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Present state of knowledge of long term behaviour of materials used as soil reinforcements

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ABSTRACT : Long term behaviour of the main metallic and synthetic materials used in soil reinforcement is examined, having regard to required service lives of the order of a century. Present-day knowledge of this area is summarized, and attention is drawn to major gaps where a particular and systematic research and experimental effort is still required.

1 - INTRODUCTION

1.1 Service life

There is a worldwide agreement that most civil engineering structures should be designed for a minimum service life of about a century. It is of course important to recall the difference between service life and lifetime : for as long as it is maintained in service, a structure must remain safe, i.e. an acceptable step away from the ultimate limit state of resistance or deformation, synonymous with failure.

Service life and durability are concepts which have become particularly important with the advent and increasing use of mechanically stabilized earthworks. For, unlike other civil engineering structures, their load bearing elements are difficult to inspect - and impossible to maintain. They are, in addition, buried in soil, a complex environment with physical and chemical characteristics which may vary greatly from site to site. Any guarantee to the effect that soil reinforcing materials have a service life of some one hundred years must be based on a sure knowledge of how their properties will evolve over the long term in extremely varied actual conditions of application.

1.2 Reinforcement materials

There are currently two large families of materials catering for the stabilization of backfill-based structures ; metallic reinforcements and plastic products. Metallic products are usually in the form of galvanized steel strips, but meshes may also be encountered and stainless steel or aluminium alloy strips have been used in the past. Plastics come in the form of polyester or polypropylene geotextile sheets, polyethylene grids, or polyethylene-coated polyester fibre belts.

2 - GALVANIZED STEEL

Up to now, galvanized steel has been the material used in the vast majority of mechanically stabilized embankments. Indeed, whenever major tensile forces are expected, steel continues to be the sole material used in civil engineering as a whole.

The prevalence of steel is due to its unique combination of qualities : tenacity, high modulus of elasticity, ductility, favourable economics. Its corrosion mechanisms and kinetics have been known for a long time ; it has been used in a wide variety of environments over very long periods, and can be protected to ensure that it can do its job for the time specified. Such experience is a major advantage.

In the reinforcing strips used by Terre Armée, durability is achieved by a combination of galvanization and a sacrificial thickness of steel. Galvanization is a technique which has been used for a good century now ; ever-improving, it protects 10% of world steel production. In soil reinforcement applications, a zinc coating has the additional merit of standing up well to rough treatment on construction sites during handling, backfilling and compaction.

2.1 Steel protected by zinc.

The corrosion of metals in an aqueous medium is solely electrochemical in nature : it is connected with the formation of micro-cells resulting from any heterogeneousness in the metal's surface or surroundings. A metal's tendency to corrode depends on the difference in potential it develops vis-à-vis an electrolytic medium. As this difference is greater for zinc, iron remains protected as long as there is any zinc nearby.

The behaviour of a galvanized steel strip in humid soil may be summarized as follows :

Phase 1 : Only the zinc, a tight and adherent coating, comes directly into contact with the soil. The zinc's oxidation reactions lead to the gradual formation of corrosion products which remain attached to the strip's surface and bind in adjacent soil particles. As the electrolyte changes, the reactions become slower.

Phase 2 : The zinc has completely disappeared in places, exposing the steel. Nearby zinc, however, continues to provide cathodic protection, and the steel does not corrode (Fig. 1). The soil round about becomes increasingly richer in zinc compounds (hydroxides, oxychlorides, carbonates ...) and forms an adherent gangue.

Phase 3 : The steel begins to dissolve in an environment which is very different from what it was at the outset, and much more slowly than if it had never been galvanized. The rate of the corrosion's advance continues to decline as time goes by.

The time spent in each phase will obviously depend on how aggressive the environment is ; indeed, the main aim of research has been to classify soils according to their chemical and electrochemical characteristics, in order to identify those most commonly encountered and estimate the maximum rate of corrosion to be expected.

2.2 Different soil-types

Data analysis techniques were used to assess the relative importance of corrosion-influencing factors : it was found that the aggressiveness of a backfill could be defined by reference to four parameters :

- its resistivity (measured after one hour's saturation with distilled water)
- its pH (as measured in water extracted from this mixture)
- chloride content
- and sulphate content.

The histograms below show the distribution of values found for these parameters in a representative population of 235 backfills. Borderlines were also drawn on these graphs to delimit common backfills of low aggressiveness (Fig. 2).

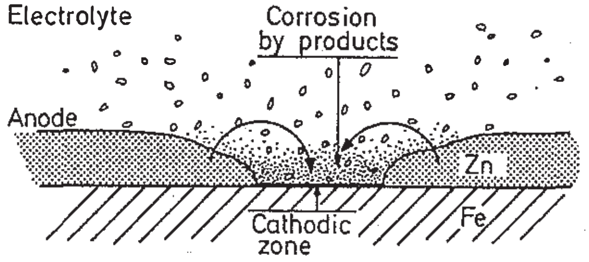

Fig.1 - Cathodic protection of steel by zinc

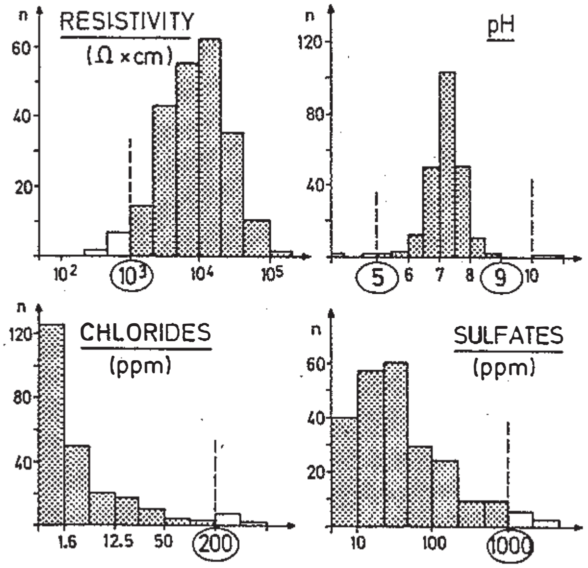

Fig. 2 - Electro/chemical characteristics of 235 backfills.

2.3 Previous research results

Valuable data on the order of magnitude of metal losses over long periods were initially obtained from publications concerned with the performance of galvanized steel culverts, forced conduits, and steel sheet piling or piles. But the most significant source from the point of view of soil reinforcement remains the report, written by M. Romanoff, on the experiments carried out by N.B.S. (U.S.A.) between 1910 and 1955. Thousands of samples of steel, galvanized or not, were buried at 128 different sites ; disregarding those placed near the surface in very clayey or organic soils, the first finding is that galvanized steel, after some ten years, has corroded four times more slowly than ordinary steel. Secondly, the average rate at which thickness is lost decreases over time ; the process may be described by the equation $P = AT^n$, where T is time, and A and n are constants representing soil characteristics, n always being < 1.

For example there are random backfills where the corrosion rate falls from 10μ per year at the end of the first year to 3μ after 10 years, tending towards 1μ per year after 100 years.

2.4 Research by Terre Armée.

Since 1970, Terre Armée Internationale has been pursuing its own programme of research aimed at confirming prior findings and carrying investigations further forward. Three main lines of experimentation are being simultaneously pursued :

1. A reference framework was provided by placing strip samples in boxes filled with selected soils which are kept in conditions identical to real backfills. Samples are removed and weighed at regular intervals. These tests show, for example, that the transition from zinc to iron has no effect on the slopes of weight loss curves (Fig. 3).
2. The same soils, and many others, were placed together with strip samples in a total of 200 cells (Fig. 4) where periodic measurements are made of instantaneous corrosion currents. Faraday's law is then applied to calculate the corresponding metal loss. Such measurements have been going on for twelve years now, agreeing well with the reference test findings.
3. Lengths of strip or durability samples are removed from structures currently in service (the oldest will soon be 20 years old) and here, too, average loss of thickness is measured.

All results for what might be considered routine-type backfills by reason of their physical and electrochemical characteristics and their water content - including those obtained during inspections of actual structures - are shown together in figure 5. The scale being logarithmic, a function of the type $P = AT^n$ would appear as a straight line. The first impression gained from this graph is that this is a very coherent set of results, from the point of view both of numerical values and of the slopes of the curves. The points for field measurements are very much in line with the curves for experimental results and confirm the reliability of the laboratory measurements.

Straight lines can then be drawn on either side of this cluster of results and extrapolated over the period of service normally required, the extrapolation coefficient being of the order of 5 or 6 (trials extending over 12 to 18 years for a service life of 70 to 100 years). In the case of a rather aggressive backfill at the end of the range of common soils, the likely rate of corrosion is represented by $P = 25T^{0,65}$. This amounts to a combined loss of zinc and iron of 400µm per face at 70 years (in routine design calculations a notional 500µm of steel is deducted per face). In practice, though, most values will be situated towards the lower end of the range, as evidenced by the points plotted after inspections of actual structures.

3 - PASSIVABLE METALS

In the early days of Terre Armée's construction method, other metallic materials were also used for reinforcing strips, such as the aluminium alloy ASTM 5086 or the stainless steel AISI 430. These "passivated" metals are protected by a surface layer of oxide, expected to be extremely stable. And yet, some ten years later, problems were occuring in a number of cases. The experiments on the basis of which these materials had been specified,

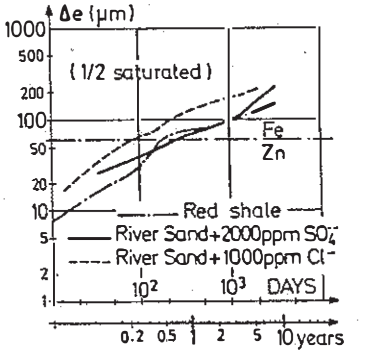

Fig. 3 - Transition from zinc to iron in aggressive soils.

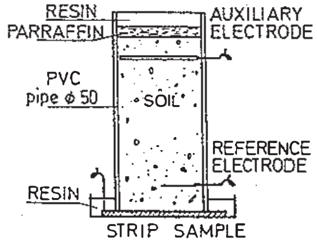

Fig. 4 - Corrosion cell

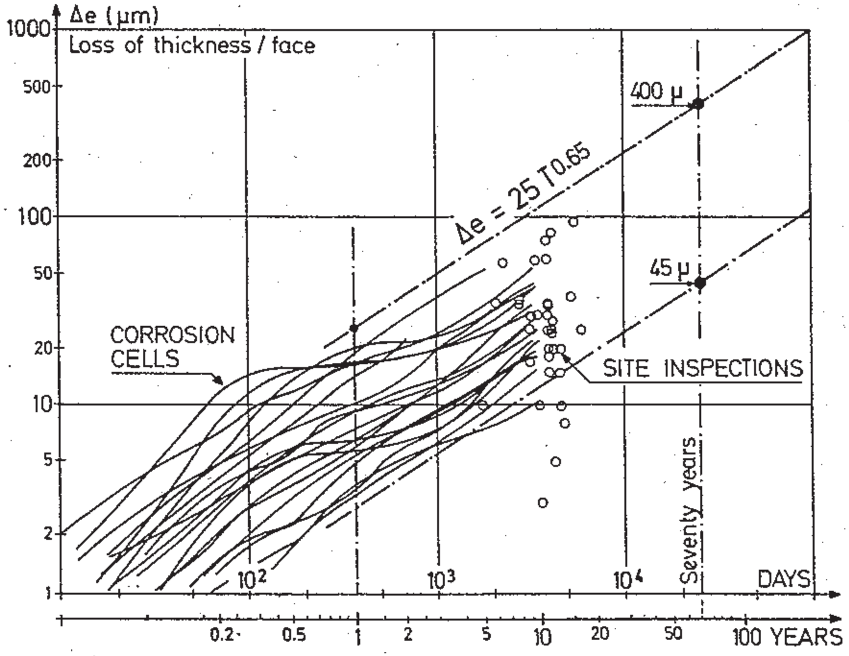

Fig. 5 - Actual loss of thickness in routine backfills.

while well designed, had been too short in duration and insufficient in number ; far too little is known, even now, of how these alloys corrode in soils.

Galvanized steel, on the other hand, has a "clean" accident-free record. Well established long before the development of the Terre Armée technique, it has since benefited from a further twenty years of operational applications and specific research.

4 - PLASTICS

The first retaining structure to be reinforced with plastic was built by Terre Armée at Poitiers (France) in 1970. Belts woven from high tenacity polyester yarns were incorporated in a structure forming part of a temporary development. When samples were first removed, in 1981, the yarns had lost a lot of their initial strength. In 1987, during a more thorough examination (the structure had since been taken out of service), the belts were found to have completely deteriorated where they entered the facing panels, as a result of hydrolysis in the vicinity of concrete. Many came away at the pull of a hand. In lengths of belt removed from the backfill, this time far from the facing, up to 35% of strength had been lost due to mechanical and chemical degradation, while chemical degradation alone accounted for a deterioration of some 4,5% in individual fibres. This experience further confirms the fact that when new materials, in particular synthetics, are used for soil reinforcement purposes, a variety of very real problems arise; these will be rapidly reviewed hereunder.

4.1 The desired mechanical properties of reinforcing materials.

A material must have a certain tenacity, the extent to which it may strain must be limited and, above all, any deformation must not progress over time : a material subject to creep poses problems, particularly when used with a relatively rigid facing.

A material must be hard and ductile enough to withstand impact shocks, puncturing by pebbles and the tracks of site equipment. Such mechanical aggression must not be able to seriously reduce a reinforcement product's strength, either sooner or later.

4.2 The degradation of polymers.

Degradation processes and their kinetics must first of all be identified. These follow a particular pattern in each individual material ; thus, the polyester rate of hydrolysis accelerates over time, while that one of steel corrosion slows down. The morphology of degradation plays an important role : homogeneous dissolution promotes steady ductile behaviour, whereas localised cracking will result in brittle unpredictable behaviour.

Unlike rust on steel, deterioration in a plastic is difficult, even impossible, to see. The process may be started off by different factors :

- water, liquid or in the form of vapour, can penetrate into the molecular structure and act as a plasticizer sometimes greatly modifying the original mechanical properties. It also acts chemically by hydrolysis, a process which may be speeded up by salts and other substances dissolved in the water.
- light and UV rays have the effect of initiating and encouraging oxidation reactions in polymers. Prolonged exposure to light, prior to a "burial" in soil, may compromise its resistance to other forms of degradation.
- oxidation associated with increased temperature, aging mechanisms prompted by certain metallic ions present in soils, surface interactions leading to environmental stress cracking, the action of solvents, the gradual restructuring of molecules, etc ...all of these factors may be involved.

4.3 The effect of temperature

The vulnerability of polymers to the causes of degradation is largely dependent on raw materials, used additives, and manufacturing processes. Morever all degradation phenomena are accelerated by increased temperature : a rise from 10° to 20° C results, for example, in multiplying the rate of hydrolysis of polyester by a factor of 4.5, while creep in polyethylene increases tenfold. And, contrary to the commonly held view, soil temperatures vary to a depth of several meters ; near the surface, and near the facing (where, furthermore, stresses are high ...), diurnal and seasonal variations are even further accentuated by the effects of sunlight.

Since temperature affects degradation in an exponential way, following an Arrhenian law, it is not the average temperature at a site which determines a polymer's behaviour. Thus, near the facing, and in a temperate zone, hydrolysis in polyester advances 2,5 times faster, and the time to creep failure in polyethylene is 6 times shorter than it would be at a depth of some ten meters, at constant average site temperature ($\simeq$ 10°C). Temperature is therefore a significant variable which must not be overlooked when designing structures involving synthetic reinforcing materials. Such considerations are of uppermost importance in hot countries.

5 - THE CASE OF POLYETHYLENE

High density polyethylene (HDPE) is highly resistant to most aggressive chemicals, which makes it at first an attractive candidate for in-the-soil applications. Some of its weaker mechanical properties can be improved by drawing during manufacture, which promotes molecular orientation. Anyway over time and under a given load, HDPE continuously deforms until it fails : this is the phenomenon known as creep. Failure comes rapidly when the load is heavy, being preceded by major deformation : this is termed ductile failure.Under smaller loads, failure comes more slowly - but may be very sudden when it does occur, with no any preceding deformation phase : this is brittle failure, which is very difficult to predict (Fig 6).

We are aware of only one area of application of polyethylene, namely buried pipelines, where conditions are sufficiently similar and experience of long enough standing to be of relevance in the field of soil reinforcement. Such pipelines have been used for gas distribution for some thirty years now. In North America, cracks occurred in some pipes after just a few years, posing extremely serious problems for network operators. It was realized that mere extrapolation of the results of short term trials (about a year) did not allow an imminent brittle failure to be foreseen: the laws governing HDPE's ductile behaviour, with the pipe swelling prior to bursting, do not apply where the pipe splits suddenly in a brittle way (Fig. 7).

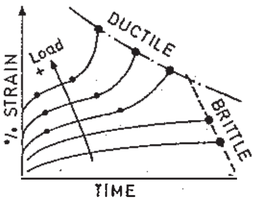

Fig.6 - Creep and failure modes of HDPE.

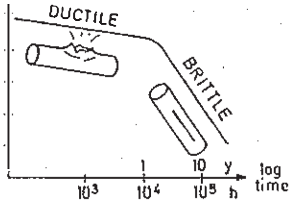

Fig.⁷ - Case of some HDPE gas pipes.

In addition, the process of brittle failure, to which polyethylene is intrinsically prone, may be greatly accelerated in certain environments which favour the development of cracks and existing defects, even if microscopic, especially in the zones subject to most stress. Thus, contact with water, or oil, may reduce a given resin's time to brittle failure in air by factors of, respectively, ten and one thousand. The result is a very considerable shift in the position of the boundaries of the brittle failure zone.

Given these uncertainties, HDPE gas pipes are used only in accordance with the following conditions, as laid down by the ASTM and the Plastic Pipe Institute :

1. Service life must never exceed 50 years.
2. Tensile stress must not, in practice, exceed 10% of short term breaking stress (and possibly less, depending on a maximum deformation criterion).
3. In addition, each product must have come through a series of qualifying tests carried out at different temperatures. Relying itself on certain correlations, this approach aims at ensuring that, in the conditions of use, there is no risk of the brittle failure zone being reached before the end of the service life.

In the present state of knowledge and not to mention the various aggravating factors encountered in soil reinforcement applications (installation, temperature..), it would seem prudent to refer to such specifications.

6 - THE CASE OF POLYESTER

The polyester (PETP) fibres used in many geotextiles pose few problems of creep, at usual temperatures. They are, however, vulnerable to hydrolysis, the chemical reaction process whereby a molecule of water causes a molecular chain to divide, creating new acid and alcohol chain extremities (Fig. 8). Molecular structure may be disrupted by other external factors such as certain chemicals, or UV rays. Fast-acting, the latter too cause chain scissions, and later substantially reduce resistance to hydrolysis.

Even in soils with a very low water content, the air is always saturated with water vapour, relative humidity being 100%. Some polyester products appear protected, encased in polyethylene ; this envelope is not, however, proof against water vapour, and within a few months the polyester fibres inside will be in a saturated environment.

Hydrolytic phenomena in polyester have been investigated above all by Mac-Mahon, (1959), though only in pure water and at temperatures in the 60-100°C range (Fig.9). In these conditions, molecular weight is halved in eight months at 80°C ; six years would be required at 60°C, and several hundred years, one might assume, at usual site temperature. However, no

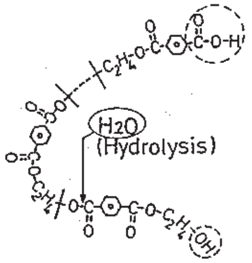

Fig.8 - Hydrolysis of a PETP molecula.

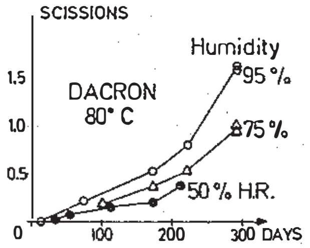

Fig.9 - Average number of scissions/molecula (Mac-Mahon).

systematic investigation of the effects of pH and certain catalytic phenomena has yet been carried out or published - though it is agreed that hydrolysis advances much faster in the presence of bases, particularly lime.

Mac-Mahon also studied the relationship between the kinetics of chain scissions (which accelerate over time) and changes in mechanical properties. He found that initially there was a relatively slow decline in mechanical strength, which fell in proportion to the average number of scissions in the macromolecular chains. The most striking discovery was, however, the existence of a transition zone beyond which the effect of hydrolysis on mechanical strength became catastrophic. The knee in the curve comes where the rate of degradation corresponds to about a halving of molecular weight (Fig. 10). Ultimately, then, accelerating hydrolysis in conjunction with the existence of a critical degradation threshold leads to a sudden collapse of mechanical strength.

There is little available experimental data on in-the-soil performance of polyesters over any appreciable period of time, except for a major report from the French Textile Institute, concerned with samples of geotextiles 3 to 11 years old. Most were used in drainage or separation functions, where mechanical characteristics are of less relevance. Unfortunately, little is revealed of the initial material characteristics or exact conditions of exposure, and the results are not very precise. Anyway, if loss of mechanical strength is compared with the number of chain scissions (derived from a titration of acid chain extremities), there is a certain consistency with Mac-Mahon's results (Fig 11), and therefore with presumptive effects of hydrolysis.

Moreover, the average rate of chemical degradation is about 50 times greater than might have been expected from the pure water results. This unfavourable outturn, probably due to chemical characteristics of the soils and aggravated by short term exposure to UV rays, prompts many questions about the life expectancy of structures incorporating polyester reinforcements.

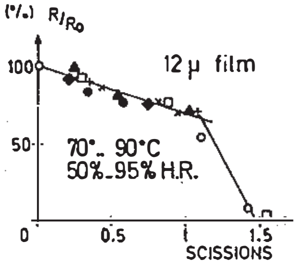

Fig.10 - Hydrolysis of PETP film. Residual strength (Mac-Mahon).

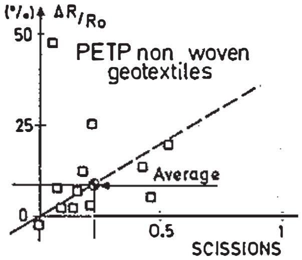

Fig.11 - Samples of buried geotextiles. Loss of strength (ITF).

A tremendous amount of experimental work remains to be done, then, before sound specifications can be laid down for structures other than temporary.

7 - CONCLUSION

More than twenty years experience of the behaviour and aging of buried strips all points to the need for an open-minded, progressive and pragmatic approach to all new materials. Their individual degradation mechanisms must first be identified ; behavioural laws which take into account the various phenomena observed must then be derived from basic experimentation ; and, finally, long term tests must be embarked upon, in a variety of true-to-life environments, in order to determine reliable values for the different parameters of these laws. Given the service lives required in this field, and the magnitude of the risks, the duration of such trials is of paramount importance.

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