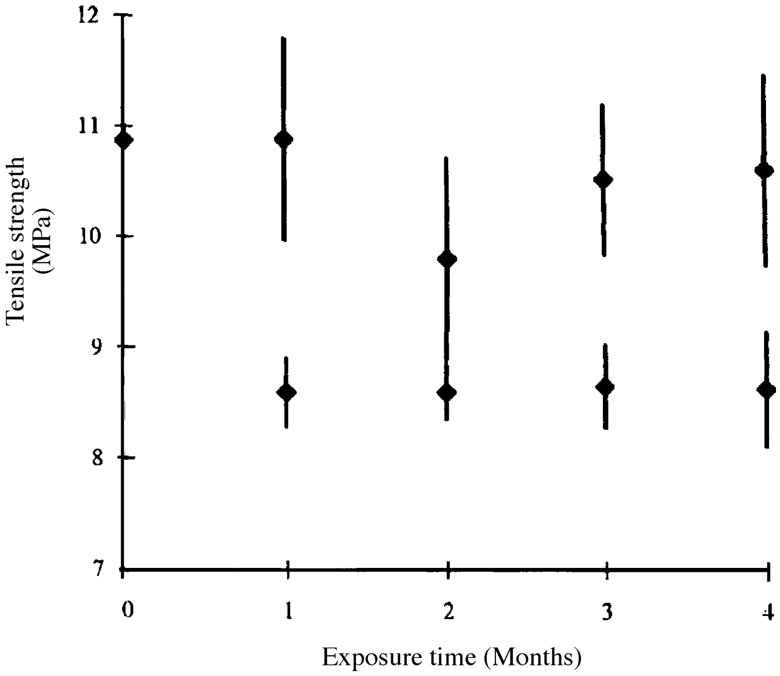

Fig. 3. LDPE degradation trial (4 months): Bank samples (lower set); Buried samples (upper set); Tensile strength (bar represent 95% confidence limits).

$$E_p = \frac{I - I_o}{I} \qquad (2)$$

Where: *Ep* = elongation at break; *I* = elongation in gauge length at break (mm); I_0 = original gauge length (mm). *Ep* can be conveniently expressed as a percentage.

Elongation retention is largely dependent on polymer type and composition. “Relative to tensile strength, the elongation appears more sensitive to changes occurring during photodegradation” (Wypych 1990, p. 251). Wypych (1990) also noted that no correlation existed between percentage elongation and tensile strength, elongation being more indicative of changes in the amorphous phase, whilst tensile strength was more dependent on crystalline polymer regions.

Other parameters such as break factor – the maximum load divided by the minimum width – and percentage elongation at yield – the elongation produced in gauge length of the test piece at yield stress, which is first marked as an inflexion of the stress/strain curve, expressed as a percentage of the original gauge length - were also calculated., They were very similar to the more common measurements of tensile strength and elongation at break respectively. Sample means were calculated for each parameter, together with two-sided confidence limits of the mean. The confidence limits “give an interval in which the true mean is expected to lie with specified confidence” (Gilbert 1987, p. 137) in this case 95 %.

Results of tensile strength and percentage elongation at break indicated that some degradation had occurred, with significant decreases in values occurring between control samples at point 0, and those tested later (Fig. 3). Subsequent weeks showed little further degradation. Confidence limits were predictably greater for exposed samples than controls, as a result of material variations brought about through exposure. Although mean values differed from the second to the sixth week, at all times confidence limits overlapped, making predictions of further degradation inconclusive. The slight rise in tensile strength and elongation values for suspended samples after an extended exposure period, raised the possibility of differing degradation rates resulting from variations in stranding position. Consideration was given to the possibility that bank-side samples may have been subjected to greater physical weathering from contact with earth and vegetation on the bank. Physical abrasion in this manner could be the cause of flaws in the material, resulting in a lowering of tensile property values.

It was noted during tensile testing that test pieces within samples showed a wide variation in their responses. Even after exposure, some strips reacted in a similar manner to control samples, whilst others failed very prematurely. The premature failure seemed to initiate from a defect within the strip. These two very different responses resulted in a very broad range of results for samples, as indicated in the confidence limits (Fig. 3).

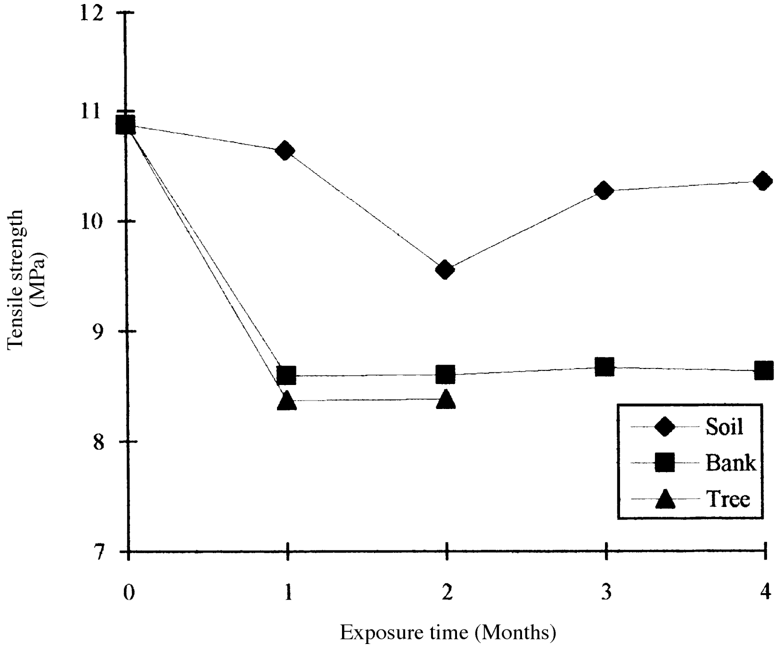

Fig. 4. LDPE degradation trial (four months): sample tensile strength for three exposure areas.

Measurements of both tensile strength and elongation showed that significant degradation occurred during the first month of exposure for bank-side and tree samples (Fig. 3). Subsequent months, indicated little change in the tensile properties. Figs. 4 and 5 show a close relationship between bank-side and suspended samples, which deviate from that shown by the buried specimens.

The obvious differences in tensile properties of the specimens after burial are likely to result from sunlight exclusion. Other factors such as less physical abrasion must also be considered. Slight decreases in tensile properties for the buried samples may have resulted from biodegradation. This process would have been limited without prior breakdown by photodegradation.

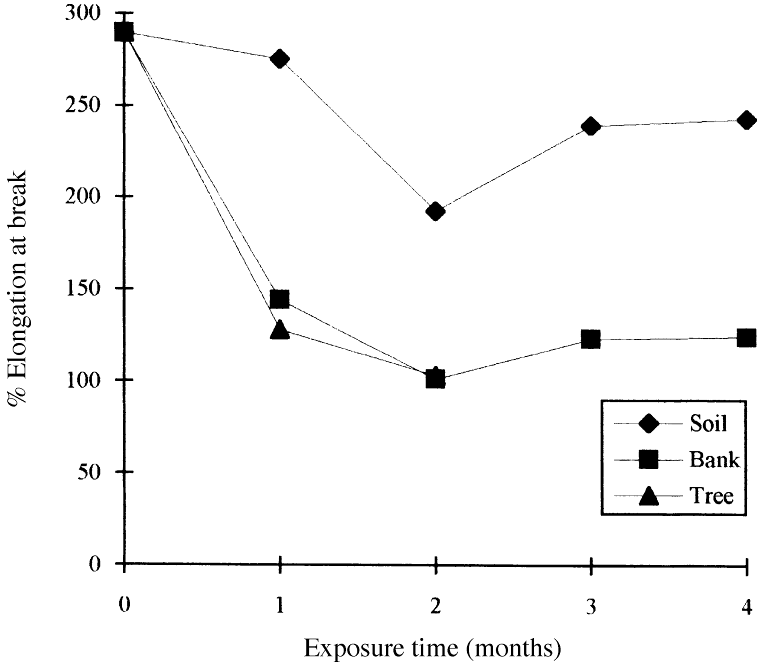

Fig. 5. LDPE Degradation trial (four months): sample % elongation at break for three exposure areas.

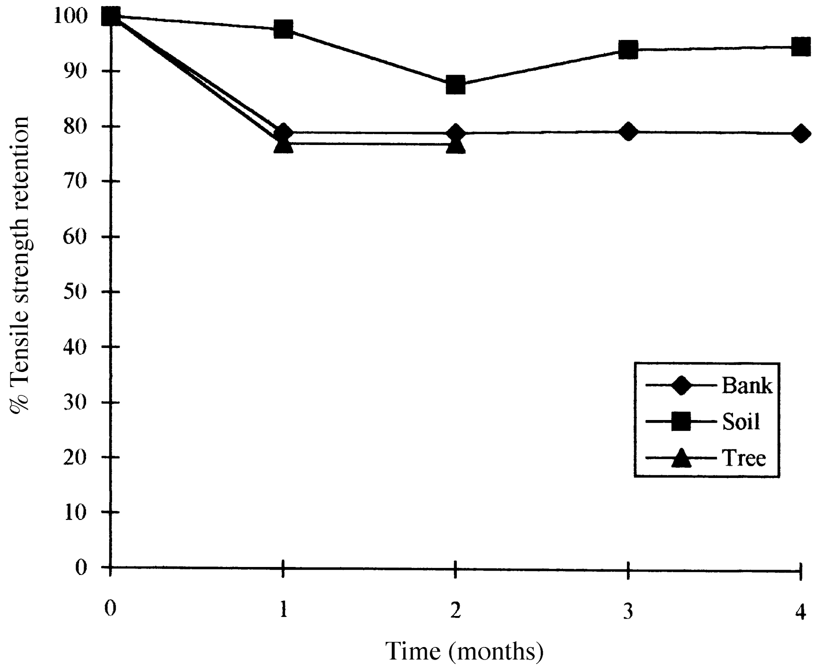

Fig. 6. LDPE Degradation trials (four months): Sample % tensile strength retention at three exposure areas.

Wypych (1990) discussed plastic degradation in relation to percentage retention of tensile properties such as strength and elongation. Fig. 6 shows results in this format for the three stranding positions. Buried samples showed the greatest tensile strength retention, dropping no lower than 90%, whilst bank-side and suspended samples showed similar retention rates at approximately 80%. Based on the known relationship between decreasing molecular weight and decreasing tensile strength (Wypych 1990), results appeared to demonstrate that some decrease in molecular weight occurred during the first month of exposure for bank-side and suspended samples, but with little further loss. Reduction in molecular weight of these samples as opposed to buried samples is likely to be due to photodegradation of exposed specimens. Slight decreases in tensile strength (and molecular weight) of buried samples not exposed to photodegradation may be explained by losses of low molecular weight contaminants in the polymer which are easily biodegraded (Seal 1988).

Although decreasing tensile strength may be related to reduced molecular weight, losses may be accounted for by photo or biodegradation, as seen above. Elongation retention is known to exhibit greater sensitivity to changes occurring during photodegradation and correlates well to chemical changes during photo-oxidation. Elongation retention results show retention as low as 35 % for bank-side and suspended samples, as opposed to 75% for buried samples, possibly indicating the overall importance of photodegradation in the degradation process. Overall, samples did not exhibit rapid degradation upon exposure to environmental conditions. Initial changes in physical properties were rapid, but were followed by little subsequent activity.

On rinsing samples after exposure, buried samples were shown to maintain their original appearance, whilst bank-side and suspended samples exhibited obvious colour bleaching and dirt impregnation. This is an area which could be investigated in future work. Plastics are frequently buried in coastal dune systems and the authors have subjected biodegradable plastics to similar studies. Degradation of plastics was supposed to be complete over a 30 day time period, but because of periodic burial, the plastic strips were still basically intact after 4 months (unfortunately, a large scale storm took away these boards). The conclusion was clear, plastics degrade very slowly in the beach environment.

Conclusions

Light and mobile litter i.e. plastic sheeting, is transported to beaches by rivers in estuarine areas prior to fragmentation either in the riverine environment or beach. Degradation observations over a 4 month period indicated that initial plastic (LDPE) breakdown in rivers was rapid, especially during the first week of exposure. Subsequent breakdown was slow and, during the survey period, samples did not reach a stage where fragmentation was likely. Sample burial altered the degradation process suggesting photodegradation as the principal cause of sample deterioration. It was not possible to predict lifetimes for plastics in rivers from the test results as they could not realistically be subjected to abrasive actions that would have been encountered during transportation. Similarly, it is very difficult to test plastic sheeting fragmentation on beaches. In the light of recent complaints and subsequent research regarding plastic sheeting accumulation in the Bristol Channel estuary (Williams et al. 1993b) the potential for riverine contributions to this problem remains high. Very little work has been carried out with regard to this litter source but it is postulated that in 'flashy' river areas e.g. the Mediterranean, much beach plastic litter originates from rivers.

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