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Waterproofing of tunnels using geomembranes: durability and design aspects

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Summary

Waterproofing of underground structures and tunnels is of overwhelming importance for the long-term durability and effectiveness of the works and for the possible impact on the surrounding environment. In conventional tunnelling, polymeric waterproofing membranes are commonly used with this aim, but some aspects of design and durability of these materials are still not well known.

In this work, a methodology based on risk analysis is proposed to choose, among the possible technologies, the best one for the boundary conditions and constrains of the project. With this aim, a specific procedure is developed, at first evaluating the risk without waterproofing and then applying different technologies assessing their effect in terms of costs and risk. This tool, based on the Monte Carlo method, gives a statistical evaluation of the initial and residual risk and evaluates the effectiveness of the different scenarios.

Furthermore, nowadays tunnel design requires about 150 years of lifespan and consequently attention has to be paid to the long-term durability of waterproofing systems. Therefore, an accelerated ageing test specifically designed for tunnel waterproofing is developed and carried out on two commercial geomembranes, in order to define their behaviour and to test their properties after degradation. Moreover, eight different formulations of plasticized PVC membrane are produced and studied, to evaluate the effect of different concentrations of plasticizer on the behaviour of the waterproofing membrane.

The loads acting on the waterproofing system during the service life of the tunnel are analysed and compared to the available properties of the membranes, in order to define the time of end-of-life of the waterproofing system from the long-term extrapolation of the degradation of the membranes.

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Chapter 1

Introduction

The waterproofing of tunnels and underground structures is a key aspect in order to guarantee quality and effectiveness of the infrastructures and to reduce the potential impact on the surrounding areas. The attention on this aspect has intensified during the last decades as a consequence of the increase of requirements on the internal operational quality of the tunnel (e.g. dry surface) and of the design lifespan of the infrastructures (sometimes bigger than 150 years).

Nowadays, the technology of waterproofing includes many different technical solutions for the construction and operation phases. However, at the state of the art, the most used technology for long-term waterproofing of conventional tunnels and excavations is the use of watertight geoemembranes. These materials, in association with other elements (i.e. geotextile, drainage pipes, high drainage capacity geocomposites) form the waterproofing system.

Although the consequences of ineffectiveness of the waterproofing in terms of cost, disruptions and refurbishment works are well known, there is still a lack of information on some design aspects of waterproofing systems.

In this study, two aspects will be analysed: the selection of the best waterproofing technology for a specific project on the basis of a long-term cost evaluation and the assessment of durability of geomembranes when applied in underground structures.

The first issue will be faced through the definition of a procedure based on the risk assessment approach in order to perform, in the first phases of the design, a comparison among different technologies and establish the one that provides the lower residual risk with an acceptable cost. The focus will be to consider not only the initial cost of the system but also the potential cost of repair of the waterproofing during operation.

The durability of the waterproofing systems will be assessed defining and studying the potential actions on the system, both with literature review and analysis of the design standards and with laboratory tests on commercial geomembranes.

Moreover, the degradation mechanisms of the materials composing the waterproofing system will be analysed with particular attention on plasticized polyvinyl chloride (PVC-P), that is one of the most diffused materials for tunnel waterproofing geomembranes. To study the degradation of PVC-P geomembranes in the conditions of application in tunnels, a specific designed accelerated ageing test will be described and the results of accelerated ageing tests on two commercial membranes will be discussed.

Moreover, different PVC-P formulations will be analysed in order to better define the relation between the degradation of the geomembrane and the change in the mechanical properties. From this study, a model will be defined to extrapolate the degradation to long duration in order to define the behaviour of the geomembranes during the whole life of the underground structure.

Finally, the results of the study of degradation mechanisms and those of the analysis of the actions on the waterproofing system will allow to establish the end-of-life time of the two commercial geomembranes in different environmental conditions.

Chapter 2

Water and underground structures

2.1 Water interaction with underground structures

[1] The mutual action and influence of water and underground structures is of overwhelming importance both for the good construction and operation of the structure itself and for the preservation of the environment.

Inflows of water have been recognized as essential actors inducing damage in underground structures (Asakura and Kojima, 2003; CETU, 2015; Howard, 1991; ITA WG 6, 2001; Richards, 1998). From the analysis of damages occurred to Swiss road tunnels, Sandrone and Labiouse (2011) identify in water one of the most important elements for deterioration of structures and loss of efficiency. Moreover, they highlight that damage is strictly linked to the type, quality or absence of a waterproofing system. This damage implies high costs for maintenance and refurbishment and can lead to expensive disruptions of service.

On the other hand, underground water has to be preserved from pollution and underground flows have to be maintained to ensure the availability of this essential resource.

Therefore, all possible interactions have to be carefully analysed when planning to built an underground infrastructure.

2.1.1 Environmental issues

Environmental preservation during construction and operation of an underground structure is of great importance, also keeping in mind the huge impact

[1]The content of this chapter is partially part of the published paper Luciani and Peila (2019)

that public opinion concerns has on the success of a project.

The first interaction with underground water is the possible variation of the groundwater level. A drawdown of the groundwater level entails the reduction or elimination of water flux of springs and wells (Banzato et al., 2011; Beitnes, 2002; Celico et al., 2005; Loew et al., 2007; Loew and Zappa, 2009; Moon and Fernandez, 2010; Nishigaki, 2010; Olofsson, 1991; Piccinini and Vincenzi, 2010; Vincenzi et al., 2014) and, in the worst cases, the drawdown of the level of surface rivers and lakes (Kværner and Snilsberg, 2008; Lindstrøm and Kveen, 2005). These phenomena can seriously damage the life and economies of the surrounding environments and populations and can require extra costs for the construction of new wells and pipes to compensate the reduction of water availability. The alteration of flux from springs has also an impact on the fauna, reducing the availability of water for wild animals and the flow rate of streams (Vincenzi et al., 2009).

Moreover, the reduction of the pore pressure caused by lowering of groundwater level can induce settlements that affect the stability of surface buildings and infrastructures both for shallow tunnels in soil (Yoo et al., 2012) and for deep tunnels (Zangerl et al., 2008).

Furthermore, when big underground structures (e.g. metro station, deep structures) are constructed, especially if orthogonally to the underground water flow direction, the structure can act as a barrier to the flux inducing the so called 'dam effect' (Attard et al., 2016; Font-Capo et al., 2015). The dam effect results in lowering the water-table level downstream, with the previously mentioned possible consequences, and uprising it upstream. The latter condition may call for flooding of existing underground structures (e.g. underpasses, basements).

The impact on the flora of groundwater level drawdown is strongly dependent on the kind of plants and trees present which may be more or less dependent on the constant presence of groundwater for their evolution. The lowering of the watertable can cause harms to the vegetation and some long-term studies have highlighted that, if the watertable level lowers, the species of plants change with the substitution of species sensible to the groundwater with other less dependent from this parameter, alterating the original ecosystem (Froend and Sommer, 2010; Kværner and Snilsberg, 2008; Zheng et al., 2017). On the other hand, the uprising of the watertable level can drown the roots of plants and crops that can not withstand a saturated soil environment (Olofsson, 1991).

Another potential concern about the impact on the environment of tunnel construction is pollution. Pollutant agents can diffuse from the tunnel to the soil and consequently to the groundwater both during construction (e.g. cement additives, chemical injections) and during operation (e.g. traffic pollution, spills due to traffic accidents in the tunnel). As an example, the former case had great impact in the case of Hallandsås tunnel in Sweden and Romeriksporten tunnel in Norway where, to face the water inflows in the tunnel during construction, acrylamide and methylacrylamide containing injections where used. These chemicals, resulted toxic, polluted the groundwater and caused death of fishes in surface rivers, economical damage to local farmers and great concerns of the population about the tunnel with several years of interruptions of the construction works (Sjölander-Lindqvist, 2004; Weideborg et al., 2001).

Moreover, a tunnel acts as a drain, connecting all the underground waters intercepted and, therefore, possibly connecting different aquifers along the alignment. This is a big concern when the tunnel connects a polluted or salted water aquifer with a drinkable one, thus globally reducing the quality of the water resources.

At the contrary, in some cases the effect of a tunnel can be positive for the environment. It is the case, for example, of tunnels specifically designed to drain groundwater from unstable slopes to avoid landslides (Peila et al., 2016; Sun et al., 2010). Moreover, tunnels and underground structures are used to avoid flooding during relevant raining events, thus preserving the environment from further damage (Rieker, 2006).

2.1.2 Construction issues

Underground water strongly influences stages and technologies of construction of underground structures.

Filtration forces reduce the stability of the face and of the walls of the excavation and require the use of water management techniques during construction phase and/or of reinforcements and soil consolidation (Perazzelli et al., 2014; Zingg and Anagnostou, 2016). Moreover, water can cause the degradation of rock/soil mechanical properties and, if a flux occurs, it can induces the creation of voids outside the lining with possible damaging effect on the structure.

Furthermore, water affects the work environment, making the tunnelling operations more difficult for the manpower. The impact is both on the human feeling of the jobsite and on the safety level of using tools and electricity in a wet environment. The tools and machineries are often sensible to water and a constant wet condition can damage them or accelerate their degradation. Therefore, pumping devices have to be foreseen to avoid constant presence of water on the working area.

The work environment becomes more insidious in the case of relatively extreme temperatures of the air, such as very low ones in northern Countries or mountainous sites, and of the water. The water temperature can be very low due to water inflows from glaciers, such as in the Montebianco tunnel where it decreased of about 11°C during excavation, or relatively high, such as for for presence of thermal waters (Maréchal et al., 1999) or for deep tunnels where temperatures of 40–48°C can be reached (Parisi et al., 2017).

In extreme cases of water inflow, flooding of the tunnel and of the jobsite can occur. This causes serious damage to the machineries and, in the worst cases, fatalities. Sometimes, the flooding can also induce the filling of the tunnel with soil, requiring further excavation efforts. Appropriate systems of drainage and monitoring in advancement have to be installed to avoid these phenomena.

Finally, in presence of limestone, karst can be associated to water. The presence of karst voids can be tricky for the prosecution of the works, causing delays in the schedule and possible risks for workers. The risk related to karst is increased by the possibility of intersecting big voids filled with water. This has been for example the case of Gran Sasso tunnel: during the excavation of this tunnel a big karsic void has been encountered and water at high pressure rapidly flooded the tunnel causing fatalities and damages to the machineries, beyond severe water level drawdown.

2.1.3 Structural issues

Water pore pressure is a load acting on any underground structure below the water table, therefore the structure has to be designed to bear this load or a total drained structure has to be designed. Nevertheless, in the case of drained tunnels, hydraulic loads can exist on the lining if the drainage system is not correctly designed or if it is stuck due to fine particles filling or degradation. In effect in these conditions, the drainage layer applies directly the load on the secondary lining that, if not specifically designed, can not withstand this load (Shin et al., 2005).

If the structure does not drain underground water, the hydraulic load due to water pressure has to be considered on the structure. When dam effect occurs, the upstream load is higher and the downstream one is lower, thus requiring specific analysis on the structural design. Anomalous hydraulic loads on the structure can be induced also by punctual inflows in the tunnel locally lowering the hydraulic pressure (Attard et al., 2016; Pujades et al., 2012; Xu et al., 2014).

Furthermore, buoyancy forces have to be considered in the design, particularly for big underground structure (e.g. metro stations) that can be damaged by uplifting forces. In these cases specific anchoring structures are usually designed to increase the resistance to uplift.

Water infiltration through the lining damages the structural materials and accelerates their degradation. Many guidelines have been developed to identify the possible damage occurring to tunnel linings and water is always recognized as one of the main causes (CETU, 2015; Howard, 1991; US Federal Highway Administartion, 2003). In old masonry tunnels, bricks are sensible to water and the damaging effect is enhanced by aggressive waters. Moreover, mortars become brittle and loose strength in presence of water, and they can swell if chemical interaction with solutes in the fluid occurs. In concrete tunnels, the concrete natural degradation can be accelerated by water inflows. Even though concrete with low water-cement ratio, i.e. $w/c < 0.5$, are considered waterproof, construction joints, honey combs and cracks due to stresses or shrinkage act as preferred ways for water inflow. The leakage causes loss of cement, reducing the strength of the material, and, on the long term, the water flow increases the width of cracks, intensifying the income. Moreover, aggressive waters can react with aggregates and cause their degradation.

On the other hand, calcium carbonate precipitating in the cracks can reduce their width and limit the flow.

The presence of water is also the basic condition for rebar corrosion in reinforced concrete. This phenomenon results in concrete cracking, spalling and reduction of section of both concrete and steel with consequent reduction of resistance. Corrosion is enhanced in presence of chlorides coming from groundwater, from de-icing salts or sea water.

In cold environments, freeze/thaw cycles of the water inside the lining increase the width of cracks and further reduce the structural capacity of the lining itself (Richards, 1998).

2.1.4 Operational issues

Water influences also the long-term operational effectiveness of an underground structure.

In cold environment, water leakage causes ice formation reducing tunnel available section for traffic (e.g. in railway tunnels) or for secondary aims, such as ventilation shafts. The presence of icicles is also risky for traffic tunnels where the fall of icicles can cause accidents and fatalities. Moreover, the presence of water or ice on the road pavement or the railways can be the cause of accidents.

Water dripping on railways infrastructure can be dangerous: on the ballast can induce settlement of the track, on the tracks can cause the breaking of rail due to corrosion and the triggering of the track signalling circuits (Dammyr et al., 2014). Water inflows can damage the electric plants, corrode the wires with possible snap under tension, damage the accessory tools (e.g. ventilation, lightening, service plants) and corrode fasteners of interior finishes (e.g. fans, lights) (Dammyr et al., 2014; US Federal Highway Administartion, 2003).

If water causes damages to the linings, concrete blocks can fall with possible risks for traffic safety and with disruption and long rehabilitation times (Asakura and Kojima, 2003).

Moreover, water can transport fine particles in the tunnel, requiring periodical washing of the surface for traffic tunnels, or cause the sedimentation of salts in the drainage system, with possible blockage of the pipes and consequent maintenance needs and flooding of the tunnel.

2.2 Waterproofing approaches

Generally speaking, two different approaches to water management for underground structures exist: drained and undrained. The former permits a controlled water inflow in the tunnel through the drainage system (drainage layer, drainage

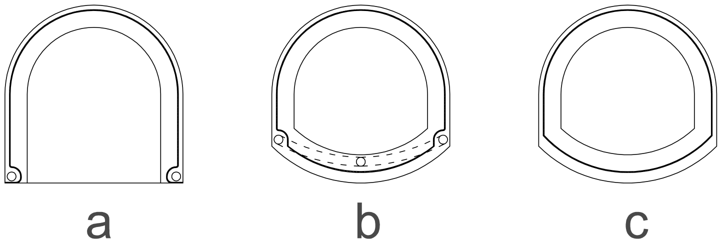


Figure 2.1: Waterproofing approaches: (a) drained only crown, (b) drained full-round, (c) undrained full-round

pipes) and induces watertable drawdown and hydraulic load reduction. At the contrary, the latter avoids any water inflow applying higher loads on the linings and eliminating environmental impact on the groundwater level.

A further difference in the approach exists between full-round waterproofing, usually applied in tunnels under the watertable, and waterproofing only in the crown, also known as 'umbrella approach'. While the former can be both drained or undrained, the latter is necessary a drained approach (Figure 2.1). The choice on the approach to be applied in a project depends on the geological and hydrogeological conditions and on the excavation technologies. On the other hand, the approach chosen influences the structural design and the maintenance plan, e.g. the lining of an undrained tunnel should withstand an higher load than those of a drained one while a drained tunnel will require more maintenance to ensure the effectiveness of the drainage system.

Three classical geological and hydrogeological situations may be identified and will be analysed in more details in the following: shallow tunnels in soil, deep tunnels in rock below the water table level, and tunnels above the water table level.

In shallow tunnels below the water table, the main issue is to avoid drainage in order to prevent possible effects on the surface due to groundwater level drawdown. Therefore, the tunnel has to be sealed with full-round undrained waterproofing. Consequently, the secondary lining has to be designed to bear the hydraulic load. A grouted annulus around the tunnel can be created to reduce the filtration through the soil and to bear part of the load.

In deep tunnels in rock, the main problem is usually the high hydrostatic load that is often impossible to bear for watertight linings (Wang et al., 2008). In these cases, both drained and undrained full-round approach are possible. The undrained approach has to be limited to those situations where important environmental constraints limit the drainage of the water table and where it is technically and economically possible to design a lining that is able to bear the hydrostatic load. An undrained full-round waterproofing can be achieved by a membrane or by sealing of the rock by systematic injection of pre- and post-grouting for conventional tunnelling and by waterproof concrete segments with gaskets for TBM tunnels. In this case the load is totally transferred to the final lining. However, the systematic use of grouting has sometimes resulted in the failure of the project for economic reasons and because of technical difficulties to systematically apply this technique. When environmental constrains are not so strong, a drained approach can be preferable. This can be achieved by a lining permitting a controlled water inflow, keeping a defined height of ground water level around the tunnel (Shin et al., 2014). This solution can be not acceptable for traffic tunnels due to operation constraints, while can be easiest for hydraulic tunnels, e.g. in the case of the Pont Ventoux tunnel (Perello et al., 2007). In order to restore potential environmental harms, compensatory measures can be required if a drained approach is used: new shafts or waterworks may be constructed to assure supply to local inhabitants if the drawdown of the ground water level affects the water resources of local water supply systems. It is better to foresee in advance this possibility, in order to timely provide a solution to these problems, thus limiting inconvenience and claims.

The drained water, if it is not polluted before it reaches the portals, may be a precious resource for the mitigation systems and can be used for the waterworks or taken to surface rivers. For example, in the case of the Colle di Tenda railway tunnel (1889-1898) the excavation time was increased by the great water inflows faced due to a spring crossed by the tunnel. In 1990 a parallel tunnel was excavated in order to create a collection point of the spring for the local water supply network that now serves the area needs (Banzato et al., 2011). In any case, polluted water, even water from road drainage inside the tunnel, must not be taken to water supply network or to rivers, but must be taken to sewage and be treated.

Nevertheless, the problem of lowering the flow rate of streams and rivers as a consequence of groundwater level drawdown still remains. Little artificial lakes filled with rainwater or with water coming from the water supply network, may guarantee the watering for animals and the water resource for local activities. However, it is impossible to keep a constant flow of the streams even in summer to permit the life of fishes.

In tunnels excavated above the water table level, the prevention of water leakage through the lining is the key waterproofing aim, in order to avoid damage to structures and infrastructures and reduction of the efficiency of the tunnel. In conventional tunnelling, a drained waterproofing only in the crown is possible: the water, stopped by the waterproofing membrane, flows through the drainage layer to the base of the tunnel, where it is collected in the drainage pipes and taken outside the tunnel. For these applications, the drainage system has to be designed correctly on the foreseen water inflow, in order to avoid blockages.

It is noteworthy that the water table level has to be defined keeping in mind possible variation due to tidal and seasonal changes or to long-term effects. For example, this problem appeared in the Milan Metro Line 1: during construction

(1957–1964), the water table level in the Milan area was lower than today due to the large amount of water pumped by factories in the urban area (Bonomi, 1999). The metro tunnel and stations were constructed without waterproofing. In the decades after construction, factories moved outside the urban area and this caused a slow rise of the water table level. Consequently, Line 1 tunnels were then below the water table level and expensive maintenance and refurbishment works were needed due to large water inflows. An even worse situation has been faced for the Monte Olimpino 2 railway tunnel, constructed above the water table without waterproofing systems. With time, the water table level has risen and the tunnel has suffered serious problems to the linings, and inflows of water mixed with the finest particles of the soil. The ingress of soils resulted in the creation of voids around the tunnel and in differential movements causing severe damage to the linings. It was necessary to close the tunnel and rebuild it with waterproof linings.

In tunnels excavated with segmental lining the waterproofing is insured by the waterproof segment concrete and by the use of EPDM gaskets between one segment and the other. This is usually a full-round undrained solution, even if drains can be drilled in the lining to have a controlled drained approach if needed.

Chapter 3

Waterproofing technologies

3.1 Waterproofing requirements

[1]The first step for the design of waterproofing systems for underground structures is to define the admissible water inflow in the different phases of life of the structure itself. This value has to be evaluated on the basis of the surrounding soil properties, of the possible impact on the environment and of the impact on the construction and operation effectiveness. Drainage systems and pumping plants will be designed starting from this admissible inflow value. Lindstrøm and Kveen (2005) propose a procedure to evaluate water inflow for tunnels in urban and natural areas.

While during construction water leakages can be admissible, in many operating tunnels the owner's requirements are more demanding. ITA (1991) highlights that the required degree of tightness is to be correlated to the function of the tunnel: higher for structures where people is present or subjected to ice and lower for sewage tunnel. The US Federal Highway Administration (2009) sets as allowable infiltration 0.08 l/m^2/day for road tunnels and 0.04 l/m^2/day for underground public spaces and assesses that 'no dripping or visible leakage from a single location' are permitted. In Switzerland, SIA 272 (2009) defines 4 waterproofing classes (completely dry, dry to moist, moist, moist to wet) and prescribes that tunnels should be in one of the first two classes, that means requiring no dripping water but allowing some spot moist points. The DB (2011) prescribes completely dry surface only for storerooms or workrooms and localized moisture for frost-endangered tunnel and allows for capillary moisture (but not leakages) for other tunnels. STUVA extends the German Railways scheme including a weak dripping water class for utility tunnels and a dripping water class for sewage tunnels with a maximum allowable leakage of 0.5 l/m^2/day/100m (Haack, 1991).

[1]The content of this chapter is partially part of the published paper Luciani and Peila (2019)

3.2 Waterproofing technologies during construction for conventional tunnels

3.2.1 Dewatering

The most effective technical solution to avoid water related issues during construction is dewatering that consists in the temporary lowering of local groundwater level below the level of the construction. Dewatering can be done through pumping or drainage from the surface or from the tunnel in advance of the tunnel face (Angel et al., 2015; Kalamaras et al., 2016; Logarzo et al., 2014; Zingg and Anagnostou, 2016, 2018). The pumping system has to be designed on the basis of the hydrogeological conditions.

This technology has obviously high impact on the surrounding area in terms of settlements and potential environmental harm (drainage of wells, springs, steams) and therefore it is not always applicable to shallow tunnels in urban or environmental sensible areas. Anyway, when dewatering is used, adequate geotechnical solutions have to be designed in order to reduce the subsidence area and to avoid that settlements exceed the acceptable threshold. Moreover, a monitoring system should be installed.

3.2.2 Local drainage

Local drainage, radially or in advance of the tunnel face, is applied to divert localized water inflows from the tunnel. This technology is typically applied in rock, where inflows are mainly localized in discontinuities and fault zones. The obvious disadvantages are related to the effects of drainage and lowering of water table.

3.2.3 Grouting

The reduction of water inflows from fractured rocks or soil is often obtained through injection of various mixes (Aksoy, 2008; Chieregato et al., 2014; Crespo et al., 1992; Peila and Pelizza, 2009). Injection mixes can be divided in two main types:

- cement based grouts: these are the most used mixes, made of ordinary Portland cement or microcements, sometimes added with admixtures or bentonite to reduce bleeding and flocculation; the effectiveness of the solution depends on the dimension of the voids to be filled and of the particles of the cement: smaller particles achieve to pass through smaller cracks and better fill the voids. Therefore, the principal parameters for cement are the specific surface (Blaine value) and the d_{95}, that is the opening size where 95% of the particles passes through. The ISRM (Widmann, 1996) defines as superfine cement those cements with $d_{95} < 20\mu m$. Smaller particles have quicker hydration, that have to be considered to avoid clogging of pipes. Moreover, the water-cement ratio influences the result of the injection: higher w/c induces higher permeability of the grout and possibility of leaking and erosion. The setting time of cement grouts ranges between 2 and 4 hours;

- chemical grouts: many different chemicals can be used with various application ranges and aims. The biggest advantages of these grouts are faster setting times, lower viscosity, versatility and ability to penetrate smaller cracks than microcements. On the contrary, they results more expensive than cement based grouts. Among the most used in tunnelling applications are polyurethane (PU), silicate and acrylic resins. Polyurethane resins can have very different properties depending on the chemical composition, production and reaction: mono-component resins can temporary stop small water inflows while two-component resins can be used to manage higher flows and pressures with a longer duration. Considering the expansion ratio of PU, even if expanding resins can achieve to better fill cracks and voids, a too high porous material will fail to seal completely the void. Silicate grouts have low viscosity and can penetrate very small cracks but have low resistance to water pressure and can not be used with sealing aims. Acrylic grouts have fast setting (about some seconds) and low viscosity but are very expensive and therefore seldom used for waterproofing aims during construction. They shrink in dry environment but swell again when in contact with water, thus re-sealing the crack. Environmental issues have been raised up on some chemical component (particularly for acrylic grouts) used in the past, such as acrylamide and methacrylates, that are toxic and caused contamination of water sources.

In some practical cases a combination of the two types of grouts is used: the cement based one to close the biggest cracks and, after that, a chemical injection to fill the remaining voids. This technique permits to achieve the penetration of chemical grouts using less chemical resins and, therefore, limiting the cost of the intervention.

Grouting can be done in three phases of the excavation:

- pre-grouting, ahead of the face, from the tunnel or from the surface (when possible) to reduce the water inflow before the excavation;
- post-grouting, drilling grout holes in the already excavated part of the tunnel;
- remedial grouting, locally grouting where water inflows are observed (Mahuet, 2009).

It is noteworthy that post-grouting can only be considered as a compensative technique after pre-grouting and that post-grouting alone can hardly achieve the requested results and will imply higher costs. The systematic use of grouting to seal the rock with pre and post-grouting is widely used in Northern Europe countries.

In some cases grouting can be considered effective also on the long term. From the already constructed tunnels, cement based grouts have result to maintain a good sealing effect also after years. On the contrary, not all chemical grout can have effects lasting for all the life of the work: in porous PU resins water inflow can occur with time; silicate grouts can be used only as a temporary solution because of the low chemical stability of the resin; acrylic grouts can last years but they can be disintegrated by cycles of wet/dry conditions.

3.2.4 Freezing

When excavating in soil below the water table without the possibility of water level drawdown or drainage, freezing can be a useful technique. It consists in freeze the water present in the soil ahead of the tunnel face through freezing pipes. In this way, the water can not flow in the tunnel and, moreover, the stability of the face and of the walls is increased since freezing can be also considered as a temporary soil consolidation technique.

Two technologies exist for freezing: direct and indirect freezing. The former uses liquid nitrogen at a temperature of -196°C passing through the freezing pipes inserted in the soil. Once the nitrogen has finished its path it is disperse in the air. The latter, instead, uses a solution of calcium chloride in water, called brine, at a temperature ranging between -25°C and -40°C. In this case, the brine, once passed thought the pipes in the soil, is recirculated in the refrigeration plant and resent into the freezing pipes. Indirect freezing requires more time to freeze the soil but, since it is a closed circuit, it is cheaper (Andersland and Ladanyi, 2013). The two technologies can be combined using the liquid nitrogen for the freezing phase, thus reducing the time required to initially freeze the soil, and the brine to maintain the temperature below 0°C during the excavation, reducing costs (Colombo et al., 2008).

In order to correctly design this methodology of water management, the properties of the freezed soil have to be analysed. The number and path of the pipes have to be set to guarantee the complete freezing of the surrounding soil and an adequate monitoring system should be installed to check the real effectiveness of the solution during all the construction phase (Pimentel et al., 2012a,b; Russo et al., 2015).

3.3 Long-term waterproofing technologies for conventional tunnels

As already stated in Chapter 2, the long-term waterproofing of an underground structure is of overwhelming importance for its durability and efficiency. While cement based grouts can be considered still effective on the long term, the other technologies analysed for the construction phase are not. Different technical solutions exists to manage water interaction with underground structure during all the operation life of the work, with different waterproofing approaches and possible disadvantages.

3.3.1 Permanent drainage

When a drained approach is used, permanent drainages can be drilled before or after the lining casting to permit water flow from the rock/soil and collect the water to the drainage pipes. Sometimes, micro-slotted pipes are used to guarantee the long-term effectiveness of the drain.

In case of localized water leakages, plastic half tubes can be installed on the rock or on the lining to divert the water and collect it in the drainage pipes. The half pipes can be covered by a shotcrete layer. Moreover, cuts can be done in the linings, in correspondence to construction joints or cracks, to create a preferential water flow path and some metallic or plastic profiles can be installed in the cuts to drive the water to the collection point.

These solutions are inexpensive and easy to be installed but have three main disadvantages:

- can be applied only for drained structures;
- the flow of water through the lining causes damage to the structure;
- the drains and the drainage systems can be clogged by fine particles and precipitation of dissolved salts, with potential ineffectiveness of the water management strategy and need of frequent maintenance works.

3.3.2 Watertight concrete and waterstops

The lining concrete can be considered watertight when the water-cement ratio is lower than 0.5. However, it is unrealistic to consider the concrete of the lining perfectly continuous and watertight for the presence of construction joints and cracks due to localized stresses or shrinkage during casting.

Therefore, it is important to take adequate care in the waterproofing of joints. One of the most common technologies is the use of specific strip elements called waterstops that permit the construction joints to be waterproof by making more difficult the path of water through the cracks. These waterstops can be made of a plastic, metallic or swelling material crossing orthogonally the construction joints or installed on the joint before casting the concrete.

3.3.3 Intrados waterproofing

Intrados waterproofing systems are installed after the completion of the final lining at the intrados of the structure in order to create an internal umbrella to avoid water dropping on the infrastructure. Different solutions exist: installation of polyethylene (PE) panels or metal sheets hanged to the lining or free standing vault of lightweight concrete segments potentially with a waterproof membrane at the extrados. The water stopped by these elements should be collected in the drainage system and diverted. Problems can raise up in cold climates with the possible ice formation that should be avoided with adequate thermal isolation. In the case of PE panels, fire risk is high with possible flame diffusion and toxic fumes. A possible partial solution is to cover the PE with shotcrete. The free standing vault is more expensive but has longer duration (Dammyr et al., 2014).

The advantages of these technologies are that the waterproofing does not have any interference with the structural construction, can be inspected and replaced and can be installed only in the zones where leakages occur. On the other hand, these solutions can not be considered durable for the long term and maintenance works are usually required. Moreover, their good performance is strictly connected to the quality of sealing between the panels and a potential harm to safety is caused by the potential failure of one of the fastening elements.

This approach avoids the impacts on electric plants and infrastructures but has no effect in preventing damage to the structure.

3.3.4 Waterproofing membranes at the extrados

Waterproofing membranes are the most used technology as long-term waterproof systems in tunnels when conventional tunnelling excavation is considered. In these cases, the waterproofing element, a polymeric geomembrane, is installed between the rock or primary lining and the final lining. This technology is applicable both for umbrella approach (i.e. only waterproofing the upper tunnel to manage leakage) and for full-round waterproofing. Dammyr et al. (2014) highlight that extrados waterproofing membrane is the best solution, at the state of the art, for a long working life of the tunnel.

Generally speaking, a membrane waterproofing system is usually composed of the superposition of various layers. The first is a drainage layer that is connected to the rock mass or to the primary lining (usually not watertight) with the aim of facilitating the water flow at the extrados of the impervious layer, and it is made of non-woven fabric or geonets. Second is the regularization layer which has the aim of protecting the impervious membrane from damage due to the irregular geometry of the tunnel boundary (i.e. shotcrete or rock) and from punching effects. Usually a non-woven fabric of polypropylene with high grammage (500—1200 g/m^2), high punching resistance, fire resistance and elongation to failure, is used. The drainage layer is not always used, depending on the expected amount of water to be encountered. When a limited amount is expected, the drainage function is performed by the regularization layer.

On these two layers the waterproof membrane is located. This is the core of the system and it is composed of a membrane that can be made of plasticized polyvinyl chloride (PVC-P), polyolefines (FPO-TPO) or polymeric material joined to a bentonite layer. It must guarantee good weldability and good workability, should have high elongation to failure, high tensile strength, and high fire resistance.

The described layers are connected to the tunnel extrados by systematic use of fixing elements, which are disks or elements of the same material of the waterproof membrane, nailed to the substrate. Once the fixing elements are installed, the membrane is welded to them in order to keep the various layers in position before and during the casting. It is important to highlight that these fixing elements must be designed in order to fail before the membrane. In this way, it is possible to guarantee that, if the membrane is subjected to high shear loads during casting, the fixing element breaks, preventing any damage to the membrane itself. Velcro fastener fixings or strips may also be used as fixing elements if a composite geomembrane is used.

On the waterproof membrane a protection layer is frequently installed. This is composed of a polymeric layer with the aim of protecting the waterproof membrane against any possible job site damage before casting the concrete. This layer is not always used, but is very important particularly in the invert, which is subject to job site traffic.

When a drained system is used, a drain that is able to collect the water flowing around the tunnel should be installed. It is composed of a micro-slotted pipe installed in the lower part of the arch and connected to the drainage layer (Mahuet, 2005c). These pipes are then connected to the central drainage pipe of the tunnel, located in the invert position. The drainage system must be designed on the basis of the water inflow foreseen and of the potential deposition of fine-grained soils or salt (e.g. calcium carbonate) transported by the water.

Frequently, waterproof membranes are divided into sectors with a compartmentalization system that creates separate areas of waterproofing membrane. In this way, in the unwanted event of a water inflow, water circulation between the concrete and membrane in the longitudinal direction is prevented. This results in easier repair of the leakage using injection hoses connected to the intrados of the tunnel and usually installed before casting. The compartmentation is obtained through specifically designed polymeric strips, called waterstops, welded to the membrane and bonded to the concrete. The shape of waterstop section has several 'legs' that remain drowned in the cast concrete preventing water flow in the direction orthogonal to the waterstop. Compartmentation is not always used, but its application is increasing worldwide and in some countries it is becoming compulsory (Mahuet, 2005b; Ministère de l'Equipement, 2014).

Waterproofing membrane materials

As already stated, different materials are used for the waterproofing membranes. The most frequently and traditionally used material is plasticized Polyvinylchloride (PVC-P). Two types of PVC-P membrane are usually used: translucent membranes and coloured ones. The former has the advantage of guaranteeing the purity of the material (absence of pigments and fillers) and allowing the visual checks of weldings and of any unwanted presence of burnt material on the weldings themselves (Mahuet, 1984; Ministère de l'Equipement, 2014). The coloured membranes have the advantage of facilitating the identification of any damage to the membrane thanks to the signal layer. This consists of a two-colour membrane: the intrados layer of the membrane is made of a different coloured material with small thickness, usually only about 20% of the whole membrane thickness. If damage occurs to the surface of the membrane during installation works, the colour of the extrados layer appears and allows the damage and its position to be identified. This membrane is used in a growing number of applications and today it is required in many projects. A large number of successful applications using PVC-P are available and this technology is well known by the workers. It is important to highlight that the success of this material is due to the fact that it is flexible and easy to install, even when the substrate geometry is irregular. Moreover, it has good workability and weldability and it is self-extinguishing.

Other frequently used materials for waterproof membranes are polyolefines (FPO: Flexible polyolefine; TPO: Thermoplastic polyolefine). These are a family of polymers such as polypropylene (PP) or polyethylene (PE). They are commonly used in Germany and Switzerland. Polyolefines have a lower weldability and are stiffer than PVC-P. This results in some difficulties during installation in irregular geometries. On the other hand, polyolefines have better resistance to aggressive underground environment, especially where aromatic hydrocarbons are present.

Finally, sometimes a polymeric membrane joined with a bentonite layer is used. This technology has the advantage that the bentonite layer has swelling properties: if leakage occurs, the bentonite is self-repairing. This kind of solution is frequently used in cut-and-cover tunnels and below the invert of the tunnel (Mahuet, 2011).

More specific analyses of the properties of these materials will be provided in Chapters 6 and 7.

Installation schemes of waterproofing membranes

The elements and various layers of the waterproofing system described above are particularly important to guarantee the quality of the application, but it is the correct choice of the system as a whole that is needed to guarantee the efficiency of the long-term protection against water inflows (Figure 3.1).

The first scheme used in tunnelling, and the easiest one to install, is the single layer system. It is made of a single layer of waterproofing membrane installed above

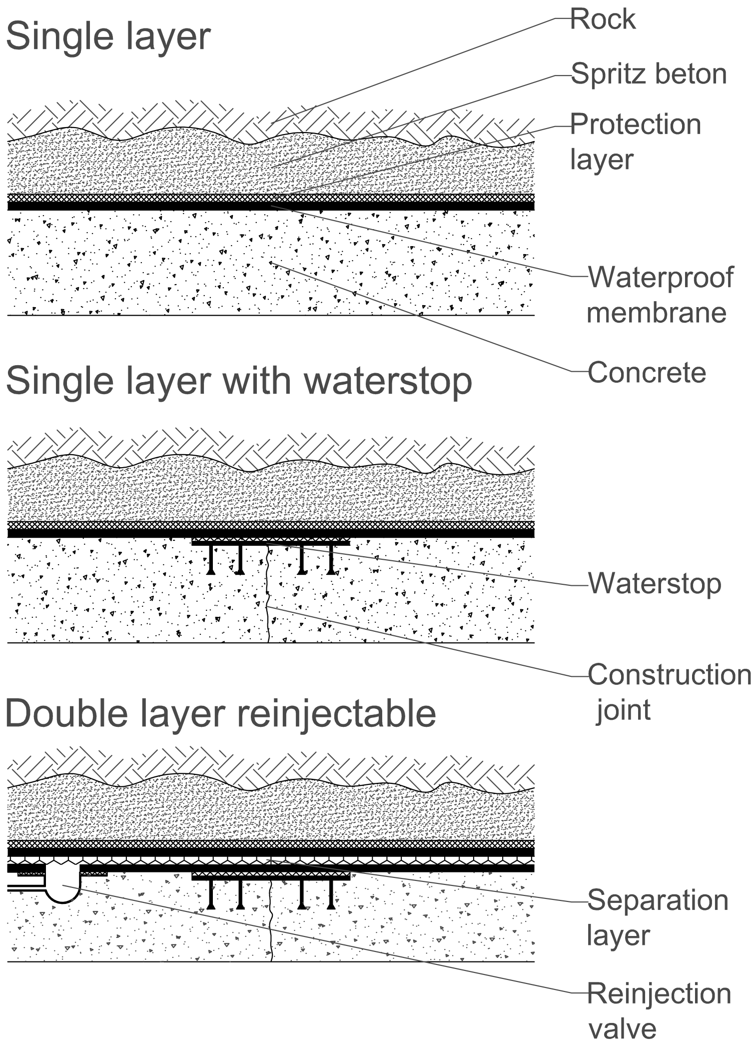


Figure 3.1: Installation schemes of waterproofing geomembranes

the protection layer and welded to the fixing elements. This system has the great disadvantage that, if damage occurs to the membrane, water is no longer controlled and it can run along the extrados of the lining till it finds a way to enter the tunnel. Due to its geometry, it is impossible to know where the damage to the membrane has occurred and no repair works can be carried out.

The improvement of the single layer technology is the compartmentalized one. One single layer of waterproofing membrane is used, but it is divided by transversal waterstops bonded in the cast concrete. In this way it is possible to create sectors of waterproofing systems of about 100—200 m^2. The compartmentalization allows an easy identification of the damage and of the position where inject the resin to repair the leakage. This can be performed using injection pipes that are usually installed through the final lining at the moment of casting. The problem with injections is that it has to be carried out in the layer between the waterproof membrane and the cast concrete, which may be not regular, and an uncontrolled amount of resins may be necessary. This scheme has been widely used, e.g. in Milan Metro Line (Italy) or in Farringdon Station of Crossrail in London (UK) (Dal Negro et al., 2016).

Finally, the most complete and upgraded scheme is the double layer system. This scheme is obtained with two layers of waterproofing geomembrane welded together and divided into sectors using waterstops. In this way, separate sectors of about 60—80 m^2 are created and the system makes it possible to avoid the adhesion of the two membranes.

Beside the self-evident advantage of having a double barrier against water inflow (especially in the long term), this scheme allows injection for repair to be made exactly between the two layers, with a high efficiency of the injection and with no waste of resin. Moreover, this scheme permits testing of the membrane using a vacuum system, identifying if there is any damage to either of the two membranes after installation and before casting the lining, thus permitting an immediate repair (Zotti and Cunegatti, 2014).

Possible sources of damage to waterproofing membranes

The main issues that can affect the efficiency of a waterproof membrane in conventional tunnelling are linked to the operational procedures and to the works for casting the lining in place. They can be summarized in the following main categories:

- irregular surface of the substrate, which can lead to excessive tensions in the membrane during concrete casting;
- voids in the concrete in the crown due to incorrect casting. The presence of voids may facilitate water flow along the tunnel, making it difficult to identify the inflow point;
- low-temperature environment can make it difficult to install the membrane due to the stiffer behaviour of the material. This issue is more critical when polyolefines are used;
- damage to the waterproof membrane during rebars installation or other tunnelling works. This aspect is critical on the job site since the activities are usually carried out by different shifts. Careful instruction of the shift workers and job site management control is required;
- when a full-round approach is used, problems arise for the connection of the waterproofing membranes installed in the invert and those installed later in the crown because the membranes are often not aligned. Moreover, the

position of the connection point and the presence of the rebars of the invert make the welding very difficult, possibly causing wrong or incorrect bonding.

Testing and quality checking

Since the effectiveness of the whole waterproofing system is strictly depending on the quality of the installation, on site testing and quality checks are important. The membrane is a factory manufactured product, therefore its quality is directly controlled during the production and certified by the supplier.

The first check to be done on site is the quality and smoothness of the substrate, that have to comply with the required geometric constrains to avoid damages to the membrane.

Another crucial aspect of the watertight system is the quality of welds. The first level of control is the visual inspection in order to check the correct penetration and continuity of welds and the absence of burnt material. A manual hook or a screwdriver can be used to verify the continuity. Long welds are usually done with a double welding machine, that creates two parallel welds with a channel in between. The aim of the channel is to allow for testing: the extremes of the channel are closed with clumps and pressured air is pumped in the channel through a needle with a pressure of 2 bar. The test is considered passed if after 10 minutes the pressure lowers less than 10% of the original value. Otherwise, the leakage point has to be identified and reparation welding has to be done. For joints and patches, where double welded seams are usually not possible, the welding can be checked with a vacuum bell: soap solution is applied over the weld, the bell is put on the weld to be tested and vacuum is created (about 0.2 bars). The presence of holes will avoid the vacuum build-up and bubbles will show their location. The parameters of the welding tools (i.e. temperature, pressure, speed) have to be checked daily to be adapted to the environmental conditions of the job-site (temperature, humidity).

Risks related to waterproof geomembranes installation

The risks related to the waterproofing with geomembranes are due to work at high during the installation, heat and burn by the welding tools.

The use of geosynthetics (geomembranes, geotextiles) can create a potential risk in case of fire before the casting of final lining when the material is installed. The storage of material in the tunnel and the maximum length of non-covered installed material should be limited considering the potential risk of flame propagation. In case of fire the polymeric material can produce fumes and toxic substances (e.g. CO, HCl, NO_x).

3.3.5 Waterproofing sprayed membrane

Waterproofing sprayed membranes are sometimes used in tunnelling by applying a thin layer of sprayed polymeric membrane on the shotcrete (Holter and Foord, 2015; Holter et al., 2014; ITAtech, 2013). The most relevant advantage of this technology is that it can be easily applied in situations with an irregular or complicated geometry.

The waterproofing material is usually ethylvinylacetate (EVA), methylmethacrylate (MMA) or polyuria resins (Lemke, 2014) and is sprayed directly on the shotcrete used as first phase lining to create a bond onto it. The application can be done both manually and by robots with the same technologies used for shotcrete (Makhlouf and Holter, 2008). The automatized application permits a better control of the treated area and of the thickness and reduces the potential health issues to the manpower. The thickness of the sprayed membrane is usually in the range of about 2–4 mm, but it depends on the roughness of the substrate and on the material used: if the substrate has a more even surface more material is needed in order to fulfil the cavities and to have the required minimum thickness. Therefore, the quality of the substrate layer is very important for the effectiveness of this technology. If the substrate is too rough, the thickness of the layer must be incremented or a regularization layer of shotcrete has to be applied before the sprayed membrane. In most cases, the shotcrete regularization layer should have a thickness of 3 cm with a maximum aggregate size of 4 mm, in order to guarantee the texture of the surface and to avoid trapped air in the sprayed membrane.

The final lining is applied directly on the waterproofing layer using shotcrete or cast in place concrete. Therefore, the waterproof layer remains trapped inside the two support layers, creating a unique structure (Pillai et al., 2017; Su and Bloodworth, 2016; Thomas and Dimmock, 2017). Many studies have been developed to study with mechanical tests the behaviour of this bond in compression and shear conditions. These studies report that, in case of correct installation and good quality of the material, the system shotcrete-membrane-shotcrete can be considered as a whole, since the failure is not localized in the interface between one material and the other. The quality of the bond between concrete and membrane is the key aspect of this technology. If this bond fails, water can flow and find a way to enter the tunnel and it would be very difficult to find the damaged point and to repair it. Bond efficiency is reduced by wet conditions of the substrate, by possible irregularities of the concrete (e.g. honeycombings, cracks) or by spraying of the second concrete layer in an incorrect time sequence, either too early during the curing of the membrane or too late (ITAtech, 2013; Lemke, 2014).

The membrane can be applied on a dry or moist surface but without major inflow, that is not always possible to obtain in tunnels. Before spraying the membrane, all the significant water flows have to be stopped by grouting injections or drained away through pipes.

The main issues affecting the efficiency of a sprayed membrane are (Lemke, 2014):

- irregular or wet substrate that causes insufficient bond or lack of adhesion;
- temperature and humidity of the job-site, which influence the spray application, the curing and the long-term properties of the sprayed membrane;
- the skills and care of the manpower, greatly influencing the final quality of the product.

For the above-described reasons and with the lack of long-term experience, this technology is at the state of the art considered at an experimental stage and usually applied in secondary tunnels (e.g. cross-passages, service tunnels) and is not considered as directly equivalent to waterproofing membranes. As an example, the Austrian guidelines, do not consider the sprayed membrane ‘technically equivalent’ to waterproofing with sheet membranes (ÖBV, 2015).

Testing and quality checking

Since the membrane is on-site made the quality of the final material is strongly influenced by quality of manpower and job-site environment (humidity, dust). Therefore, after the application samples of cured membrane should be collected to test the quality of the material. Moreover, hardness tests can be performed on the membrane on the job site.

The evenness of the substrate have to be checked, and too rough substrates have to be amended with regularization layers.

The quantity of sprayed material has to be measured and compared to the sprayed area, to have a rough evaluation of the thickness. However, real thickness has to be checked with gauges also to verify that the value is guaranteed in all the area. The thickness of the cured membrane has to be checked after the application using a gauge or by removing membrane patches (Clement et al., 2014).

Risks related to sprayed membranes installation

The main issues related to the use of sprayed waterproofing membranes concern the health and safety of manpower. Spraying the membrane causes dust, that can be in excessive concentrations, particularly for the workers using the nozzle (Holter, 2015). Moreover, some of the polymeric material used are toxic, such as methacrylates, that are forbidden in some Countries.

In case of fire the potential risk of flame propagations and toxic fume production is to be considered. It is strictly depending on the used polymer formulation.

3.4 Waterproofing of tunnel excavated with full-face shielded TBMs

In full-face mechanized tunnelling, during construction water is usually controlled by the proper use of full-chamber counterpressure (EPB, Slurry Shield, Variable density machines) and with tail seals.

In the long term, when the final lining is made of segmental lining,the long-term waterproofing of the structure relies on the waterproof concrete of the segments, on the use of gaskets and, partially, on the backfilling.

3.4.1 Gasket

Gaskets are elements made of elastomeric material, usually Ethylene-Propylene Diene Monomer (EPDM) applied on the lateral side of a segment in such a way that their contact will allow a watertight joint between the segments and the rings of the lining. The geometry of the profile of the gasket has been greatly improved over the years, aiming to optimize the use of the material, avoid spalling of the concrete near the groove during the compression and maximizing the connection effect induced by gasket deformation. Since the rubber used has a high deformation at traction but not at compression, the profiles have been studied in order to use the material as much as possible in traction and maximize their ability to control the water pressure.

Moreover, the shape is designed to have a total EPDM area non higher than the area of the groove where the gasket is installed. This is due to the fact that the material is incompressible, and if all the voids will be closed during compression the gasket has not to apply too high stresses on the surface of the groove and damage the nearby concrete (Bomben and Bringiotti, 2013).

The design of these elements requires careful assessment of the geometry of installation to guarantee their watertightness. The design gap and off-set values must be defined, since the efficiency of the gasket depends on them (Guglielmetti et al., 2008; Schurch, 2006; Taillebois, 2005). STUVA (2005) has defined laboratory tests to measure the performance of gaskets with different gap and off-set values.

Gaskets may be glued to the groove in the segment or can be bonded to the segment during casting. In the former case the glue is applied in the groove after segment curing, while in the latter case the gasket is directly installed in the molds before casting and, once the segment has been cured, the gasket is mechanically bonded to the concrete. This last solution is more expensive but ensures a complete bond with the segment, while the glued solution is subjected to possible detachments if the glue is not applied correctly or with the correct timing.

Gaskets provide effective water control if correctly installed and designed and can tolerate high water pressure. However, great care should be taken during segment installation since incorrect installation of the segments can affect their efficiency. For example, overturning of the gasket due to friction of one segment against the other during ring assembly can lead to the expulsion of the gasket from the groove.

Long-term durability of gaskets has to be considered, since rubber becomes stiffer at low temperatures and loses mechanical properties at high temperature. Therefore, it is important to study the behaviour of the gasket with accelerated ageing tests (ISO 11346, 2014; Shi et al., 2015). Moreover, interactions with the chemicals present in the soil or in the underground water have to be analysed. In some cases, different types of materials have been used to guarantee the durability of the gasket in hostile environmental conditions (e.g. EPDM is not suitable for soils with hydrocarbons).

Besides EPDM, also hydrophilic materials are used for gaskets and a hydrophilic cordon is inserted in the profile, maximizing the watertightness of the gasket, which is guaranteed by the pressure on the rubber section and by the swelling of the hydrophilic material when it comes in contact with water (Mahuet et al., 2005). This technology has been applied, for example, in the Circle Line Metro Project in Singapore (Shirlaw et al., 2016).

3.4.2 Backfilling

Due to the overexcavation and the shield and seal brushes thickness a gap is present between segmental lining and soil. The backfilling of this gap is needed to fix the position of segments and to avoid settlements (ITAtech, 2014; Peila et al., 2015; Shah et al., 2018; Thewes and Budach, 2009; Youn and Breitenbücher, 2014). Backfilling is also partially contributing to the water management around the tunnel.

Different technologies are used for this operation, as clearly summarized by Thewes and Budach (2009). The most used technologies are pea gravel, consisting in filling the void with gravel potentially with mortar, two-component grouts (with cement and bentonite) and conventional mortar injection through the shield. Two-component grouts are becoming more and more popular. They are made of water, cement, retarders, bentonite or other elements and an accelerator component that, once mixed, gel in few second. Therefore, it is important to design the injection pipes and injection procedures carefully in order to avoid blockage of the pipes and to completely fill the void annulus around the segments. The gel time of the grout can be set by changing the mixture design in order to achieve the most suitable match between the job-site needs and the timely stopping of settlement (Shah et al., 2018).

Pea gravel creates a draining annulus around the tunnel. Therefore, it has to be post-injected through holes in the segments to avoid water circulation along the tunnel. On the contrary, conventional mortar and two-component cement grout fill the gap completely and immediately, thus contributing to the waterproofing effect due to their very low permeability.

3.5 Tunnel repair and refurbishment

When leakages occur in an underground structure several technologies are available to repair or manage the water, depending on the leakage quantity, location and on the operation requirement of the infrastructure.

The first step for designing a repair work is to identify the location of inflow, the type of water-leakage cracks and the chemical properties leaking water. The inflow can be in some spot defect of lining, in some localized cracks or can be diffuse along a relevant part of the structure. The cracks are characterized by their width and leakage amount and can be divided in static cracks and dynamic cracks. ISO/TR 16475 (2011) and Mahuet (2009) suggest some parameters for cracks width and water inflow values. In concrete tunnels, preferential paths for water inflow are construction joints and dilatation joints while in masonry structures the flow can be more diffused due to the high quantity of discontinuity joints. The most relevant water properties are chemical composition (pH, hardness, dissolved salts), pressure and temperature.

In the design of repair work the boundary constraints have to be considered: if repair works require disruption of the tunnel they have to be quick, or, at the contrary, if the disruption is not possible, the work schedule and technology have to be adapted to the operation conditions of the structure. Moreover, fire resistance of the materials, the possible effect of accidental impact on the waterproofing and of suction due to vehicles have to be considered.

The aim of reparation works can be either to block the leakage or to drain the water from the lining. Mahuet (2009) reposts a detailed description of the state of the art of all the possible water leakage repair techniques used in underground structures.

3.5.1 Injections

For local inflows injections are usually the most applied solution for crack waterproofing or void filling. The injected materials are:

- acrylic resins: these resins have low viscosity (similar to water) allowing them to penetrate in small cracks (>0.1 mm). In contact with water they react creating a watertight gel with low adhesion to concrete but good to polymeric materials, such as geomembranes and waterstops. They are used to repair small cracks, porous zones in the lining and construction joints. Since they are sensible to dilution, are not suitable for high water inflows;

- polyurethane resins: they are the same class of resins used for grouting whose properties are described in Paragraph 3.2.3. They are applied to stop high water inflows, to fill static or dynamic cracks of relatively big width (>1.5 mm) and for dilatation joints. However, the expansion of PU resins creates an open porosity that can not ensure the complete watertightness and the adhesion to concrete is not high;

- epoxy resins: they are used both for waterproofing and for repair of concrete structure since they have good mechanical properties and adherence. However, they are not suitable for dynamic cracks because they are stiff;

- cement-based grouts: this is a big family of different formulations of microfine cement, or cement mixed with bentonite or acrylic or polyurethane resins. These grouts are used to fill static cracks and big voids behind the linings or to repair masonry or concrete structures. They generally have good adhesion with concrete and mechanical properties but are sensible to big water flows;

- bentonite grout: it is used for cracks bigger than 0.1 mm with small water inflows. It usesthe swelling capacity of bentonite in presence of water, that makes it good for situations with variation of groundwater level. However, it is not suitable in presence of see water.

In repair works the injected quantities are usually small (1–5 l/m), therefore the use of chemical resins, more expensive than cement one but more effective, is more diffused than in construction phase waterproofing. The most used for cracks repair are acrylic and epoxy resins.

The execution of repair injection starts with the drilling of holes next to the crack or joint. The holes are drilled diagonally at the side of the crack to better intersect the discontinuity plan that can be not vertical. The geometry of the hole has to be designed to avoid that the concrete between the hole and the crack can be damaged from the injection pressure and to avoid to intersect rebars if the structure is made of reinforced concrete. The diameter of the hole is function of the viscosity of the material and of the pressure to be reached, while the pitch between two holes is defined with tests on site, with an order of magnitude of about 15 cm. When construction joints with waterstops are injected, the drilling direction have to be carefully chosen to avoid damaging the waterstop and to arrive to inject at the extrados of it. Once the holes are drilled, nozzles are inserted in them and injected. The injection pressure has to be defined to avoid any further damage to the structure. In some cases, to confine the injection, a V shaped opening is created at the intrados of the crack and sealed with mortar.

A particular application is the repair injection of compartmented or re-injectable extrados waterproofing membranes. In this case acrylic resins are used for their low viscosity and good adherence to geomembranes. Once the damaged compartment has been identified, the injection hoses installed before casting have to be find. From these hoses the water flow can be checked and measured. At first coloured water injection is suggested to clean the hoses and the compartment, to verify the continuity of the pipes and to check if blockages exists. The use of coloured water permits to identify the leakage and control when the injected water is flowing out from the circuit. The resin is then injected until it flows back from one of the other hoses. To have an effective repair of the leakage the compartment has to be completely filled, therefore the injection is done from the center to the side for horizontal compartment and from the bottom to the top for vertical ones. The curing time of the resin has to be setted to permit the complete injection. When a protection layer or a double layer system are used the filling is more effective due to the easier flow of the resin on geomembranes. Moreover, if a vacuum system is applied, the separation geonets ensures that the two geomembranes are not stuck together. The injection of a compartment has to be done only if relevant inflows occur, because, once injected, it is not possible to further use the injection hoses.

3.5.2 Sealing

To stop small water leakage through cracks a sealing can be done with mortars, polyurethane or modified polymers. A groove has to be cut in the lining along the crack with a pneumatic hammer or with a double saw. The use of the double saw permits to obtain parallel and smooth boundaries for the flexible polymeric materials, while for mortars a V shaped cut is enough. The sealing materials is kept in position with some fasteners. The application of the sealing material have to exceed the length of the crack at both the extremity of about 20 cm.

3.5.3 Surface waterproofing

When the water leakage is diffused, a treatment of the intrados surface of the lining can be used. This consists in covering the lining with mineral waterproofing mortars with or without polymer added or waterpoofing sprayed epoxy resins or EVA resins. The polymeric membrane can be applied both with or without a reinforcing net. The use of the reinforcing net permits to the waterproofing material to withstand some deformation of the substrate, while, without it, it is not able to.

The EVA sprayed membranes, analogue to the one used for long-term waterproofing, are covered with a shotcrete layer to reduce fire issues. These last solution is therefore equivalent to the construction of a sprayed membrane waterproofing.

3.5.4 Permanent drainage

A permanent drainage can be used to manage water leakage appeared during operation. The technical solution are similar to those described in Paragraphs 3.3.1

and 3.3.3.

For inflows localized in cracks or joints a groove can be cut in the lining along the crack and different types of profiles used to catch the water and divert it to the drainage system. The profiles can be an elastomeric (EPDM) seals, a metallic or polymeric sheets mechanically fixed to the lining at the side of the crack, a polymeric half-pipe inserted in the groove and fixed with mortar. The lateral connection of these element to the concrete has to be adequately waterproofed with neoprene gaskets. If the structure is subjected to ice, the profile has to be thermally isolated through polyurethane or polypropylene foams. Some of these technologies can be used also without the cut of the groove (e.g. polymeric or metallic sheets). To enhance the effect of drainage some holes can be drilled in the bottom of the groove to create a preferential path for water and concentrate the leakages in the drained joints.

For generalized water inflows an intrados surface drainage or a free standing or anchored waterproof lining can be considered. The surface drainage is usually obtained with geospacer or geonets composited with waterproofing membranes bolted to the lining. The free standing system is a steel structure filled with concrete or a pre-cast concrete segment lining with a waterproof membrane at the extrados. The anchored solution is composed by galvanized or inox steel plates anchored to the rock or to the lining, avoiding water dripping in the tunnel. Finally, when the original structure is not waterproof, a geomembrane waterproofing system can be installed and a further concrete layer cast, thus creating a condition analogue to that of Paragraph 3.3.4. These solutions are effective but strongly affect the section of the tunnel. Therefore, in many cases are not suitable, such as in railway or road tunnels, when the section can not be reduced.

Chapter 4

Waterproofing technology selection through risk management

4.1 Risk management

Risk management is a widely applied approach diffused also in rock mechanic and tunnel engineering (Brown, 2012; Feng and Hudson, 2015; Guglielmetti et al., 2008). The effort of this approach is focused on reducing as much as possible the epistemic uncertainties related to the project, aiming to avoid the occurrence of unforeseen increases in costs and times of construction (ISO 73, 2009). To reach such an aim, all the possible hazard scenarios have to be identified and evaluated from the very beginning of the design and updated systematically and continually during the development of the project and of the construction.

During detailed design phase only small changes are possible. Therefore, the first phases of the project are of overwhelming importance for the good result of the work.

4.1.1 Definitions and generality

Different terminologies have been developed in the years for risk management in different countries and fields of applications. ISO 73 (2009) has standardized the main terms for risk management for all application fields while ITIG (2012) has developed a standard terminology for tunnel industry in accordance with ITA.

The following definitions, according to ISO 73 (2009), will be used hereinafter in this work:

- hazard, source of a potential harm;

- likelihood, chance of something happening. It can be expressed qualitatively with general descriptions or mathematically as a probability or a frequency of occurrence;
- consequence, outcome of an event;
- risk, effect of uncertainty on objectives. Risk (R) is expressed as the combination of the consequences (C) of an hazard event and its likelihood (L), as

$$R = C \cdot L \tag{4.1}$$

Risk management is the process of identifying the risks, through risk assessment, and the possible countermeasures to eliminate or mitigate them.

When the risk is not acceptable, risk treatment is evaluated in order to identify the best mitigation measure, that can act on avoiding the risk, eliminating its source or reducing its consequences or its likelihood. Risk assessment is then iterated considering the mitigation measures until the risk fulfils the risk criteria. The final value of the risk is called residual risk.

Risk criteria has to be carefully defined. As a matter of facts, no work is risk free. Therefore, the risk owner has to define the minimum value of risk that he accepts to assume. On one hand, the risk should be reduced as much as possible, always considering that it is impossible to remove it completely because the aleatory uncertainties can not be avoided. On the other hand, mitigation measures for minimizing the risk can be very demanding in terms of technical choices or economic cost. Therefore, the risk criteria has to be set on the lower risk value that is economically and technically reasonable. This value is referred to as 'as low as reasonably practicable' also known as ALARP.

4.1.2 Evaluation tools

Risk management relies on several tools (Eskesen et al., 2004) allowing to systematically perform the required steps:

- risk register, that allows to identify and list the potential hazards. In the risk register the hazards are collected in families and the causes and possible consequences of each hazard are listed. It should be created at the very beginning of the project by a multidisciplinary panel of experts on the basis of critical review of previous cases and experiences (Guglielmetti et al., 2008). The register should be updated along all the design and construction with the new hazards rising and with the new information obtained;

- event tree, a scheme allowing to establish systematically the cause - consequence relationship among the hazards. It permits also a probabilistic approach because the value of probability of the initial event is divided at each level among the different outcomes, leading to the definition of the probability of all the final outcomes of the tree;

- fault tree, a scheme that analyses the causal connections leading to a certain hazard permitting both qualitative and quantitative (i.e. probabilistic) assessment of the relationships;

- risk matrix, a graphical representation of the possible levels of risk and of the thresholds of the risk acceptance criteria. The matrix has on the axes the index of consequences and the index of likelihood and therefore each point of the risk matrix is a value of risk computed following Equation 4.1. Risk matrices are usually combined with a colour scale of the level of risk defined using the risk acceptance criteria. The effect of risk treatment is represented on a risk matrix as the translation of the intersection point closer to one axis or to the origin (Figure 4.1). This is an easy-to-read tool that permits visual identification of the most demanding risk conditions and of the fulfilment of the risk acceptance criteria.

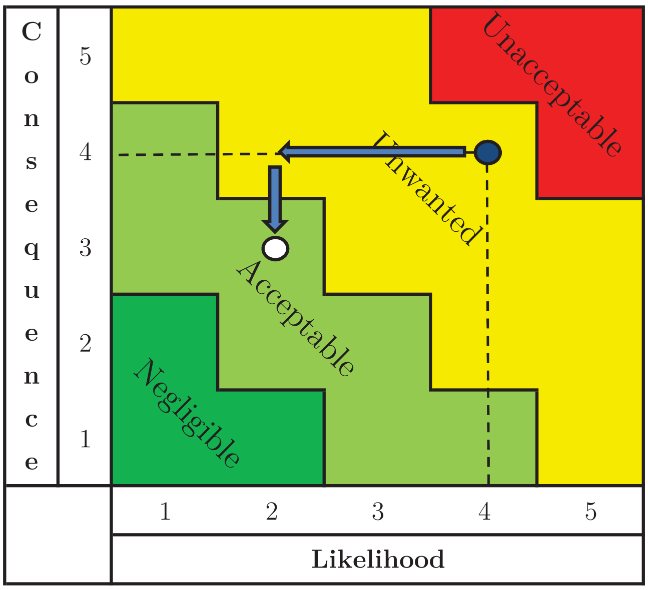


Figure 4.1: Example of a risk matrix, with the definition of the initial risk (blue spot) and of the residual risk (white spot)

Monte Carlo method

The Monte Carlo method is a research approach that, on the basis of probabilistic models of a system, permits to perform simulations on the system itself. This method is widely applied in different fields, from nuclear physics to complex mathematical problems, and is one of the most used tools for probabilistic risk analysis (Kalos and Whitlock, 2009). The Monte Carlo method is particularly useful in those situations where several stochastic variables are involved in the system and where the relationships are complex and can not be easily established in terms of analytical expressions, such as in many risk analysis cases.

The most tricky phase of this method is the definition of the model of the system under analysis because it concerns the definition of the relationships among the elements of the system and it is necessary subjected to biases due to the point of view or to the partial imagine representation. Once the model has been established and the probabilistic distribution of all the stochastic variables defined, the Monte Carlo method permits to simulate the outcomes of the system obtaining a probabilistic distribution of the results through iterations. An higher number of iterations results in a more representative outcome. However, increasing the iterations results in increasing the computational effort, that can be very demanding for complex models.

4.2 Risk management approach for the design of tunnel waterproofing

As already stated, risk management is widely applied in underground constructions. However, it has not been systematically applied to water management and to the design and selection of waterproofing technologies. This approach can be powerful in taking into account from the very beginning of the design all the possible implications of using different water management approaches. It allows a cost-benefit evaluation, a comparison among different solutions and an estimation of their efficiency. Moreover, risk management permits to spread the focus not only on the construction phase but on the whole operation life of the infrastructure, keeping in mind maintenance and repair works, that can lead to different evaluations in terms of cost-benefit comparison.

Therefore, a risk management tool focused on waterproofing of underground structures has been developed (Luciani et al., 2018) and will be analysed in the following. The aim is to obtain a tool for the first stages of the design, to evaluate different water management solutions and choose the most suitable for the project. Therefore, the level of detail of the input information can not be too much high, since many parameters can be not available at the beginning of the project.

Moreover, the procedure has to be focused on the long-term evaluation of the risk, in order to consider the operation phase that is the one more concerning the owner and/or administrator of the infrastructure. As already stated in Chapter 3, in many cases the water management solutions used during construction are not long-term solutions and other technologies are installed specifically for the operation phase.

4.2.1 Structure

The structure of the proposed method follows the steps of risk management. The hazards are listed in a risk register and likelihood and consequences are evaluated. Then, the initial risk is computed qualitatively or quantitatively with an event tree. The mitigation measures are evaluated through a fault tree and the risk is re-computed and compared to the risk acceptance criteria.

Risk register

The risk register has been fulfil basing on literature review, case histories and personal experience of designers, owners, suppliers and workers. Since the focus is on the operation phase, the issues related to the interaction with water during construction have not been considered. The other interactions, analysed in Chapter 2, have been taken into account and all the potential hazards listed and divided into three families: environmental, structural and operation (Figure 4.2).

For the consequences, five categories have been defined: injury to third parties, damage or economic loss to third parties, harm to the environment, disruption, economic loss to the owner. These are derived from ITA (Eskesen et al., 2004) but adapted to the specific frame of application of this tool. In effects, ITA (Eskesen et al., 2004) proposes 7 categories: injury to workers and safety crew, injury to third parties, damage to third party property, harm to the environment, delay, economic loss to the owner, loss of goodwill. These categories are specifically developed for tunnel industry but are clearly focused on the construction phase. Therefore, since this procedure is focused on the operation phase, the injuries to workers are neglected and the delays are substituted with disruption times. Moreover, the loss of goodwill, that is a very important but hardly estimable parameter, has been neglected. This is also due to the fact that the goodwill of public opinion is much less impacting during the operation phase than during design and construction.

Table 4.1 reports the defined levels of severity for the consequence category considering 5 possible values. Similarly, the likelihood is estimated qualitatively with an index parameter from 1 to 5 following Table 4.2.

The quantitative value expressed in terms of probability can be obtained in a row way from the same table or computed through an event tree.

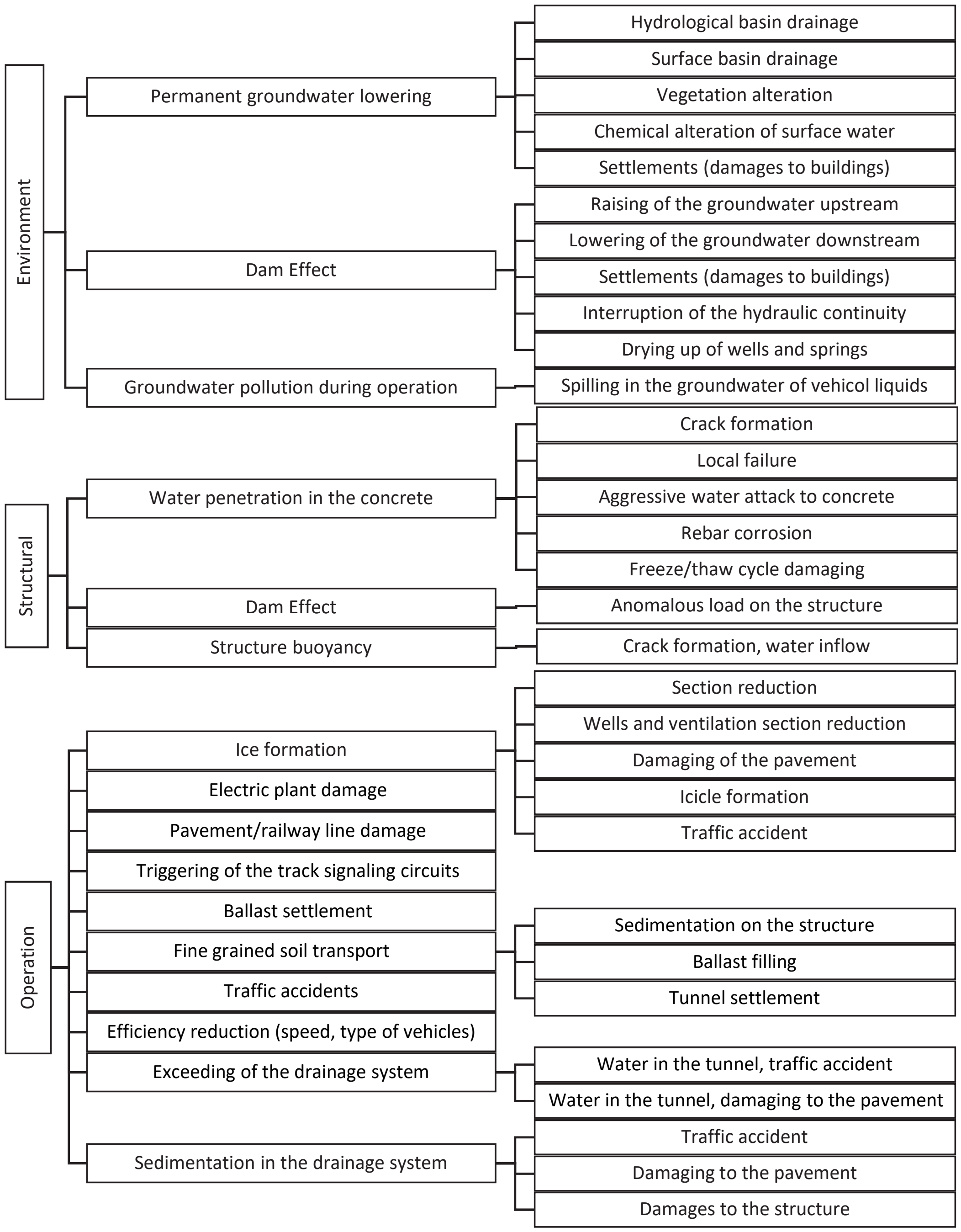


Figure 4.2: Scheme of the risk register divided in the three families

Table 4.1: Qualitative description of the levels of severity of the five categories of consequences. (MI= minor injury, SI= serious injury, F= fatality)

Level of severity	Injury to third parties	Damage or economic loss to third parties (Million €)	Harm to the environment	Disruption	Economic loss to the owner (Million €)
1	-	<0.003	Temporary minor	<1/2 hour	<0.03
2	1 MI	0.003–0.03	Temporary severe	1–6 hours	0.03–0.3
3	1 SI, 1<MI<10	0.03–0.3	Long-term effects	6–24 hours	0.3–3
4	1 F, 1<SI<10	0.3–3	Permanent minor	1–7 days	3–30
5	F>1, SI>10	>3	Permanent severe	>7 days	>30

Table 4.2: Qualitative description of the levels of likelihood

Index	Description	Probability
1	Very unlikely	0.0001
2	Unlikely	0.001
3	Occasional	0.01
4	Likely	0.1
5	Very likely	1

Qualitative risk evaluation

Once the user has defined the likelihood and consequence indices from the previous tables, a first qualitative estimation of the initial risk can be done through risk matrices. The indices of consequence and likelihood of each event and category of consequence are multiplied according to the definition of risk of Equation 4.1 and the risk expressed in a range from 1 to 25. From these values and from the graphical representation in the risk matrix, the most demanding hazards can be identified.

On the basis of the project-depending risk acceptance criteria, four levels of risk can be defined and identified with colors on the risk matrix: negligible, acceptable, unacceptable, unwanted.

Event tree

Since many of the hazardous events in the risk register are somehow linked by cause-consequence relationships, an event tree has been developed to connect all the hazards and to permit the quantitative evaluation of the probability of each hazard. All the events have been connected to the initial event of water inflow, that is level 1 of the tree. A total of six levels have been identified. In some cases, the same hazard is the final outcome of more than one branch of the tree. In these situation the probability is the sum of the probability obtained in each branch.

Another event tree has been developed for the issues related to the presence of groundwater not directly connected to water inflow, such as buoyancy and dam effect. However, in this case the waterproofing systems can hardly change the initial risk and only specific designed solutions are effective.

Knowing the probability $P(A)$ of the event of level n, the probability of its outcomes at level n+1 can be computed if the conditional probability is defined. The conditional probability $P(B|A)$ is defined as the probability that B occurs when A occurs. In the model this is a value that depends on the relationship between the different hazards and has to be estimated or hypnotized by the designer on the base of experience and specific evaluations. Once this value is assessed, the probability of B in the level n+1 can be computed as

$$P(B) = P(A)P(B|A) \tag{4.2}$$

In this way the probability of all the events in the event tree can be computed from the combined probabilities.

It is clear that the definition of the input values of the probability in the event tree is the key and difficult aspect of this approach. At the state of the art it is not possible to assess a clear and rigorous relation among all the events. Therefore, the evaluation of the probability can be only based on the experience. Moreover, many of these relations depend on project-specific conditions (hydrogeological environment, construction technique, final use of the underground structure). Consequently, it is of overwhelming importance that the values of probability are defined in each case by a multidisciplinary panel of experts (Guglielmetti et al., 2008).

In a rigorous way, the developed scheme is not exactly an event tree, because some events give more than one outcome that are not reciprocally excluding. For this reason the sum of the probabilities of the branches may be higher than the probability of the original event.

Quantitative risk evaluation

The use of the event tree permits a quantitative evaluation of the likelihood, that coupled to a quantitative definition of the consequences, allows the computation of the risk. If the probability is not directly defined by the user but only the indices of likelihood of Table 4.2 are assessed, these indices are converted in a probability using the correlation in that Table.

For estimating quantitatively the consequences a cost value has been associated to the description of the 5 level of each category of consequence. For some category (i.e. damage or economic loss to third parties and to the owner) the value is already expressed as a cost in Table 4.1. For the injury to third parties, the consequence is expressed as a number of fatalities, serious and minor injuries. These can be converted in economic value using the statistical data produced by the insurance agencies or public administrations. In this model the data are those reported by Italian Ministry of Infrastructures and Transport (Ministero delle Infrastrutture e dei Trasporti, 2011) from the analysis of the cost of injuries on the Italian road network (Table 4.3).

Table 4.3: Cost for injuries from Italian Ministry of Infrastructures and Transport (Ministero delle Infrastrutture e dei Trasporti, 2011)

	Cost per unit (€)
Fatality	1500000
Serious injury	197000
Minor injury	17000

The value of an harm to the environment is only assessable on the basis of project specific economical evaluations of the areas nearby the underground structure. The value of the environment has to be defined considering the economic value of the area, the loss of tourist or agricultural incomes, the value of the natural resources (e.g. clean water), the cost of reclamation works. For each level of consequence a percentage of the estimated value will be considered.

The cost of one hour of disruption is the parameter used to convert the disruption category. This value is strictly related to the project and to the use of the underground structure: a national road tunnel can have null or very low disruption cost, while for metro lines, highways or railways disruption is very expensive due to the loss of tolls or economic incomes and for the cost of substitutive services. For hydraulic tunnels the disruption is directly linked to the stop of the plant, implying very high costs. As an example, the disruption for 1 month during summer of one way of the Milan metro line between two station has been estimated in one million Euro, while for the Brenner Base Tunnel the same value is the estimate for one hour of disruption (Dammyr et al., 2014).

Some specific cost can be inserted to give a more detailed value for some hazards, such as the value of surrounding building and the value of the electric plants in the tunnel, that are usually known with a reasonable precision at the begin of the design.

Once all the consequences are estimated as a cost, the risk is computed considering the probability of each hazard and its cost. In order to obtain not only the mean value of the risk expressed as a cost, but its whole distribution of probability the Monte Carlo method is used. The input variables are the consequences, that are described with simple distributions of probability:

- for the levels of consequences defined only by one value (i.e. some of the values of the injury to third parties) the probability is constant;
- for the levels of consequences defined by a range (e.g. 0.3–3 Million Euro) a uniform probability in the range is used;
- for the levels of consequences defined only by a lower limit (e.g. >3 million Euro) an exponential expression of the probability is used in order to consider, but limit, the extreme cases.

In each step of iteration the following computations are executed:

- for each level of the event tree a random value between 0 and 1 is extracted: if the probability assigned to that event is equal or higher than the random number the event occurs and the following level is computed. Otherwise, the event does not occur and consequently all the derived events do not occur. At the end of the computation to all the hazardous events in the event tree is assigned an boolean occurrence index (1 or 0) defining which are occurring (1) and which are not (0);
- for each consequence category, on the basis of the level of consequence assigned by the user and of the defined probability distributions, a random value is extracted from the probability distribution and assigned to the consequence;
- the occurrence index of each hazard is multiplied by the corresponding consequences: the once corresponding to event not occurring are zeroed;
- all the remaining costs are summed giving the value of the risk.

The procedure is iterated, obtaining several values of cost that give the probability distribution of the risk.

Mitigation measures effect

At this stage the initial risk has been evaluated qualitatively and/or quantitatively. If this value does not fulfil the risk acceptance criteria, a risk treatment strategy has to be defined, that, in the case of waterproofing of tunnels on the long term, consists mainly in mitigation measures. These mitigation measures (i.e.

waterproofing technologies and water management solutions) do not impact on the consequences of the hazards but only on the likelihood of water inflow.

Therefore, the evaluation of the effect of a technical solution implies the evaluation of how much that solution is able to reduce the likelihood of water inflow. This assessment is achievable using a fault tree. For each solution a fault tree can be defined considering all the possible events that can induce the failure of the waterproofing and the consequent water inflow. Giving a likelihood value to the possible causes of ineffectiveness of the technical solution, the combined probability of water inflow can be assessed. This likelihood is then used as input value of the event tree in the first level.

Aiming to perform a long-term evaluation, the possibility, availability and efficiency of repair of damages during the operational life of the work should be considered. This is possible reducing the likelihood of water inflow obtained from the fault tree taking into account the effectiveness of the repair. Moreover, in order to perform a cost-benefit evaluation, the cost of the mitigation measure and of the potential repair or maintenance works has to be computed. Figure 4.3 reports the flow-chart of the mitigation measure evaluation considering both the repair works and the cost of the measure.

The scheme is used into each Monte Carlo iteration step as follow:

- the probability of water inflow is computed through the fault tree and the cost of the mitigation measure is added at the investment value;

- a random value between 0 and 1 is extracted: if the probability of water inflow is lower than the random number the failure does not occur and a probability of water inflow equal to 0 is inserted in the first level of the event tree. Otherwise, the mitigation measure is not effective. If repair is not possible, the water inflow value in the event tree is set to the original one (the mitigation measure does not have any effect);

- if repair is possible, its effectiveness is considered and the probability of failure after repair is computed by multiplying the effectiveness and the probability of failure of the mitigation measure. Moreover, the cost of repair is added to the investment value;

- a random value between 0 and 1 is extracted: if the probability of failure after repair is lower than the random number the failure does not occur and a probability of water inflow equal to 0 is inserted in the first level of the event tree. Otherwise, the repair is not effective and the water inflow value in the event tree is set to the original one (the mitigation measure does not have any effect);

- all the steps described above for the risk evaluation are computed: event tree computation, consequences estimation and risk evaluation.

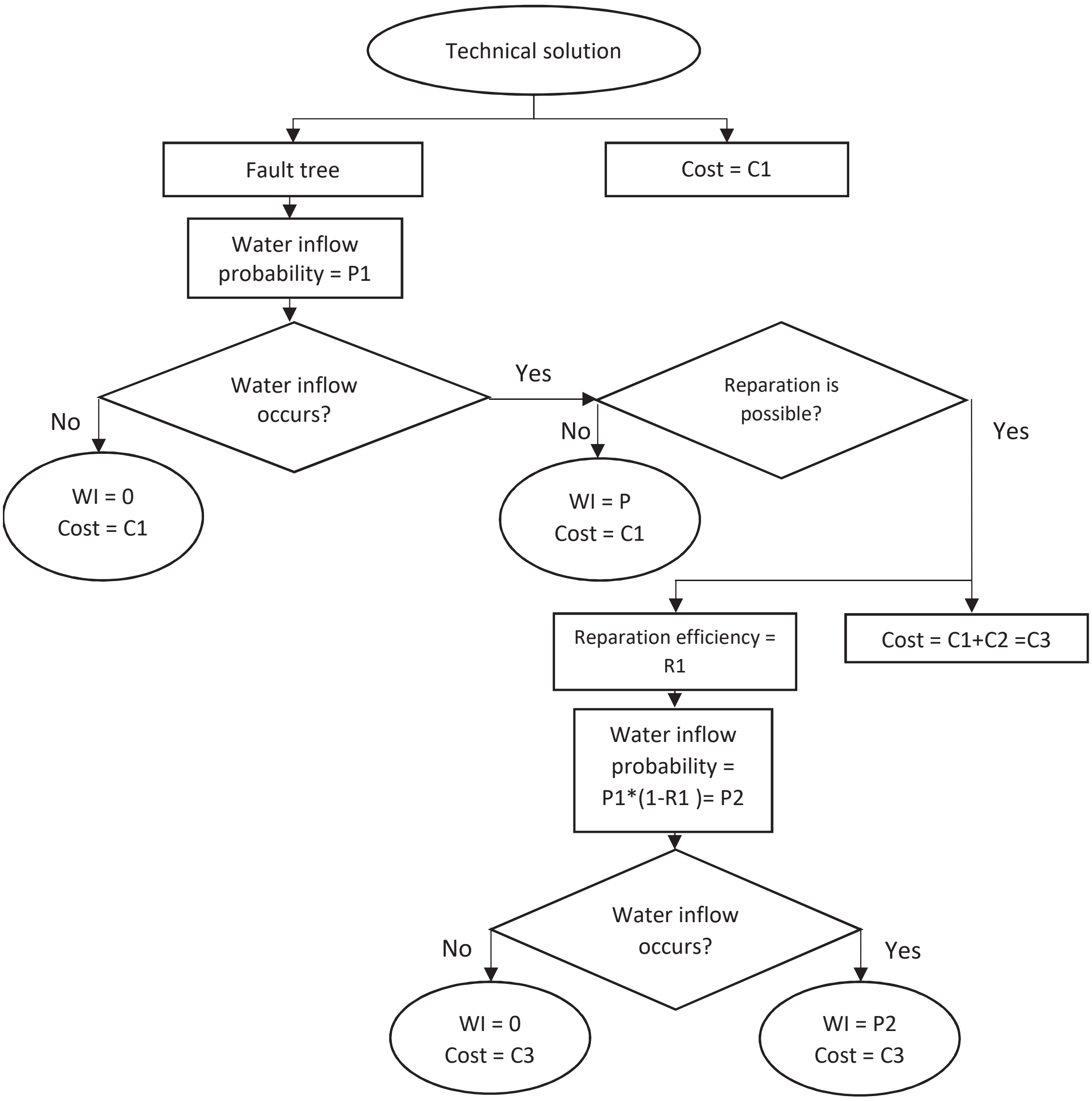


Figure 4.3: Flow-chart for taking into account the mitigation measure

The results are several couples of values of residual risk and investment cost.

Mitigation measures considered

As analysed in Chapter 3, the technical solutions available for dealing with water interaction with underground structures are many. Since this tool is focused on the long-term operation, only those solutions effective during the operation and for a long term are considered (i.e. injections, waterproofing membrane).

Injections are used during construction but can be considered still effective on the long term depending on the execution and technology. The effect of water inflow reduction can diminish with time, therefore, a long-term efficiency value, ranging from 0 to 1, has been considered. This value describes the likelihood that, in the long term, the injections are suitable to reduce the water inflow. It is greatly dependent on the type of material injected. As already stated in Chapter 3, cement based grouts have result to be still effective after years, while chemical grouts have to be considered temporary. Moreover, the lifespan of the work has to be compared to the estimated life of the injection to asses if it is to be considered in the long-term waterproofing.

Moreover, the effectiveness of injections in stopping water inflows is a function of the quality of the design and execution of the intervention, that is considered as a parameter in the computation.

Waterproofing membranes are considered with all the possible configurations described in Chapter 3: single layer, injectable double layer and testable double layer. The fault tree considers the issues related to welding quality and execution and those related to substrate, casting and installation phases.

The quality of the manpower is taken into account to reduce the probability of failure of welds. The testing and quality checking of the welds are considered reducing the probability of their failure and considering it zero when all the welds are tested.

The quality of the substrate and the presence of a protection layer are taken into account reducing the corresponding probabilities of damages to the membrane. The presence of a second layer halves the probability of water inflow. The possibility of repair works through injections is considered as described above while the possibility of vacuum testing the membranes after their installation zeros the failure probability due to damage before the test.

Outputs analysis

The results of the proposed procedure can be analysed in different ways:

- asses the distribution of probability of the initial risk and establish the potential need of mitigation measures;

- evaluate the effectiveness of a mitigation measure in terms of reduction of the initial risk by comparing it to the residual one and perform a cost-benefit evaluation between the cost of installation and repair during operation and the risk related costs;

- compare different mitigation measures technologies in terms of efficiency and of long-term cost-benefit evaluation.

The last consideration is the most relevant for waterproofing solutions of underground structures. In effects, the evaluation on the long term of the cost of different solutions can influence the choice of the technology: the possibility of easy and relatively cheap repair works for some of the available solutions can reduce very much the operational costs in terms of maintenance and disruption times due to refurbishment works.

4.2.2 Interface and computational tool

The described procedure has been implemented in a Matlab script that performs the iterations and the computations. To permit a more easy and user friendly data input, a Visual basic Excel interface has been created. The output of the procedure are Matlab graphs and exports of the results of the computation in txt files.

4.2.3 Application case

The developed procedure has been tested simulating a possible project situation of a metro tunnel in urban area excavated by conventional tunnelling below watertable. The use of cement based injection in the construction phase is considered, with a long-term efficiency of 50%, in order to take into account possible errors in the design and execution of the intervention leading to water inflows. For the long term, waterproofing membranes are considered with a full round drained approach. Three different installation schemes are analysed:

- scheme 1: single layer waterproofing membrane, with compartmentalization, regulation layer and appropriate fixing elements. Welds are spot checked with channel pressure test;

- scheme 2: double layer waterproofing membrane,with protection layer and injection valves for repair during operation. All welds are tested with channel pressure test;

- scheme 3: double layer waterproofing membrane testable with vacuum system, with protection layer and injection valves for repair during operation. All welds are tested with channel pressure test.

Table 4.4: Effectiveness of the three schemes

	Effectiveness of the waterproofing system (%)	Probability of need of repair (%)	Residual probability of water inflow (%)
Scheme 1	87.820	not reparable	12.180
Scheme 2	88.981	11.019	1.653
Scheme 3	99.918	0.082	0.014

Table 4.5: Mean risk cost for the four simulated conditions

	Mean risk cost (€/m)
Without waterproofing	5139.90
Scheme 1	595.21
Scheme 2	441.61
Scheme 3	275.86

The cost of disruption has been evaluated at 2000 €/hour, while the injuries costs are those reported in Table 4.3. In an urban environment, in absence of relevant natural resources and landfills, the environment is estimated about 100000 €/ha. For the climatic position, the project is not subjected to ice formation risk, that is neglected in the event tree.

The computation is iterated 100000 times.

Outcomes

From the simulations the effectiveness of the three technical solution has been computed from the probability of water inflow after the installation. Moreover, the simulations give the value of probability of need of repair works during operation, when this is possible (i.e. Schemes 2 and 3). The results are summarized in Table 4.4.

The effectiveness increases with the augmentation of the quality of the waterproofing technology, with very high values for Scheme 3. Moreover, the possibility of repair potential damage further reduces the residual probability of water inflow for Schemes 2 and 3.

The mean risk value follows the trend of the effectiveness as reported in Table 4.5.

The reduction of the mean cost is not high and is lower than the difference in the initial investment for the waterproofing system. If the evaluation is limited only to this observation, the best solution can be the cheapest.

However, the long-term cost-benefit evaluation has to be computed considering also the cost and probability of potential repair works on the waterproofing systems.

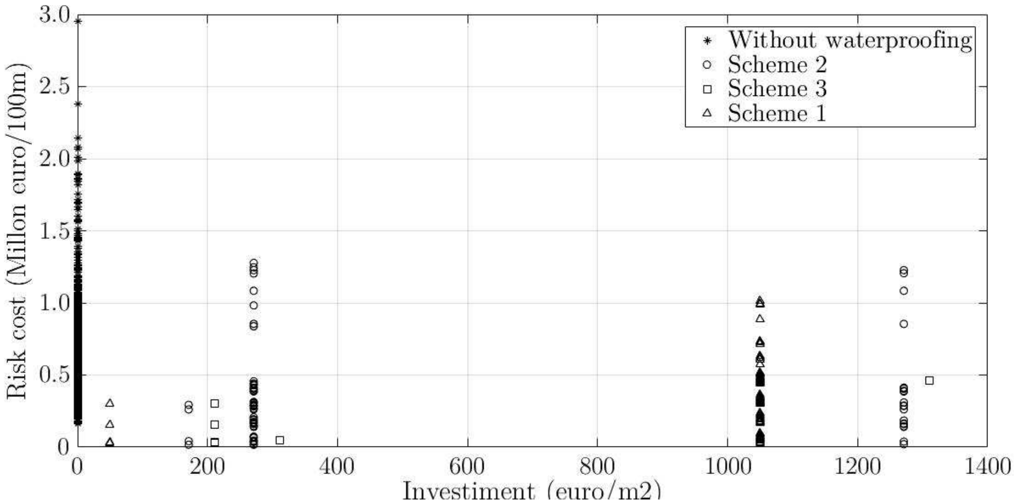


Figure 4.4: Cost-benefit comparison of the four simulated conditions

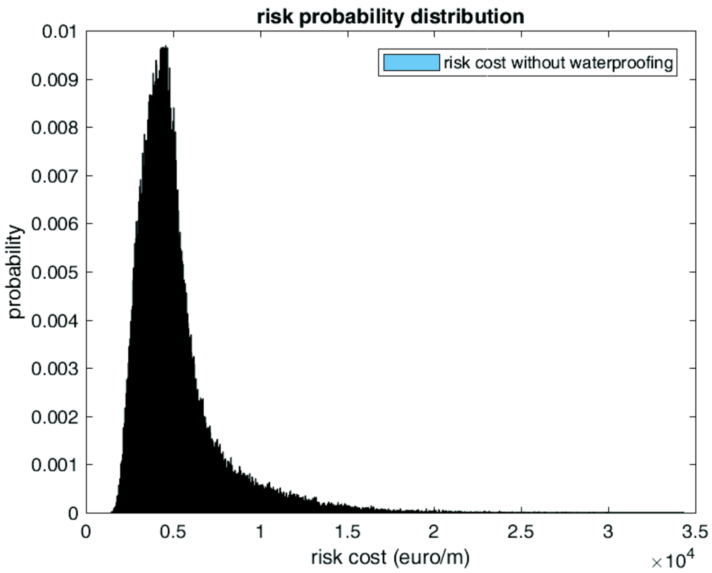


Figure 4.5: Probability distribution of the initial risk without waterproofing

Figure 4.4 reports the cost-benefit comparison of the four simulated conditions taking into account the repair of the waterproofing systems when water inflow occurs.

The case without waterproofing has obviously zero investment cost, but high values of the risk. The distribution of probability of this risk is reported in Figure 4.5. It is clear from this figure that the maximum risk has lower probability but that the mean risk is not enough to describe all the possible outcomes.

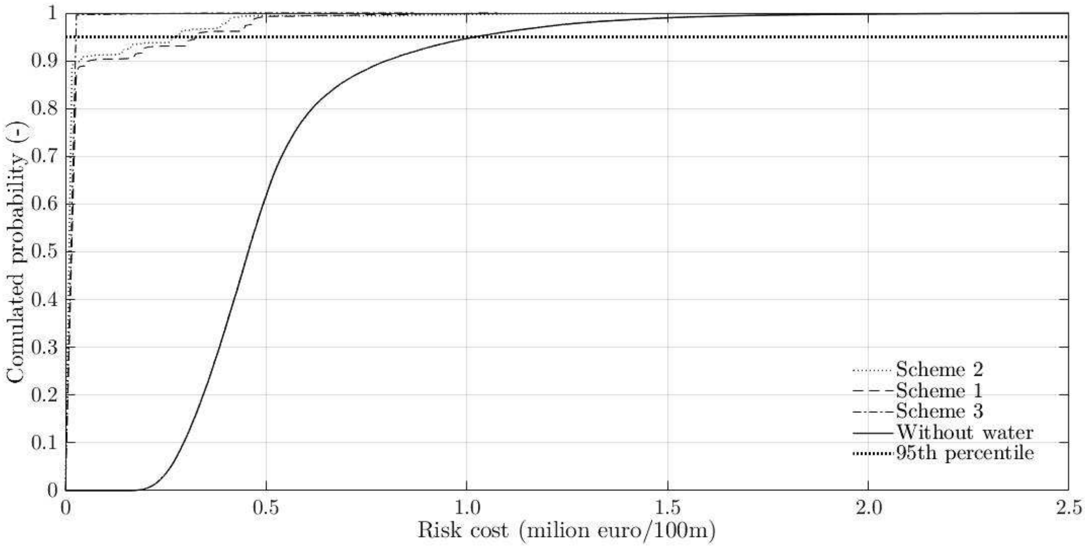


Figure 4.6: Cumulated probability distribution of the risk in the four simulated conditions

The initial cost of Scheme 1 is lower than the others, but, since it is not possible in this scheme to repair the waterproofing without invasive works on the concrete layer, the cost in case of water inflow is high and this situation has a probability of 12.18%. At the contrary, Schemes 2 and 3 permit to repair the waterproofing with lower costs and they require invasive repair works only when the first repair is not effective (that is in the 1.65% of cases for Scheme 2 and in the 0.014% of cases for Scheme 3).

Another way to analyse the outcomes of the simulation is to define the acceptable percentile and define the residual risk for that value. Figure 4.6 shows the cumulated probability of the four simulated conditions. If we define an acceptable limit at the 95^{th} percentile, the value of risk exceeding the threshold can be evaluated.

These considerations give more information to perform a better choice of the more convenient waterproofing solution. The choice has to be made taking into account the acceptable risk value assumed by the owner of the structure and the lifespan of the work.

4.3 Observations on the risk assessment procedure for waterproofing solution

Risk analysis proved to be a useful tool for the choice of the waterproofing solution. The developed procedure allows to take into account the cost of the solution along all the operation life of the infrastructure, permitting to consider the possibility of repair. This procedure computes the effectiveness of each waterproofing system and permits to compare it with those of different solutions. Moreover, it is possible to evaluate the risk correlated to each system on the basis of the project-based conditions (e.g. cost of disruption, environmental impact).

To better refine the results, the definitions of the probability of failure of each waterproofing system should be further studied, possibly with the analysis of the real data coming from on site tests on installed systems.

Furthermore, the reliability of the results of this method is strongly influenced by the assessment of the probability input values in the event tree. Therefore, it is of overwhelming importance to base such assessment on the opinion of a multidisciplinary panel of experts.

This tool can not directly give the evaluation of the best solution, because the choice has to be made on the basis of many aspects, such as the acceptable risk threshold that depends on many parameters that could be both technical and political.

Moreover, this method does not take into account the durability of the systems: the waterproofing solution are supposed to be effective for all the lifespan of the infrastructure. Therefore, the durability has to be assessed before, in order to have a realistic result.

Chapter 5

Assessment of durability of waterproofing systems

5.1 Assessment of durability

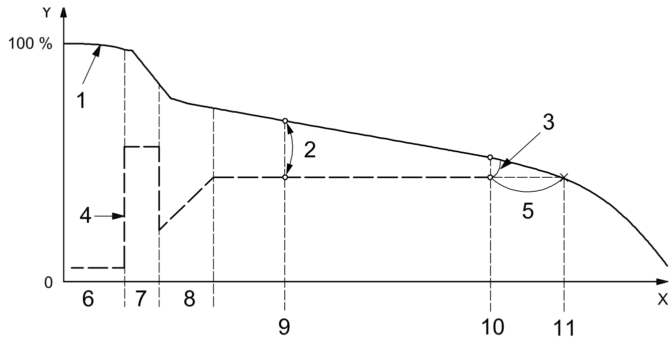
As already stated in Chapter 3, standard requirements for traffic and railways tunnels are nowadays very high, requiring dry or almost dry internal surface. Moreover, the lifespan of modern infrastructures is often of 100 years or more (e.g. Brenner Base Tunnel has been design for a lifespan of 200 years and Crossrail London for 120 years). Furthermore, when waterproofing systems are installed between the primary and final lining, it is not possible to perform any ordinary maintenance or substitution.

From all the previous considerations, it is clear that the durability of the materials used for waterproofing and of the whole waterproofing system is one of the key issues in order to avoid damage or unforeseen costs and disruptions.

For these reasons, designers need to verify if the chosen system is able to perform the requested function for all the needed time, or for an economically reasonable time before major refurbishment works have to be performed.

The conditions of acceptability have to be clearly assessed. This assessment relies on two evaluations: on one side the definition of the required properties (functional, mechanicals, physicals) of the system and of the single elements, on the other side the analysis of the degradation mechanisms of the materials and the evaluation of their available properties.

Required properties may be a design fixed value (i.e. constant along all the life of the structure) or can change during the life of the structure (Figure 5.1). This last situation can be related to different construction and operation phases, e.g. for a buried geosynthetic the UV resistance can be relevant during storage and transportation but not after installation, or the required resistance to dynamic loads can be higher during installation than during tunnel operation. Available properties usually decrease with time, due to the degradation of the material.



Key

X time

Y property of a geosynthetic, expressed as a percentage of its original value

1 available property

2 margin between required and available property at intermediate time

3 margin of safety at design life

4 required property

5 margin of safety between design life and time to failure

6 duration prior to installation (storage and transportation)

7 duration of installation

8 duration of further construction

9 intermediate time during normal use

10 design life

11 time to failure

Figure 5.1: Example of available and required properties during the life phases of a material (from ISO/TS 13434 (2008))

From the comparison of available and required properties, the end-of-life time of the material can be assessed. Moreover, it is possible to compute a safety factor at the design life time or at any time as the ratio between available and required properties. Since waterproofing is not a single element but a system, this assessment has to be performed both on each single element and on the system and the end-of-life is the lowest of them.

To perform the assessment of durability it is necessary to:

- define design life of the project;
- define functions of the element (or system) considered and loads and constrains acting on it;
- quantify the required properties;
- evaluate the available properties and how they change with time.

In the following this procedure will be applied to waterproofing systems, starting with the definition of actions on them during the whole design life of the structure (i.e. for tunnels 100 years or more) and the definition of required properties. After that, the time-dependent durability of the material is analysed, with particular focus on the degradation of plasticized polyvinyl chloride (PVC-P) geomembranes, which are the most used for tunnel waterproofing.

5.2 Design functions of the elements of waterproofing system

The functions required to the different layers of the waterproofing system are defined in the following according to EN ISO 10318-1 (2015).

5.2.1 Waterproof geomembrane

The aim of the waterproofing geomembrane is to create a water impervious barrier. This layer does not have any structural function during the operational life of the tunnel. Therefore, the required properties are only watertightness and continuity.

Watertightness is guaranteed by the choice of the correct material (polymers, bitumen, bentonite composites). The continuity has to be created thought correct junctions (e.g. welding) and conserved during installation, casting and operation.

The required mechanical properties of the membrane aim to preserve the continuity of the membrane during storage, transportation, installation and casting, to avoid puncture damage during the design life and to assure the membrane to withstand the traction loads that may act on it.

5.2.2 Regularization and protection layer

The function of these layers is to protect the waterproofing layer from accidental jobsite damage or unevenness of substrate and concrete. The main required property is puncture resistance particularly during the installation phase but also during operation. Puncture resistance is a function of the material, of its thickness and production.

5.2.3 Drainage layer and pipes

The drainage layer and pipes have to guarantee the drainage of the foreseen flow rate of groundwater without overpressure around the tunnel and on the linings. This function is influenced by the kind of water and soil, the material, the thickness, the opening of geogrid or geotextile and the diameter of geopipes.

5.3 Actions on the waterproofing system during installation

5.3.1 Storage on the jobsite

The materials composing the waterproofing systems are sensible to environmental conditions and weathering: PVC, PP and PE are sensible to UV rays and heat, bentonite layers and strips are sensitive to humidity. Moreover, a wrong storage can induce evenness on the membranes, resulting in a more difficult installation phase.

Therefore, the storage of the materials on the jobsite should be in accordance with the suppliers' recommendations, storing the materials far from heating sources, and not in contact with sun rays or water (depending on the kind of material used).

No mechanical requirements exist in this phase, but chemical stability and resistance in the storage environment. If the storage is done in adequate non-aggressive environments (far from sun light, heat, humidity), the required properties are very low.

5.3.2 Installation

During installation the membrane is subjected only to his own weight. The membrane is welded or bonded to the fixing elements and the operational limits are the maximum load at the fixing and the allowed deflection of the membrane.

The strength of the connection between the fixing element and the membrane can be tested with laboratory tensile tests. When strips of the same material bolted to the substrate are used to fix the membrane, the maximum strength allowable is that of any of the welds, therefore at least as high as that of the membrane if the weld is correctly done. Therefore, potential high loads on the waterproofing layer can induce both the failure of the fixing and the damage of the membrane.

If specifically designed fixing elements are used, the hierarchy of failure principle is applied: the fixing element is designed to fail before the membrane. In this way the waterproofing layer is protected from damage due to traction or dead loads during installation, that cause the failure of the fastener and the release of the membrane from the fixing element.

The main aim of the fixing elements is to keep the membrane in position during installation and casting: therefore, the deflection should be small enough to avoid any deformation of the membrane during casting.

Furthermore, the installation of the membrane should avoid that the material is kept in tension after been fixed because tension can facilitate damages due to punctual loads after installation and during casting.

Considering a density of the membrane ranging between 950–1500 kg/m^3 (i.e. the commercial rang for HDPE and PVC-P membranes) and a thickness of 2 mm, the dead load of the membrane is 19–30 N/m^2. The dead load of the protection layer, considered totally applied on the membrane for safe, is of about 5 N/m^2. The resulting maximum total load of 35 N/m^2 is low compared to the resistance of fixing elements, also considering only one fixing element per meter.

5.3.3 Welds

In many cases the waterproofing materials are jointed by welding. If not correctly done, the welds can cause damage to the membrane, due to too high temperature or too slow speed of advancement of the welding machine. The burning of the membrane during installation is an irreversible damage, that can only be fixed welding a patch on the damaged membrane. Wrong welds can be avoided if specialized manpower and specific tools are used, setting temperature and speed of welding each day on the basis of the environmental conditions.

In polymeric materials, antioxidants are added to reduce the sensibility to heat. The presence of filler in PVC-P further reduces the sensibility to burning compared to translucid membranes: bigger attention has to be paid when welding these membranes.

Furthermore, care have to be paid when welding different materials: the glass transition temperature of the materials have to superimpose to allow a correct bonding, that is not the case for many polymers. Therefore, it is always better to use geomembranes and accessory elements (e.g. fixing elements, waterstops) of the same material.

5.3.4 Static and dynamic punctual load and jobsite traffic

As already stated in Chapter 3, one of the tricky phases for waterproofing membranes effectiveness is between installation and casting. In this phase several random static and dynamic loads can act on the membrane: jobsite traffic, accidental fall of tools and machineries, gravel and soil coverage, rebars installation, possible sparks due to rebars cutting or welding, etc.

The possible damages can be divided as:

- static puncture, due to operation loads acting on irregular substrate or in presence of stones, rebars or other edged elements;
- dynamic punching, due to the fall of tools or rebars installation. The action on the membrane is strictly function of the speed of the impact, of the kind of object and of the hardness of the substrate;
- quasi-static punching, due to jobsite traffic on the waterproofing before final lining casting.

These loads can create holes in the waterproofing geomembrane, thus affecting continuity and consequently the watertightness. But also actions inducing a reduction of the thickness of the geomembrane, without a complete perforation, compromise the effectiveness of the waterproofing: in case of deformation the thinner section will result in higher stresses and more probable failure. In this case the damage can occur only if the operation pressure and strains are sufficiently high.

One of the main sources of damage to the geomembrane in this phase is the dynamic punching due to tools and rebars but these loads are hard to be quantified because they are strongly random. Moreover, rebars can also act as a static load on the geomembrane.

The effect of static puncture due to irregular substrate is negligible in this phase because very low loads press the geomembrane on the substrate. This issues will be better analysed in the following about the casting and operation loads.

Touze-Foltz et al. (2008) summarize the results of several studies on damages on geomembrane liners used for landfills and mining applications. The authors assess that an average value of damages on a geomembrane at the end of the installation phase can be about 1–5 defects/ha when a good quality assurance is performed. The quantity of defects decreases with the increase of covered surface because bigger areas have proportionally less geometrical complex point, less hand made seams and a stricter quality control system. Moreover, Peggs (2003) reports that membrane installation impacts for the 24% of the defects and heavy equipments for the 16% during covering.

These studies are not directly developed for tunnels but for landfills, where the installation procedure is different. However, the reported values can be considered as a general indication also for the case of tunnel waterproofing.

Benneton (2008) tested the effect of soil coverage and jobsite traffic damage on waterproofing membrane considering different support soils, coverage soils, waterproofing materials (PVC, HDPE, PP Bitumen, EPDM) and different specific weight of protection geotextile (300–1200 g/m^2). Those tests allowed to define a damaging index for the different conditions. However, the author concludes that the huge range of possible combinations of different materials, substrate, thickness, does not permit to establish a general evaluation of the possible damage due to installation. It is worth to be noted that traffic load on the waterproofing system concerns only cut-and-cover tunnels and underground boxes, that are covered by soil and crushed rocks after installation. Mahuet (2005a) proposes a classification of the suggested protection layers for these conditions depending on the aggressivity of fill soil. The considered design parameter is the result of dynamic impact test on the waterproofing system. The protection system is composed by a geotextile on both sides and possibly by a protection geomembrane on the external side.

The ability of geomembranes to resist to static and dynamic loads can be analysed indirectly with the standardized test on dynamic and static punching and several indentation tests have been developed to simulate these conditions (Benneton, 2008; EN ISO 12236, 2006; EN ISO 13433, 2006). However, none of these tests can be directly related to the real actions acting on the membrane. The best solution to handle these issues is to try to avoid or limit as much as possible these loads, with an accurate installation phase of the rebars and good quality and instruction of the manpower. Moreover, the use of a protection layer of the same material of the geomembrane further reduces the probability of damage of the waterproof geomembrane, increasing the thickness to be perforated. This is particularly relevant for invert waterproofing, where the risk of punching is obviously higher. EN ISO 13719 (2016) proposes an index test to determine the long-term protection of geosynthetics barriers under static loads.

In conclusion, the requested properties for the waterproofing system to resist static and dynamic punctual load during installation are strictly dependent on the whole system (protection layer, substrate, separation layer), on the manpower care during the installation and on some mechanical properties of the material itself such as thickness, hardness, flexibility. Even if requirements exists for the waterproofing geomembrane, the most important elements are the geotextile and the protection layer, that have to guarantee the required performances. If they are correctly designed, the geomembrane should not be required for any property in this phase.

5.3.5 Fire on the jobsite

Since the material used for waterproofing systems are often sensible to fire, fire in the tunnel can be a serious issues until the final lining is cast and waterproofing membranes covered by concrete. During construction the fire can be started by incorrect use of tools for welding (e.g. oxyacetylene torches) or from random errors of manpower. Moreover, the fire can start in some accidental fire in site plants. Mahuet (2010) reports that in many cases the fire during construction starts on the geotextile layer, particularly in presence of sparks associated to metal cutting.

The response to fire is strictly depending on the material and therefore self-extinguishing materials are the only possible choice. Fire resistance has to be determined according to EN 13501 (2007) and the production of smokes and toxic fumes has to be avoided.

During the storage phase, the problem can be limited reducing the quantity of geomembrane stored in the tunnel to the one needed for one day. When the membrane is already installed, the maximum area covered by geomembrane has to be limited. For class E materials, 2500 m^2 is the limit suggested by Mahuet (2010).

Moreover, the combustion of those materials can produce smoke (e.g. white smoke from PVC-P) and toxic gasses (e.g. CO, CO_2, HCl from PVC-P) that can cause problems for the safety of the jobsite and for the health of workers.

Table 5.1: Required fire resistance classes for waterproofing material according to Mahuet (2010)

Material	Fire resistance class
Plasticized polyvinyl chloride	E
High density polyethylene	E
Polypropylene	E
Polyester	E
Geotextile	D
Bitumen	F
Bentonite	B

5.4 Actions on the waterproofing system during casting

The fresh concrete is cast using a movable framework at the intrados and using the membrane (or the protection layer if installed) as the extrados boundary. Therefore, the interaction between the fresh concrete and the membranes has to be considered.

5.4.1 Concrete hydration temperature

During hydration, concrete develops heat due to exothermic reactions and the warm concrete is directly in contact with the waterproofing membrane.

To evaluate the temperature reached during casting the main parameter is the heat of hydration of cement, q_t, expressed as kJ/kg. In adiabatic conditions the variation of temperature, $\triangle T_{ad}$ due to hydration can be computed as

$$\triangle T_{ad} = \frac{q_t c}{\gamma \rho} \tag{5.1}$$

where c is the mass of cement, γ the density of concrete and ρ the specific heat.

This heat can produce alterations in the geomembrane due to dimensional changes (i.e. shrinkage in the longitudinal direction and extension in the transversal one).

Numerical simulation of heat diffusion

To compute the temperature on the PVC layer due to hydration of the concrete, a numerical simulation has been performed through a numerical model.

The hypotheses used in the model are:

- the heat is transmitted by conduction;

- the diffusion of heat is only in the direction of the thickness of the lining because thickness is much smaller than the other 2 dimensions;
- thermal conductivity is constant;
- there is no variation of heat of hydration with temperature.

The heat conduction in one-dimension is ruled by the Fourier's equation

$$q = k\frac{\triangle T}{s} \tag{5.2}$$

where q is the flux of heat in the x direction per unit area and per unit time, k the material's conductivity, T the difference of temperature and s the thickness of the section.

The dispersion of energy ($\triangle E$) per unit area due to the difference of temperature is

$$\triangle E = \gamma s \rho \triangle T \tag{5.3}$$

where γ is the density of the material and ρ the specific heat.

Since

$$\triangle E = q\triangle t \tag{5.4}$$

with t the time, the dispersion of heat from the material per unit area per unit time due to the difference of temperature $\triangle T$ is

$$\triangle T_{out} = k\frac{\triangle T}{\gamma s^2 \rho}\triangle t \tag{5.5}$$

The geometry of the problem has been discretized in one-dimension elements to which the properties of the materials reported in Table 5.2 are assigned.

The parameters of concrete have been assumed from Eurocode 2 (EN 1992-1-2, 2004) for a temperature of 20°C. The lower limit of thermal conductivity of concrete has been used because it maximizes the result. The shotcrete parameters have been assumed equal to those of the concrete, the non-woven geotextile has been considered with two sets of parameters, those of air and those of water, to consider both the dry and the wet condition.

Time is discretized and the model computation iterated to simulate the diffusion phenomenon with time.

At the beginning of the simulation all elements have a temperature of 20°C. At the first time step, Equation 5.1 is computed for the concrete elements to obtain the increase of heat due to hydration, and a new temperature of each element is defined. At the following time step, Equation 5.5 is computed in all the elements considering the flux of heat coming from the two nearby elements due to the difference of

Table 5.2: Parameters of the material used for the simulation of heat diffusion during casting

Material	Thickness (m)	Conductivity (W/m K)	Specific heat (kJ/kg K)	Density (kg/m^3)
Rock	10	3	0.8	2700
Shotcrete	0.1	1.3	0.9	2400
Non-woven geotextile	0.002	0.026 0.60	1.005 4.18	250
PVC	0.002	0.16	1.25	1400
Concrete	0.5	1.3	0.9	2400
Steel	0.05	40	0.5	7800

Table 5.3: Cement parameters

Quantity of cement (kg/m^3)	Heat of hydration (kJ/kg)			
	1 day	3 days	7 days	28 days
400	200	350	400	440

temperature induced by hydration. The temperature of the element is redefined and the hydration of concrete computed. This process iterates for each time step.

The parameters of cement are reported in Table 5.3.

The thickness of the concrete slab, the quantity of cement and the heat of hydration considered are assumed to maximize the increase of temperature. The quantity of cement is high, considering that UNI 11417-1 (2012) reports as minimum quantity of cement 300 kg/m^3. The heat of hydration is assumed from Collepardi et al. (2009), with reference to cement CEM I 52.5 R (EN 197-1, 2011). The heat of hydration of different types of cement will result lower for the lower content of clinker.

Figure 5.2 reports the temperature on the waterproofing layer during casting and Figure 5.3 shows the duration of permanence of each temperature on the membrane.

From these graphs it is clear that the temperature of the waterproofing membrane never exceeds 45°C in the considered conditions. From the simulation, 45°C remain on the membrane for 54 hours, while 40°C for 92 hours.

Tests on PVC-P specimens

The effect of the temperature obtained from the numerical simulation has been tested on samples of PVC-P membrane. Two commercial waterproofing PVC-P

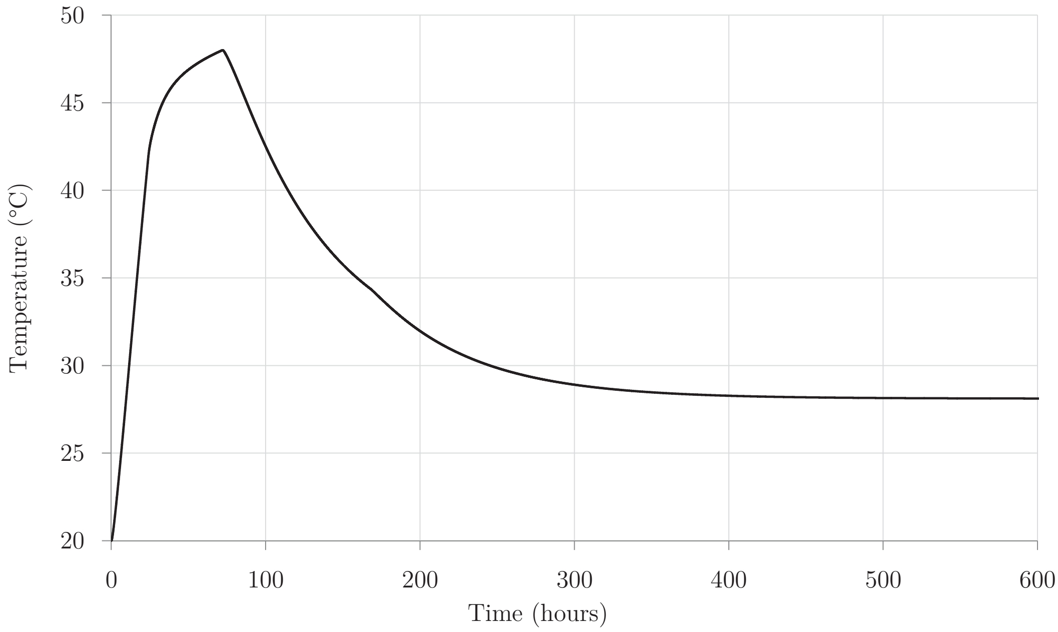


Figure 5.2: Temperature on the waterproofing membrane from casting

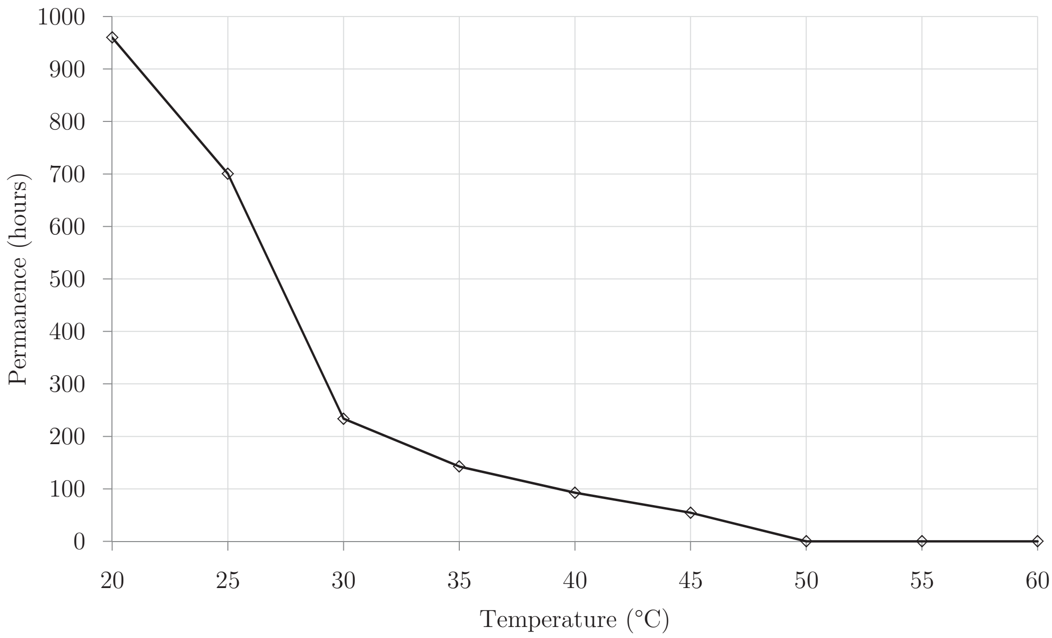


Figure 5.3: Permanence of temperature on the waterproofing membrane

membranes are used: a coloured membrane (here in after called material A) and a translucid one (here in after called material B). Both the membranes have a

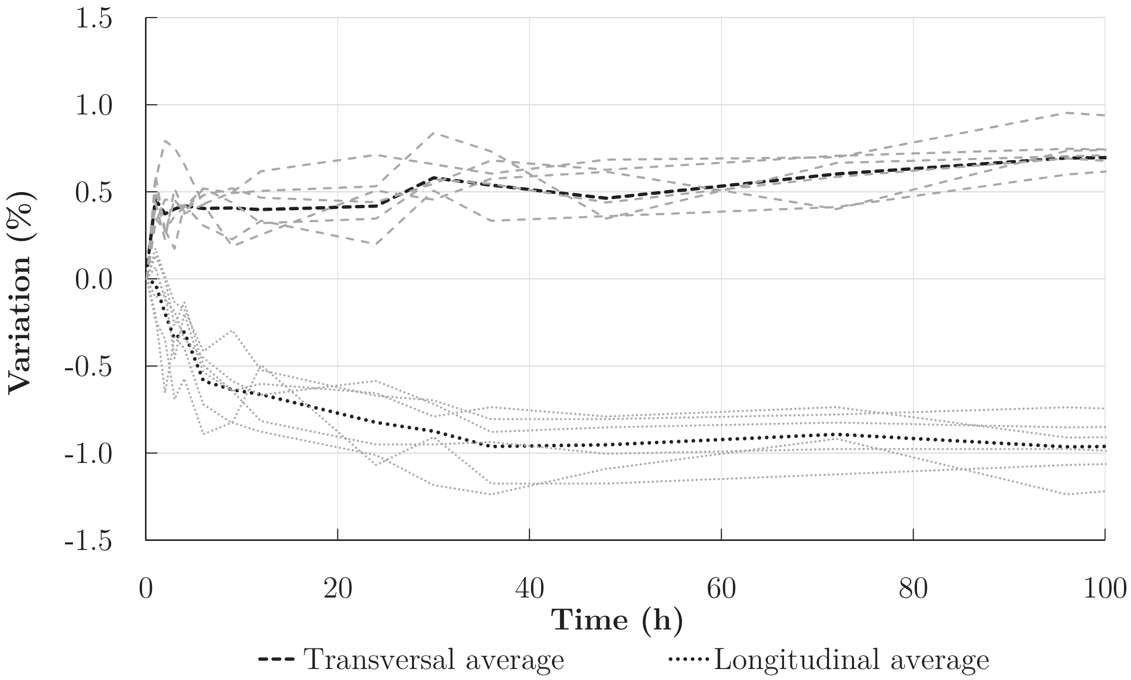


Figure 5.4: Dimension variation of material A at 45°C

thickness of 2 mm. Three specimens of 150x150 mm of both materials have been cut in the center of a roll, to avoid any possible interference due to the lateral part of the extruded material. The specimens have been stored in an oven with a fixed temperature for one week. The dimensions of the specimens are measured several times during the week with a calliper with a precision of 0.01 mm and the change in the dimension is evaluated.

Figures 5.4 and 5.5 report the results of these tests for the 6 specimens at 45°C.

The behaviour is different in the longitudinal and transversal direction of the roll. In effect, the extrusion of the membranes creates residual stresses in the material that are easily relaxed when the material is heated. The transversal direction expands while the longitudinal one shrinks. In the first hours the effect of the shrinkage is not so clear due to the concurrent expansion effect of the dilatation due to the temperature. However, since the thermal linear expansion coefficient of plasticized PVC is about 7.0 10^{-5} K^{-1}, its impact is low for this temperature ranges and it is relevant only at the beginning of the test.

After 100 hours the dimension are almost constant. The obtained values are reported in Table 5.4.

The shrinkage due to temperature increase can be estimated about 1% of the original dimension. Hypothesising that before casting the membrane is perfectly

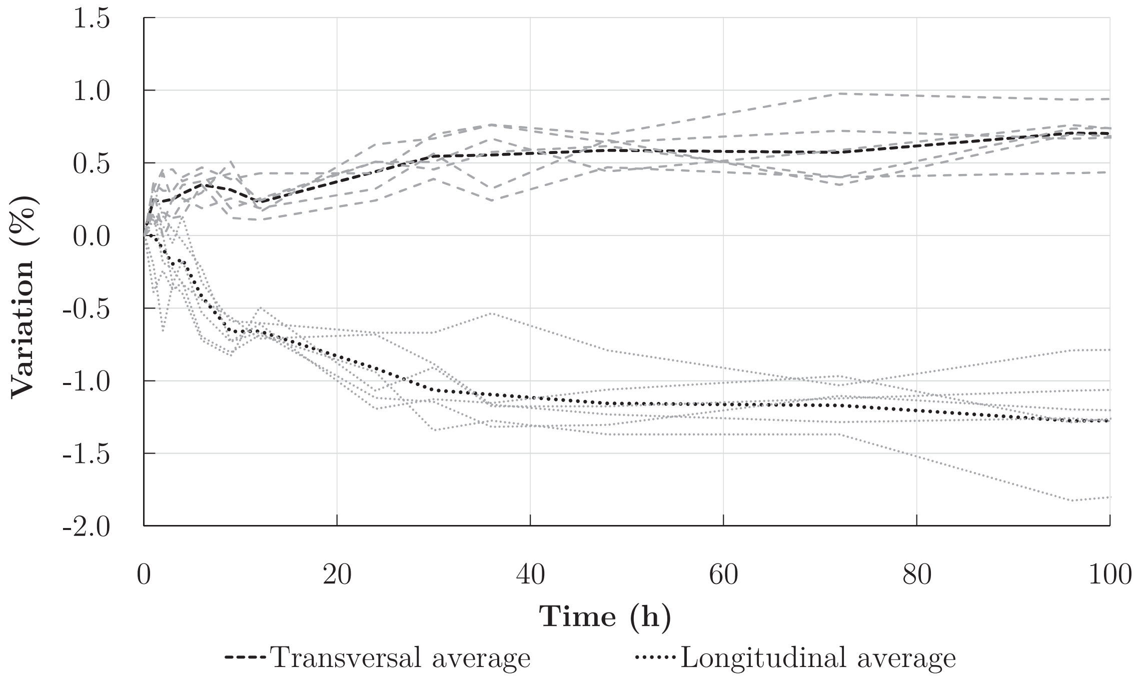


Figure 5.5: Dimension variation of material B at 45°C

Table 5.4: Values of variation of the dimension of the samples at 45°C

		Time (h)			
		0	24	48	96
Material A	Longitudinal variation (%)	0	-0.82	-0.95	-0.96
	Transversal variation (%)	0	0.42	0.46	0.69
Material B	Longitudinal variation (%)	0	-1.03	-1.16	-1.28
	Transversal variation (%)	0	0.44	0.59	0.70

fixed to the substrate without tension or excess of material, from the stress-strain plot of the tested materials (Figure 5.6) the stress related to such a deformation can be computed.

For the studied membranes the average stress due to the shrinkage is of about 1.8 N/mm^2. This value is very low, also considering that polymeric materials exhibit relaxation during life.

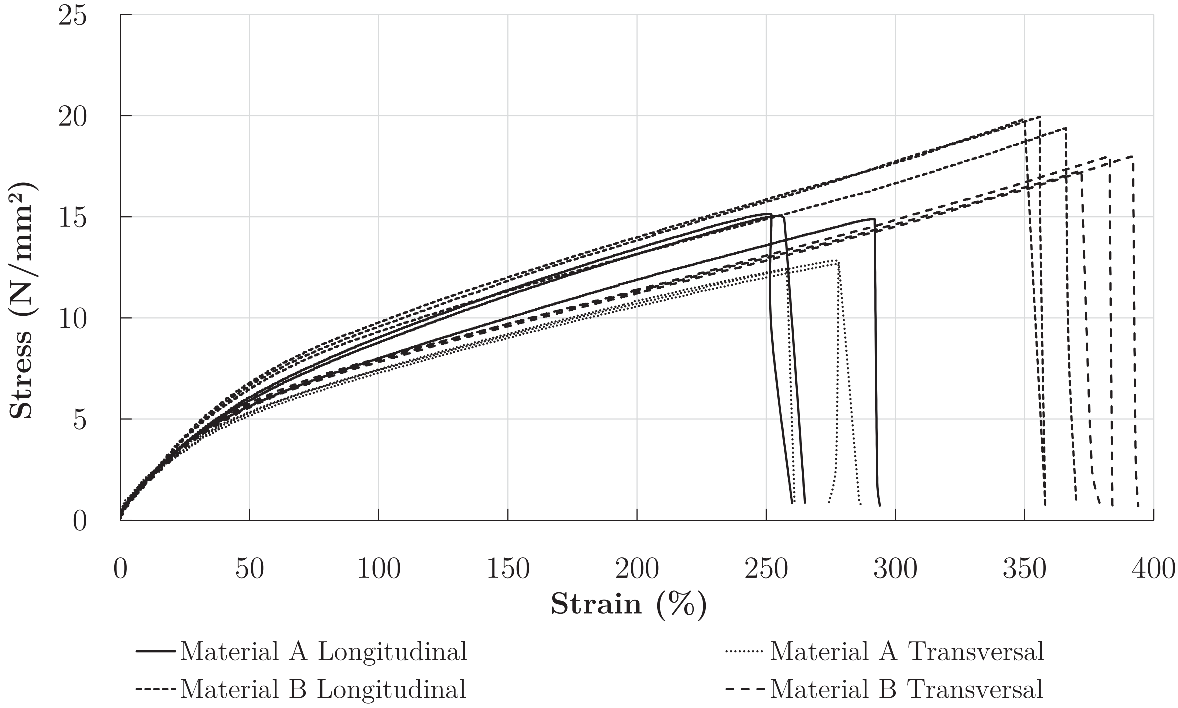


Figure 5.6: Stress-strain plot of material A and B

5.4.2 Casting pressure

During casting fresh concrete applies a pressure on the membrane, that acts as framework at the tunnel side. This pressure can induce damage on the membrane if the substrate is not smooth enough and if the regularization layer is not correctly designed.

Considering the weight of fresh concrete (25 kN/m^3), the consistency class, and the rate of placement the pressure applied by fresh concrete can be evaluated. EN 12812 (2008) refers to the methodology proposed by DIN 1812 (2010) for this evaluation: an hydrostatic value is used until a maximum characteristic pressure and then a constant pressure value is assumed, to consider the effect of setting. With these considerations, the pressure applied by fresh concrete on the waterproofing system in tunnels can be evaluated about 50–100 kPa.

Moreover, it is very important to prevent the load induced by the fluid concrete damaging or squeezing the pipe and thus affecting its long-term effectiveness.

Tests on fresh concrete pressure

To verify the effect of possible irregularity of the substrate on the membrane when fresh concrete applies pressure on it, a compression test has been performed.

The irregular substrate is simulated by a 50x50 mm concrete slab with crushed quartz gravel passing at the 4 mm sieve on the surface. The 100x100 mm specimen of PVC-P geomembrane is made of material A described in Paragraph 5.4.1. As regularization layer a 100x100 mm polypropylene 500 g/m^2 non-woven geotextile is used. The test specimen is composed by the following strata in order from the bottom to the top: a steel plate as rigid support, the PVC-P geomembrane, a thin deformable metallic layer, the regularization layer and the concrete slab. On the top of the concrete slab a 50x50 mm steel plate is applied in order to distribute the load. The thin metallic layer aims to register the deformations occurring on the surface of the geomembrane. To simulate the casting pressure a load of 100 kPa is applied for 24 hours.

To consider the possible influence of temperature, the test has been done both at room temperature (20°C) and in an oven at 45°C, to simulate the higher temperature on the membrane during casting, as derived in Paragraph 5.4.1.

After 24 hours, no relevant penetration occurs neither at 45°C nor at 20°C. The thin metallic layers only shows some little smooth deformation of about 0.1 mm. Therefore, the effect of the penetration of small gravel from the substrate is not relevant during casting. The increase of temperature due to hydration of cement has no appreciable effect on the penetration.

5.4.3 Folds formation

Flüeler et al. (2003) tested both PVC and PO membranes suitability for installation in real scale. They installed the membrane, cast and after curing removed the concrete slab. The authors report that vertical folds with a radius of curvature of up to 3 mm form in the membrane. This can be an hazardous condition for the effectiveness of the waterproofing system. In effect, the fold is a point of localized stresses and strains on the membrane higher than the nominal ones and can be therefore the cause of damage and interruption of the continuity, leading to water inflows.

The possible causes of this phenomenon are the waviness of the substrate, that induces more quantity of membrane to cover the surface, the number and position of the fixing elements, an installation with too loose membrane and the temperature of hydration. This last condition can cause an extension of the membrane, both due to thermal expansion and to stress relaxation, that produces an increasing of membrane surface compared to the surface to be covered. The thermal expansion factor for PVC-P is about 7 10^{-5} $K^{-}1$, that is very low and therefore, for the variation of temperatures considered (+25°C), thermal expansion is negligible. Stress relaxation induces expansion in the transversal direction up to 0.70% for the PVC-P membranes tested after 96 hours at 45°C, as reported in Paragraph 5.4.1. This means, for a 2 m large roll, an extension of 14 mm. This extension alone is not enough to justify the folds, but can contribute to the effect of other causes. Therefore, care has to be taken to the number of fixing elements and to the installation phase in order to avoid the formation of folds on the membrane.

5.5 Actions on the waterproofing system in operation

5.5.1 Hydraulic pressure

When the undrained waterproofing approach is used, the membrane is subjected to the pressure that water applies on the tunnel. Therefore, it has to withstand the pressure without any damage.

In drained tunnels, if the drainage system is not correctly working (due to incorrect design, high pressure, clogging), an hydraulic pressure can raise. Theoretically, in the drained approach the hydraulic pressure is withstood by the primary lining and is zeroed by the drainage layer, leaving the final lining without any additional load due to water. If the drainage is not working, the load is partially or completely transferred to the final lining. Too (2015) reports the numerical simulation of the impact of the reduction of the permeability of the drainage layer on the final lining of a tunnel. The maximum axial load and moment increase (up to 200 kNm for the moment) especially in the invert. This causes pressure on the waterproofing.

If the extrados of the final lining is perfectly smooth, the compression can never induce failure in the membrane in hydrostatic conditions because the material is confined. However, if any irregularity exists on the surface of the extrados of the final lining, this can induce local concentrated stresses and strains that can cause the formation of holes in the membrane. Since the final lining is directly cast on the membrane, its surface should be perfectly smooth, unless there are local defects (e.g. honey combs, voids, grains) or in the crown if the air bubble due to casting has not been filled.

5.5.2 Stresses between primary and final lining

During the operation life of the tunnel, the primary lining, that is often designed as a temporary support, will reduce its ability to withstand the load coming from the surrounding soil and it will fail. Consequently, this load will be transferred to the final lining through the waterproofing system that is in between the two layers. Therefore, compression and possibly shear stresses due to mutual sliding of the linings act on the geomembranes.

The compression induces the reduction of thickness of drainage layer, with consequent reduction of drainage capacity. Moreover, in presence of random unevenness of the substrate or of the final lining (e.g. honey combs, voids, grains) the

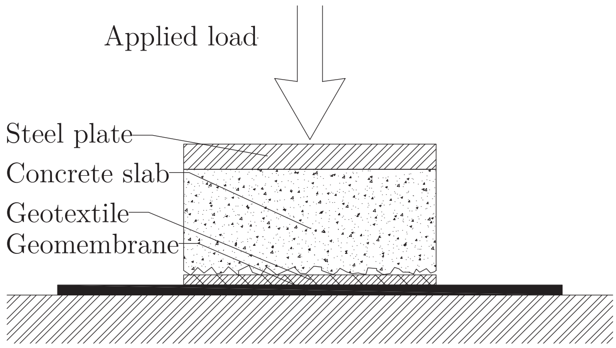


Figure 5.7: Scheme of the compression test

compression causes the reduction of the thickness of the waterproofing geomembrane, the concentration of stresses and the possible puncture.

The shear due to the mutual sliding of the linings causes tensile stresses on the membrane that can induce, in presence of irregularity and fixing elements, holes in the waterproofing system.

ÖBV (2015) suggests an acceptable value of compression ≤ 2.0 N/mm^2 on the membrane and assess that the waterproofing system should not transmit any shear stress. However, the effective compression and shear forces acting on the waterproofing system should be analysed on the basis of the specific project conditions (soil properties, lining design) and therefore can not be defined with a single general value.

Compression tests

Compression acts on the waterproofing system both during casting and during operation. The origin of compression can be the ground, the water or the fresh concrete. To simulate its effect on the membrane, compression tests have been performed.

The test consists in applying a constant load on the membrane for a fixed time simulating the strata of the waterproofing system. The same materials used in the tests described in Paragraph 5.4.2 have been used.

The layers are superimposed to simulate the composition of the waterproofing system. At the top a 50x50x5 mm steel plate is placed to distribute the load applied with weights. To reach higher pressures, the weights are loaded through a lever arm with a multiplication factor of 10. Between the concrete slab and the membrane (or regularization layer when used) a thin metallic layer is installed. The aim of this layer is to record the penetration shape of the concrete. Indeed, for its elastic behaviour PVC-P quickly recovers the original shape once the load is removed. Figure 5.7 shows the geometry of the test apparatus.

Three configurations have been analysed (Figure 5.8):

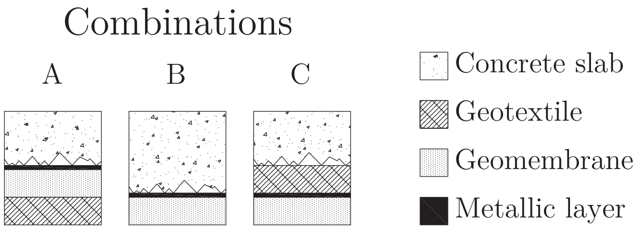


Figure 5.8: Scheme of the three tested combinations of the layers

- configuration A, where the strata, from the base to the top, are: geotextile, geomembrane, metallic layer and concrete slab. This simulates the effect of unevenness of the cast concrete on the membrane considering the presence of regularization layer;
- configuration B, where the geotextile layer is not included and the geomembrane is directly in contact with the steel base of the device. This configuration is considered to analyse the effect of geotextile;
- configuration C, where the strata, from the base to the top, are: geomembrane, metallic layer, geotextile and concrete slab. This simulates the effect of unevenness of the substrate on the membrane considering the presence of regularization layer.

The tests have been performed at 1, 2, 4 and 6 MPa of vertical pressure. Before starting the test, a pre-load of 100 kPa has been applied to the specimen in order to avoid vertical displacements due to the device setting. The vertical displacement has been measured with a digital test indicator with an accuracy of 0.01 mm after the application of the pre-load, after the application of the load and after 24 hours, in order to take into account long-term behaviour of PVC-P. On the tested specimens, the depth of penetration of the picks of the crushed quartz in the membrane is measured with a calliper immediately after the end of the test. The maximum penetration value and the mean of the ten higher values are evaluated. The tests have been performed at a temperature of 20±2°C.

Figures 5.9 and 5.10 show the values of mean and maximum penetration respectively. Figure 5.11 reports the vertical displacement measured on the concrete slab.

The penetration of configuration C is smaller than the other two and shows a lower ratio with the increase of the pressure. The penetration of combination A is the greatest one at the beginning. This is due to the higher deformability of the substrate composed by the geotextile, that permits higher penetration. However, as the pressure increases the penetration of configuration A tends to superimpose to that of the test without geotextile (configuration B). This is justified considering

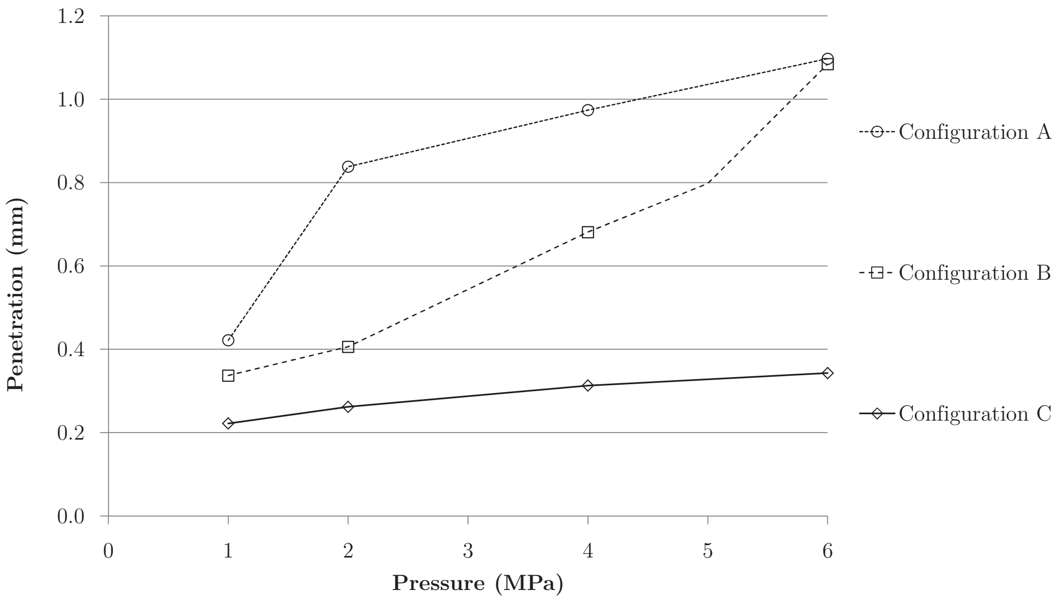


Figure 5.9: Mean penetration on the three configurations

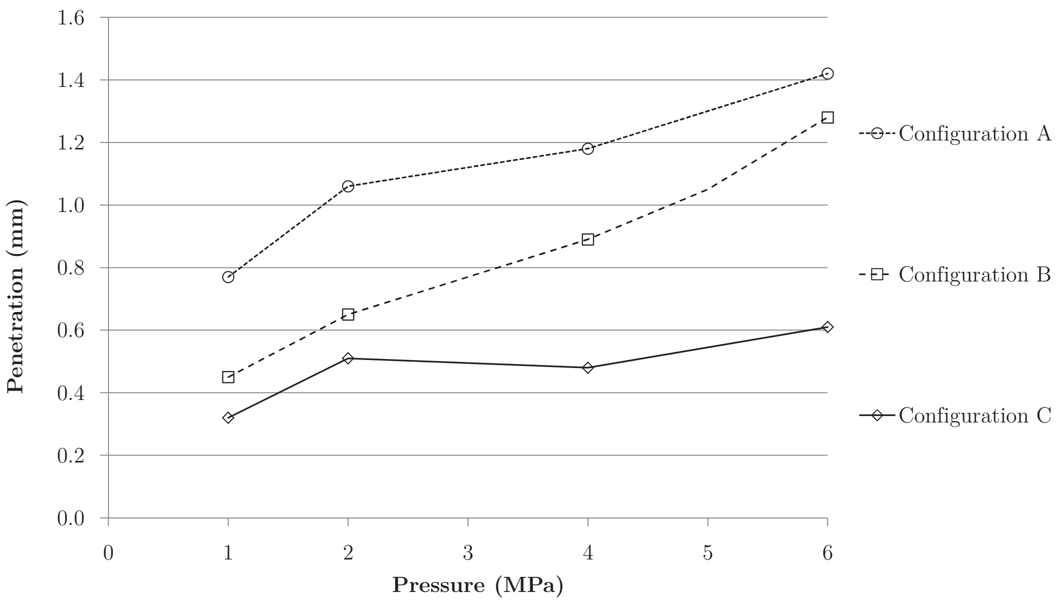


Figure 5.10: Maximum penetration on the three configurations

that for higher pressures the geotextile thickness and void ratio reduce and consequently it is no longer able to behave as a soft substrate. Therefore, the behaviour

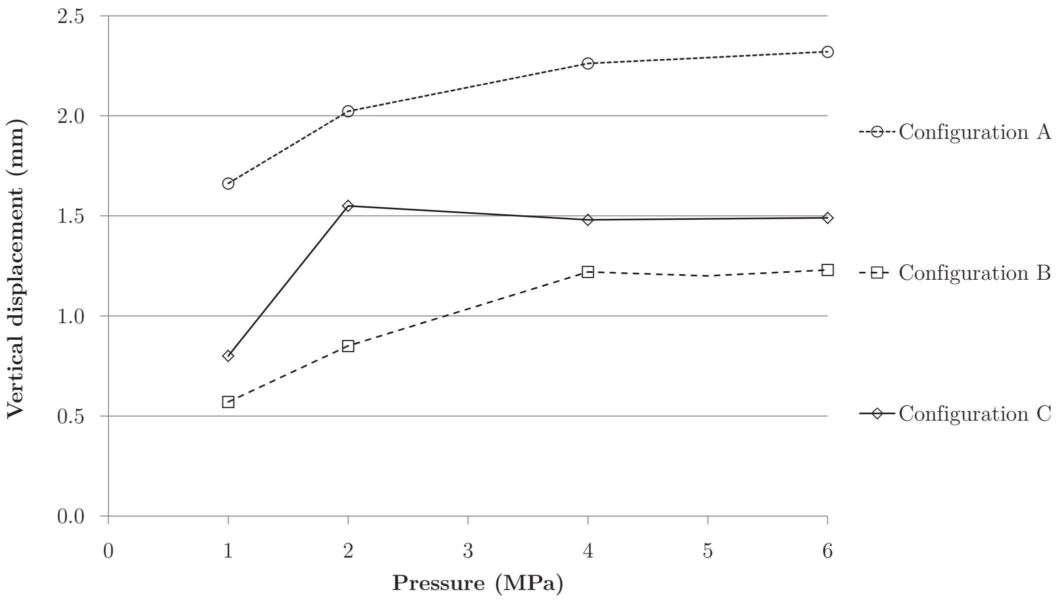


Figure 5.11: Vertical displacement measured on the concrete slab

becomes similar to that of the tests of configuration B.

These considerations are also shown by the vertical displacement. In the case of configuration B the displacement is completely due to the penetration and compression of the geomembrane, while in the other two tests the displacement is the composition of the deformation of the geotextile and of the geomembrane. Configuration C always has lower displacement because the penetration in the geomembrane is low and more than half of the displacement is due to the deformation of the geotextile. At the contrary, in configuration A the displacement is high due both to the deformation of the geotextile and to the high penetration in the geomembrane of the picks of quartz on the concrete.

As pressure increases, the vertical displacement shows an asymptotic behaviour that is due to the increase of the contact area between the concrete and the geomembrane that results in a slower increase of the real applied load.

Figure 5.12 reports the photos of the metallic layer after the test, that gives an idea of the deformation of the membrane.

Combination C has always lower and smoother deformations on the metallic layer. The difference between Combinations A and B is more evident for lower pressures and reduces with its increase.

From these tests, it is evident that the presence of geotextile strongly reduces the effect of irregularities on the substrate compared to the case without it. Furthermore, it is worth to be noted that the geotextile used, with a mass per unit

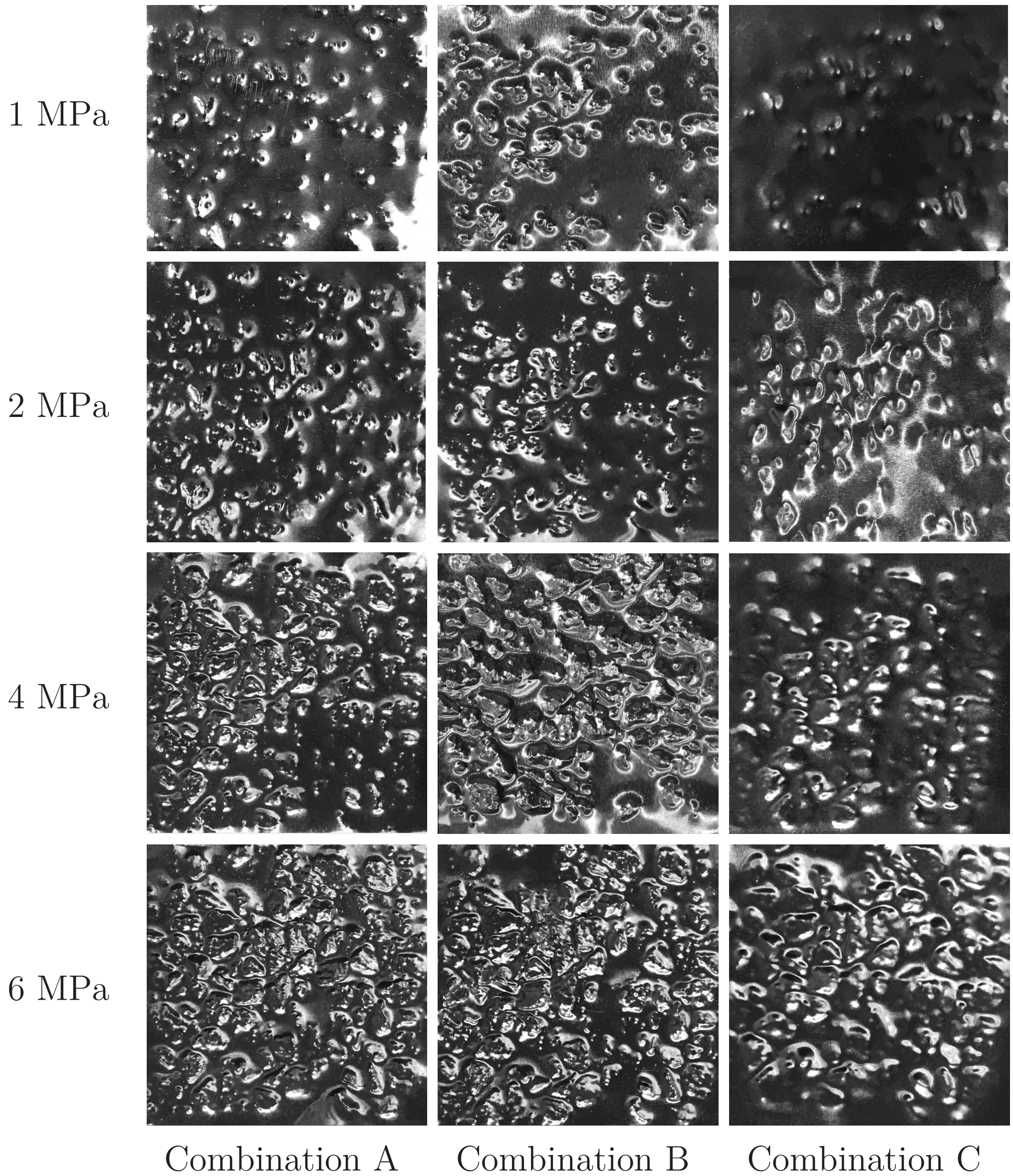


Figure 5.12: Photos of the metallic layers after the compression test

area of 500 g/m^2, is usually the minimum required for tunnel applications and that higher values of mass per unit area will result in a more effective protection.

Concerning the pressure applied on the membrane against the cast concrete, if this latter is not smooth for some irregularity (e.g. honeycombs), in the considered geometry and under pressures up to 6 MPa, no holes have been created in the membrane. However, the penetration of some grains in the membrane locally reduces the thickness and creates a possible location for failure when other actions are applied to the membrane (e.g. shrinkage due to loss of plasticizer). If a protection layer is used, it will absorb the penetrations and redistribute the pressure in a more uniform way on the waterproofing layer, thus reducing these issues.

Compression tests with spheres

The tests with the uneven concrete slab described above have the advantage of using crushed grains and therefore better simulate the real effect of honeycombs or irregular substrate. However, during the tests the grains become smoother and some of them detach from the concrete. Moreover, the geometry of the surface is randomly dependent on the position of the grains on the concrete. This implies that different tests are not made with the same uneven surface and the test is hardly repeatable.

Therefore, in order to normalize the problem to a know and repeatable geometry, steel spheres have been used to simulate the grains. Three diameters have been used: 3 mm, 6 mm and 10 mm, also considering that the prescriptions for the aggregates of shotcrete limit the maximum diameter to 8–11 mm. The test is performed on an area of 60x60 mm using a steel square shape to maintain in position the spheres. The load is applied with the same device described above on a steel plate positioned over the spheres. The vertical displacement is measured with a digital test indicator with an accuracy of 0.01 mm with one measure each 30 seconds.

A pre-load of 100 kPa is applied at the beginning of the test to eliminate the displacements due to the loose positioning of the device. The load is applied at steps of 1 MPa both during loading and during discharge. At the end the 100 kPa pre-load is applied. The loads are kept until the displacement is constant for three consecutive measurement. At the end of the test the pre-load is applied for 30 minutes. The tests are performed at a temperature of 20±2°C.

Figures 5.13 and 5.14 report the vertical displacement measured by the indicator with the variation of load.

As penetration h increases, the contact area A can be computed as

$$A = \pi r^2 \sin^2 \left[\arccos \left(1 - \frac{h}{r} \right) \right] \tag{5.6}$$

where r is the radius of the sphere. Therefore, the contact area increases with

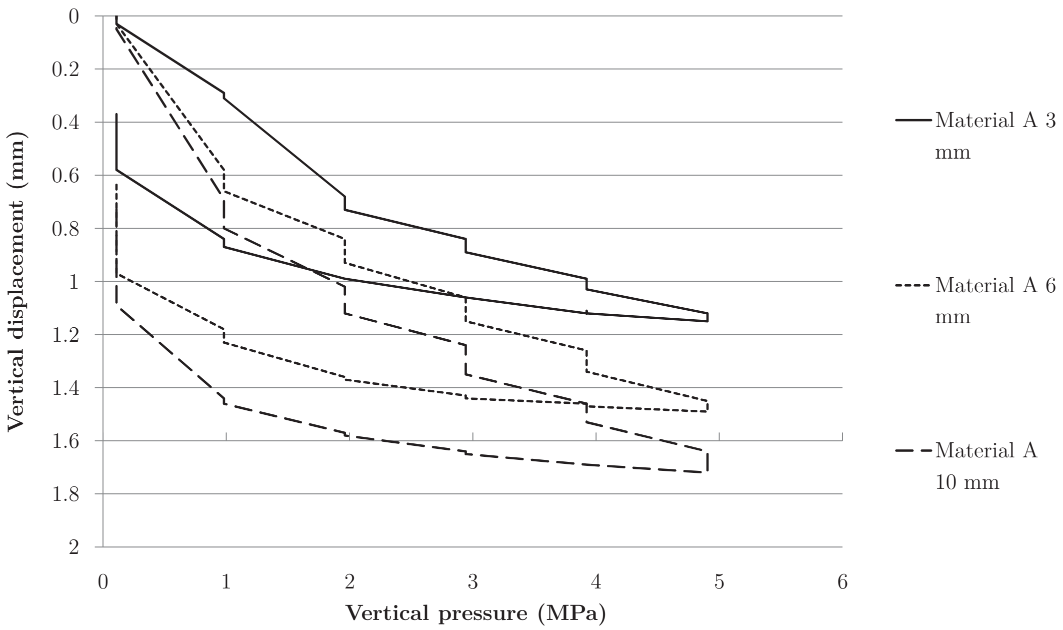


Figure 5.13: Vertical displacement for material A in compression test with spheres

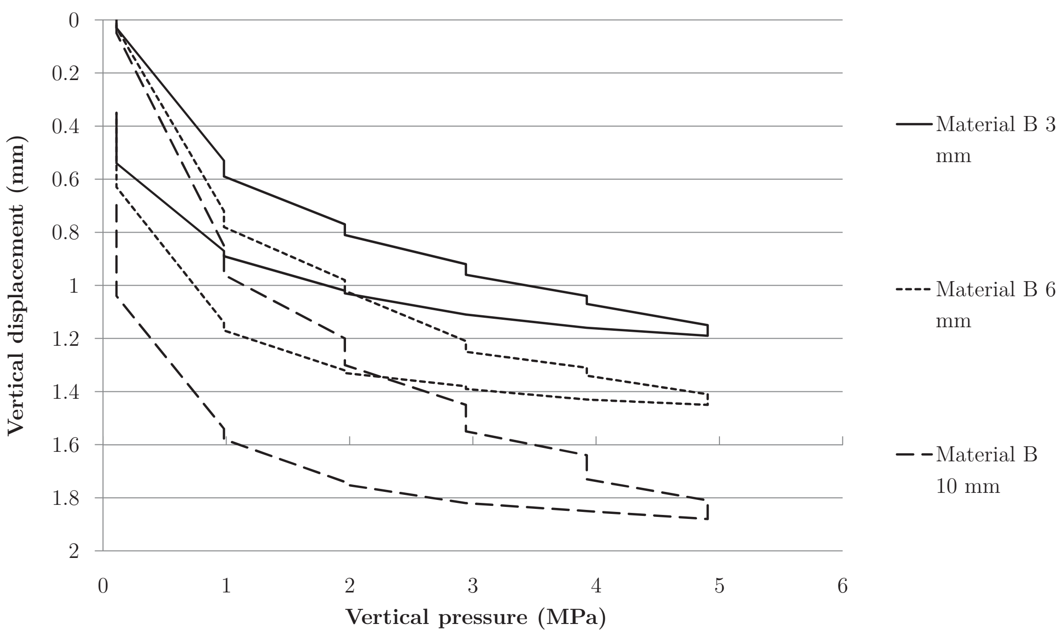


Figure 5.14: Vertical displacement for material B in compression test with spheres

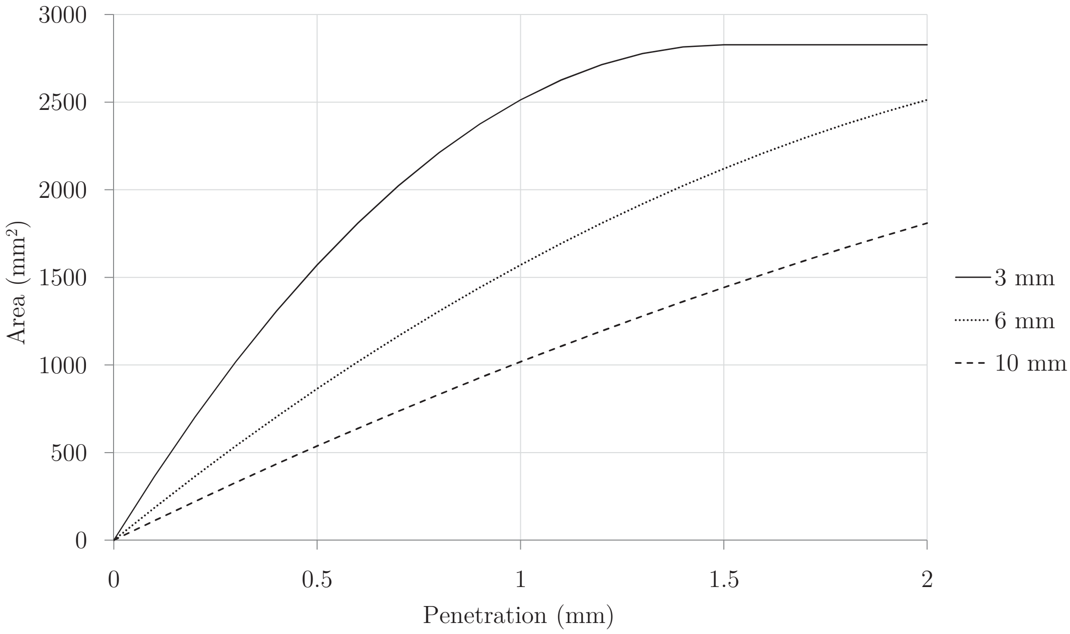


Figure 5.15: Contact area for different penetrations

the increase of h and consequently the load is distributed on a bigger area and the effect of penetration is reduced.

The total contact surface can be computed multiplying the area for the number of spheres (400 for the 3 mm test, 100 for the 6 mm and 36 for the 10 mm spheres). The number of spheres has been chosen in order to fulfil the square shape 60x60 mm with a regular square mesh.

The computed contact area is reported in Figure 5.15.

It is clear that, even if the increase of area with penetration evaluated from Equation 5.6 is smaller for smaller diameter, the higher number of spheres causes a bigger contact area with 3 mm of diameter. Consequently, since the load is better distributed in the test with smaller spheres, the effective vertical pressure is smaller in this case than for bigger spheres at the same penetration value. The effective vertical pressure tends to reduce with the dimension of the spheres to a limit value equal to the value of the nominal pressure in the hypothesis of infinitely small elements (i.e. plane surface).

These conditions simulate a standardized and homogeneously distributed irregularity of the surface of the concrete. At the contrary, the effect of some localized irregularity (e.g. a single grain) is not considered. This situation will result in higher load due to the very small contact area and can cause a breakthrough. However, a single element is unlikely to occur, while it is more possible to have a non homogeneous distribution of grains.

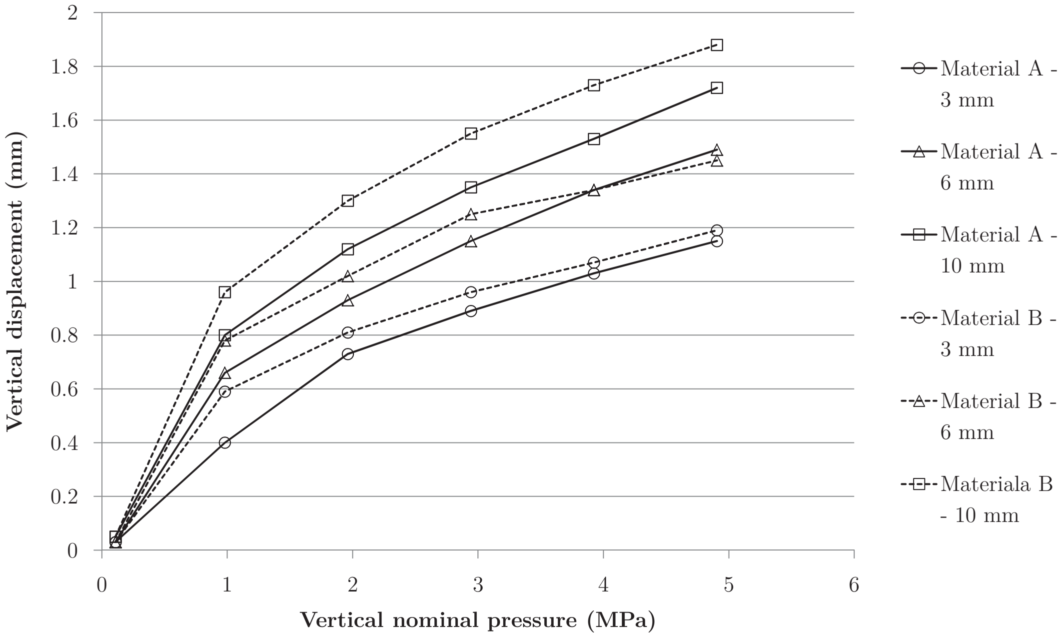


Figure 5.16: Comparison between material A and material B

The discharge path shows that a residual deformation remains in the membrane. The deformation is partially recovered immediately and partially with a slow relaxation process.

Figure 5.16 shows the comparison between material A and B maximum penetration reached for each pressure and diameter.

Material B is more subjected to penetration in comparison to material A. This difference can be due to the presence of filler that partially increases the resistance to penetration. The measured penetration never reached the whole thickness of the membrane. However, the penetration with spheres of 10 mm of diameter shows that for higher pressures the thickness of 2 mm can be reached.

A test with the direct application of 5 MPa of load without steps has been done to analyse the effect of the load path. Figure 5.17 shows the comparison between these two tests. The different load application procedure has negligible effect on the maximum and residual penetration. Underground waterproofing systems are loaded slowly when the compression comes from the degradation of primary lining or hydraulic pressure, therefore the step load application seems to be more representative.

A comparison can be made among the results of compression tests with spheres and those of the compression tests with the irregular concrete slab of configuration B (i.e. without geotextile). The penetration of spheres with diameter 3 mm in material A reproduces with good accuracy the results of test with concrete (Figure

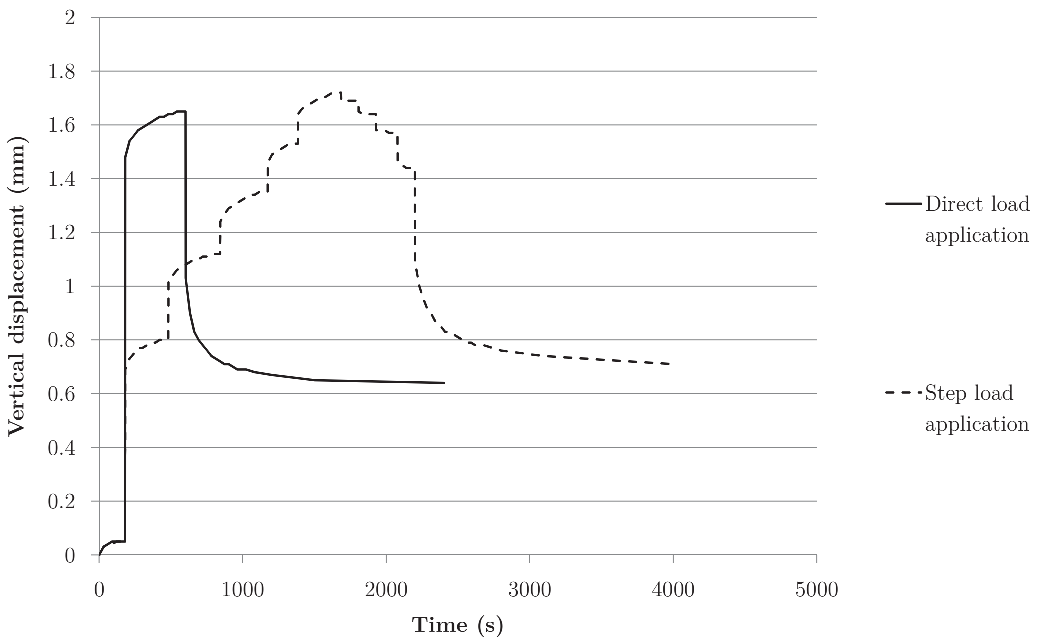


Figure 5.17: Comparison between step loading path and direct loading path

5.18). In order to better compare the results a compression test with concrete in configuration B has been developed at 5 MPa, too.

Shear tests

The behaviour of the waterproofing system under shear forces has been analysed with laboratory shear tests. The aim is to identify the shear resistance of the whole waterproofing system in order to evaluate how the shear forces between primary and final lining are transferred.

EN ISO 12957-1 (2005) reports the procedure for the determination of friction characteristics of geosynthetics. It prescribes the use of a shear box of 300x300 mm. However, ASTM D5321 (2017) and Koerner (2012) suggest that smaller boxes can be used if soil is not involved in the test, such as in the ones concerned in this study. Koerner (2012) assesses that standard geotechnical shear boxes can be used if attention is paid to guarantee that there are no internal sliding of the geosyntetics.

Therefore, to perform the tests on the waterproofing systems, a 60x60 mm shear box has been used. The geosynthetics have been bonded to a rigid metallic support of the same dimension with a rigid glue to avoid any movement inside the box. The test is performed with a speed of 1.2 mm/min and a maximum displacement of 11 mm. The applied pressure are 200, 500 and 1000 kPa.

The friction has to be evaluated on all the possible sliding surfaces of the waterproofing system and therefore different materials have been used:

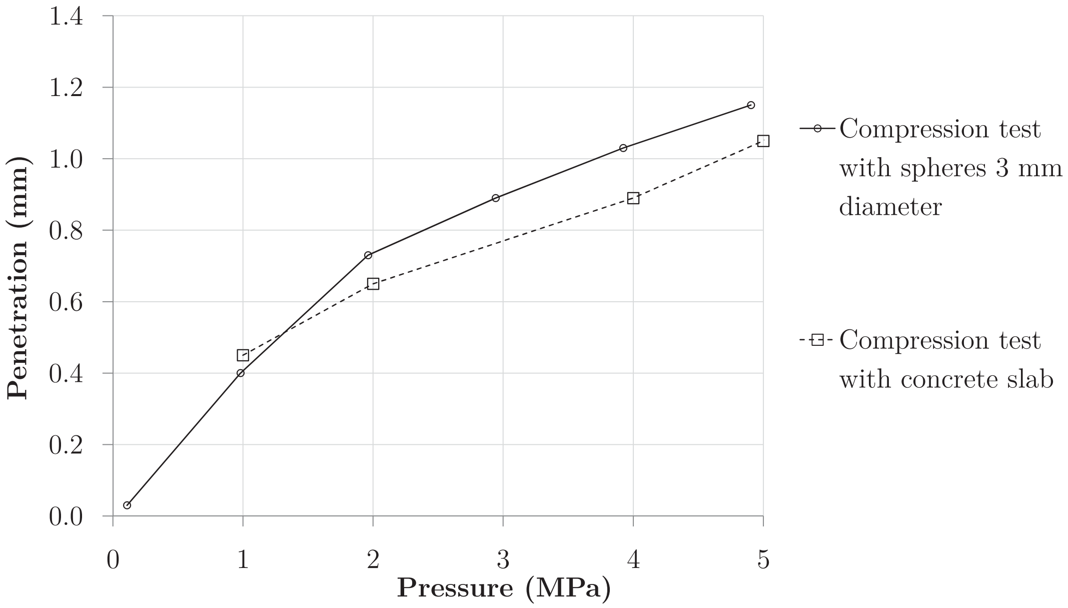


Figure 5.18: Comparison between the maximum penetration of compression test with concrete slab and the results of the compression test with spheres of 3 mm of diameter

- commercial PVC-P geomembrane 2 mm thick coloured with carbonate filler;
- PP geotextile, 500 g/m^2 as protection layer: the tests are performed both with dry geotextile and with the geotextile saturated with water to consider both the situations of presence or not of water circulation in the regularization/drainage layer;
- two concrete slabs: one smooth, to simulate the concrete cast against the membrane, and one with an irregular surface obtained with 2 mm sand grains inserted in the fresh mortar, to simulate the irregular surface of the shotcrete.

Table 5.5 summarize the tested combinations of materials.

It has not been possible to obtain satisfying results for combinations 5 and 6 due to the presence of the irregularities. In effects, during the tests the irregularities were cut by the shear box and the tests geometry resulted changed.

For all the other combinations, three tests are performed for each pressure.

The tests of combination 1 show a peak at the beginning of the sliding, probably due to the mutual penetration of the roughness of the two layer of PVC-P membrane. Indeed, the membrane surface is voluntary made not smooth to facilitate the friction during installation. After this peak the behaviour is constant for the rest of the test (Figure 5.19).

Table 5.5: Scheme of the performed shear tests

Combination number	Material	
1	PVC-P membrane	PVC-P membrane
2		Geotextile dry
3		Geotextile wet
4		Concrete smooth
5	Concrete irregular	Geotextile dry
6		Geotextile wet

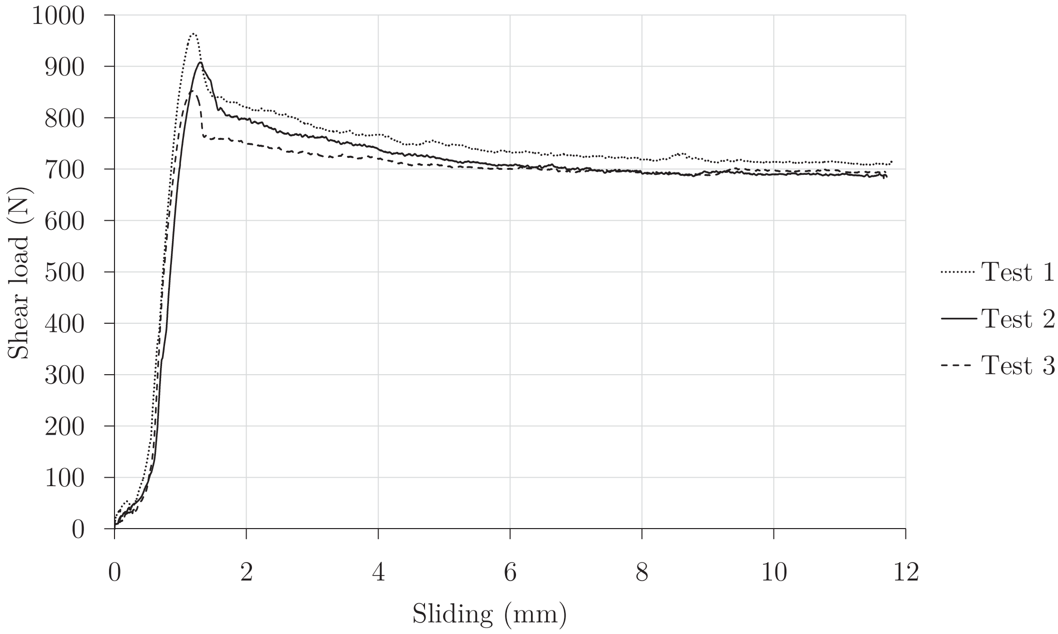


Figure 5.19: Results of the shear tests on two layers of PVC-P membrane at 500 kPa of vertical pressure

At the contrary, the tests with PVC-P membrane and geotextile, both dry and wet (combination 2 and 3), present no peak (Figure 5.20). Sometimes, during the test campaign it was necessary to repeat some of the tests with geotextile since the material was translated from the original position to the side of the sample in the direction of sliding. This is due to the fact that geotextile has very low shear resistance in its plane and the fibres slide one on the other if are randomly positioned in the direction of the movement.

For each combination the mean values of the three tests are computed for each pressure. The values of shear forces, divided for the area of the sample (3600 mm^2), give the shear stress, while the vertical pressure applied is the vertical stress.

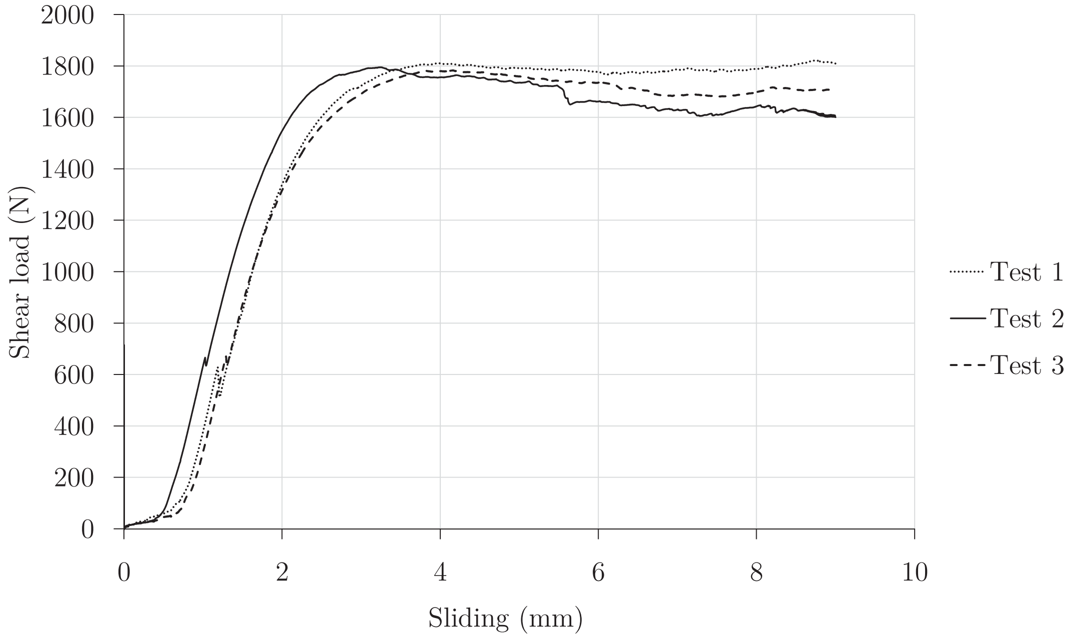


Figure 5.20: Results of the shear test between PVC-P membrane and wet geotextile at 1000kPa of vertical pressure

Table 5.6: Coefficients of friction for the tested combinations

Combination	$tan(\varphi)$ (-)
1	0.25
2	0.59
3	0.44
4	0.37

Plotting these values in a τ-σ plane, the coefficient of friction ($tan(\varphi)$) can be obtained from the line interpolating the values for the three pressures, using the equation

$$\tau = c + \sigma tan(\varphi) \tag{5.7}$$

with c being the cohesion.

In Table 5.6 the values of the coefficients of friction are reported for the 4 combinations tested.

Even if they were not tested for the reason explained above, the coefficients of friction of the combinations 5 and 6, between geotextile and shotcrete, can be considered higher than those obtained for the other combinations due to the irregular

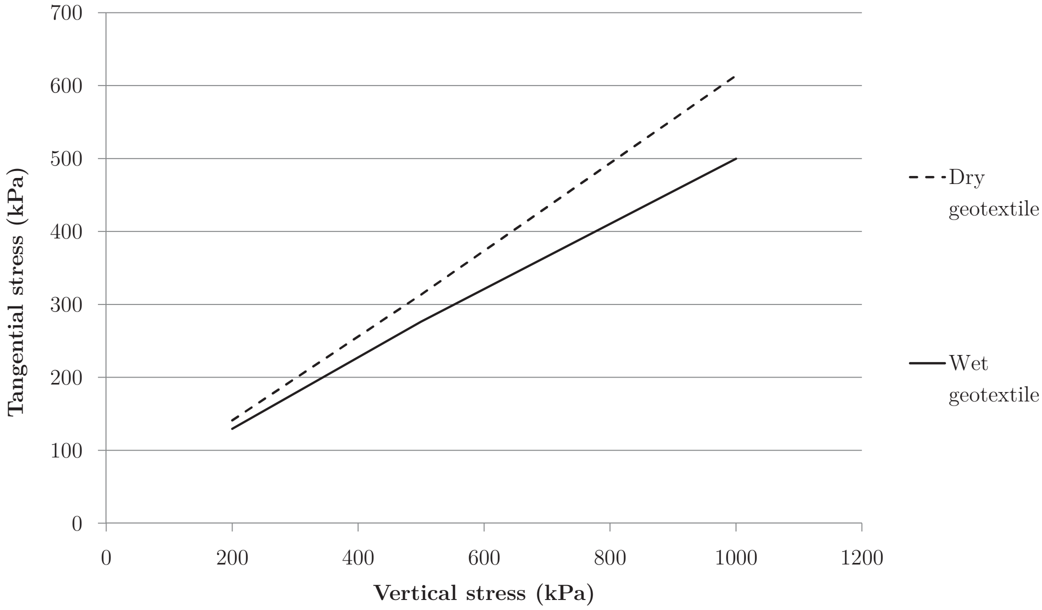


Figure 5.21: Comparison between wet and dry geotextile results

surface of the concrete that can easily penetrate the structure of the geotextile and cause high resistance to shear.

The effect of water in the geotextile is evident in lowering the friction coefficient (Figure 5.21).

From the friction coefficient reported in Table 5.6 it is possible to conclude that the sliding occurs between the membrane and the cast concrete. The other interfaces will not slide and will be subjected to a shear stress that could at maximum reach that inducing the movement in the sliding interface.

Therefore, the maximum shear stress in the membrane can be estimated of about 0.4 MPa for a pressure of 1 MPa.

5.5.3 Vibrations due to traffic

In railway and metro tunnels the passage of trains induces vibrations in the tunnel and in the surrounding soil. These vibrations are transferred from the lining to the soil through the waterproofing system.

ISO 10815 (2016) reports as range of velocity of the vibrations in tunnels due to trains 0.01–0.08 mm/s with a maximum of 1 mm/s for tunnels with bad maintenance. The frequency ranges between 1 and 100 Hz.

The order of magnitude of the displacements due to vibrations can be obtained considering the velocity as a sinusoid with the reported amplitude (A) and frequency

(f). The displacement, obtained integrating the function of the velocity, has an amplitude s given by

$$s = \frac{A}{2\pi f} \tag{5.8}$$

Therefore, considering the values reported by ISO 10815 (2016), the amplitude of displacements ranges between 1.3 10^{-2} and 1.6 10^{-5} mm.

These displacements are small compared to the dimension of the membrane and to the deformation already existing on the waterproofing system during operation due to the constant compression loads, therefore the effect of vibrations on the waterproofing system can be neglected.

5.5.4 Expansion of construction joint

In active joints and expansion joints of underground metro stations cyclic deformations up to 50% occur due to seasonal expansion of the structure. Therefore, the material on the joint (membrane or waterstop) should be able to withstand these deformations. Both PVC-P and TPO exhibit higher elongations to rupture. The visco-elasic behaviour of these materials in the range of elongation of 50% guarantees elastic recovery, while the deformation can be irreversible if the material used has a plastic deformation.

In the most demanding cases, an excess of membrane can be left in the joint to facilitate the expansion.

When TPO are used, the fatigue behaviour has to be considered in the design of active joints, while PVC-P is not affected by this phenomenon.

5.5.5 Fire

In case of fire in the tunnel during operation the heat can damage the materials, produce smoke, toxic gasses and cause the start of fire on the waterproofing system.

These phenomena can occur if the increase of temperature induced by the fire reaches the inner surface of the final lining and thus the waterproofing. From laboratory and numerical simulation, in case of the standard fire according to EN 1992 (2015), the increase of temperature does not reach the waterproofing layer because the cast concrete limits the diffusion of heat to the geomembrane (Mansour, 2010; Sakkas et al., 2019).

In order to evaluate the effect of a fire on the waterproofing geomembrane, a thermal simulation has been performed. The numerical model used is the same of Paragraph 5.4.1. In this case the hydration heat is not considered and the steel layer is removed. The temperature at the intrados is defined according to a nominal fire time-temperature curve describing the variation of temperature with time. Three fire curves have been considered (Figure 5.22), as suggested by PIARC (2004):

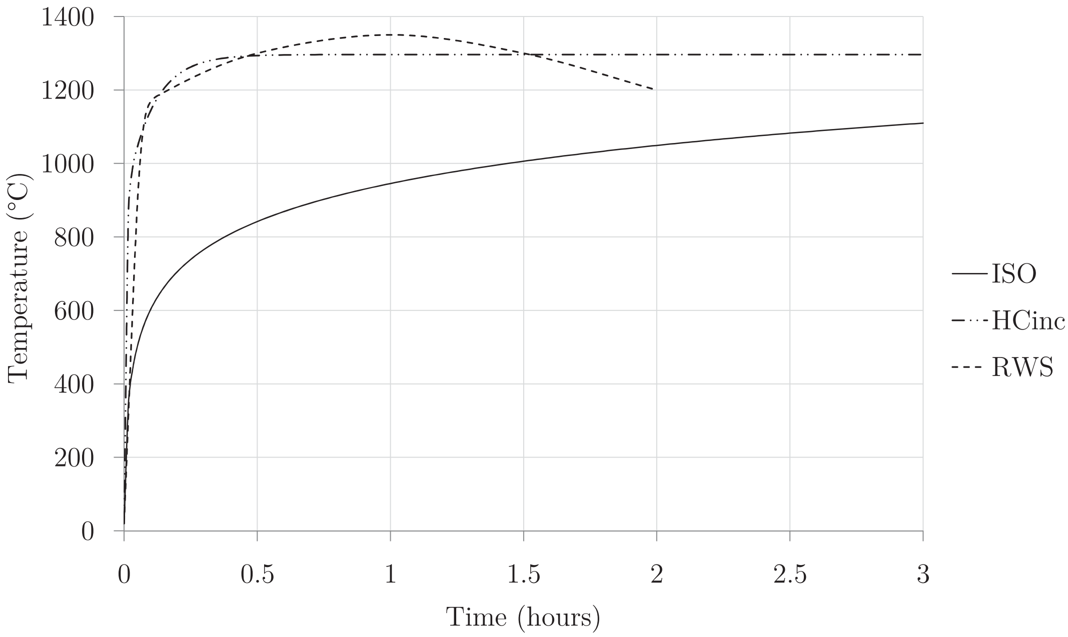


Figure 5.22: Nominal fire curves used in the simulaton

- the curve proposed by ISO 834 (ISO 834, 2014) and reported by Eurocode 1 (EN 1991-1-2, 2002) described by the equation

$$T = 20 + 345 \log_{10}(8t + 1) \tag{5.9}$$

  where T is the temperature in °C and t the time in minutes;

- the curve proposed by the Netherlands road administration (RWS) that is confirmed by experimental tests. This curve is defined by time-temperature single points (World Road Association, 1999);

- the increased Hydrocarbon temperature curve (HC_{inc}) (Ministère de l'Equipement, 2000) proposed for tunnels by French authority modifying the Hydrocarbon temperature proposed in Eurocode 1 (EN 1991-1-2, 2002) by increasing the plateau at 1300°C (Taillefer et al., 2013). This curve is similar to RWS, but is easily describable by an equation as

$$T = 20 + 1080(1 - 0.325e^{-0.1678t} - 0.675e^{-2.5t})\frac{1300}{1100} \tag{5.10}$$

The maximum duration of the fire has been assumed of 3 hours from PIARC (2004). After this time the simulation is stopped without any cooling phase in accordance to Eurocode 1 (EN 1991-1-2, 2002).

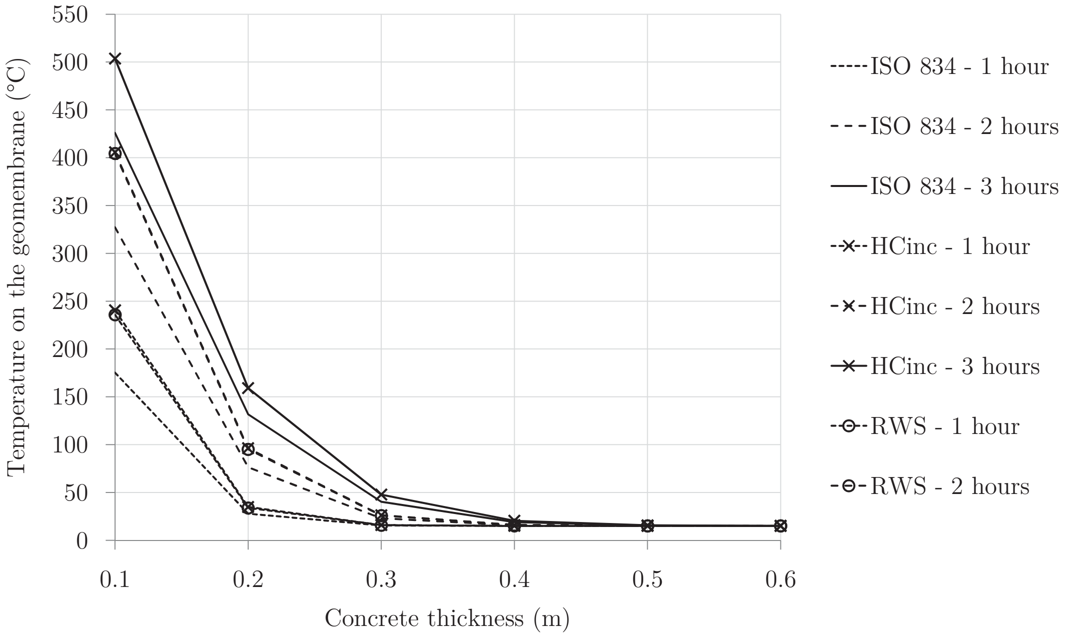


Figure 5.23: Maximum temperature on the geomembrane due to nominal fire in the tunnel for different values of concrete thickness

The thermal properties of the concrete are assumed depending on temperature, according to Eurocode 2 (EN 1992-1-2, 2004), as

$$\lambda_c(T) = 2 - 0.2451\left(\frac{T}{100}\right) + 0.0107\left(\frac{T}{100}\right)^2 \tag{5.11}$$

$$c_p(T) = \begin{cases} 900, & \text{for } 20°\text{C} \leq T \leq 100\ °\text{C} \\ 900 + (T - 100), & \text{for } 100°\text{C} \leq T \leq 200\ °\text{C} \\ 900 + (T - 200)/2, & \text{for } 200°\text{C} \leq T \leq 400\ °\text{C} \\ 1100, & \text{for } 400°\text{C} \leq T \leq 1200\ °\text{C} \end{cases}$$

where $\lambda_c(T)$ is the thermal conductivity upper limit in W/mK, $c_p(T)$ the specific heat in J/kg K and T the temperature in °C.

The temperature on the waterproofing geomembrane is estimated at different times, with the three nominal curves considered and with different values of thickness of the concrete layer.

Figure 5.23 compares the maximum temperature on the geomembrane in the analysed conditions for different values of thickness of the concrete.

For thickness higher than 0.3 m the temperature is lower than 50°C that can be considered an acceptable value for PVC-P because the degradation due to loss of HCl starts at about 100°C.

This model is approximated since it takes into account only conduction inside the concrete and not convection and radiation on the surface. Moreover, the possible spalling is only considered as a reduction of thickness and there is no variation in the properties of the concrete, influence of the rebars and of the cracks.

However, these results are consistent with the experimental data reported by Sakkas et al. (2019) and with the temperature profiles proposed in Annex A of Eurocode 2 (EN 1992-1-2, 2004).

Therefore, if the final lining, also considering possible spalling due to the fire is equal or higher than 0.3 m the effect of a fire in the tunnel does not influence the efficiency of the waterproofing geomembrane. The simulations lasting for 2 hours give as acceptable also a thickness of 0.2 m.

5.5.6 Chemical/thermal damaging

Extreme environmental conditions can cause the degradation of the materials composing the waterproofing system. Among the most common and hazardous there are hot environments and alkaline or acid water.

As already said, the temperature in deep tunnel can reach up to 50°C due to geothermal effects. Moreover, if hydrothermal flows are present the temperature can be high also in shallow tunnels. The influence of temperature on the membrane depends on the material. More information on the thermal degradation of the most common polymers used for tunnel waterproofing will be given in Chapter 7.

The chemical composition of the water influences the damage on the materials. In underground structures, the environment is alkaline for the presence of concrete and of dissolved salts in the water. However, in some cases acid waters or soils can be encountered. Particular attention has to be paid for sewage tunnels, where sulphuric acid can be developed by the flowing liquids, that can damage both linings and waterproofing membranes.

5.6 Properties of commercial geomembranes and standard requirements

The required properties of waterproofing elements reported in the technical documents and standards are summarized in the following Tables 5.7, 5.8, 5.9 and 5.10. The protection layer is not reported in these tables because it is often neglected in the technical documents or is prescribed with the same properties and materials of the waterproofing membrane but with different thickness (1.9 mm according to AFTES and 3 mm according to ÖBV (2015)).

There is variability in the prescribed properties. This is particularly evident for the resistance to impact or accidental loads, that is required with different standards and test procedures, reflecting the wide number of tests developed to try to evaluate the influence of these actions. At the contrary, some properties are common to almost all technical documents and their value are quite constant: thickness of 2 mm for the membrane without pressure, a tensile strength of about 12–17 MPa for PVC-P and 15 for TPO and an elongation of 250–300 % for PVC-P and 500 % for TPO.

Table 5.7: Required properties for protection and drainage geotextiles

Source			ÖBV (2015)		SIA 272 (2009)	DB (2011)	ANAS	BBT		RFI	Metro Milano
Material			PP (10% internal reworked)			PP or HDPE	PP non-woven long fibre	PP (5% internal reworked)			
Mass per unit area		(g/m^2)	$\geq$ 500 (crown and springs)	$\geq$ 900 (invert and cut&cover)	500–1500	500-1200	$\geq$ 400	$\geq$ 500	$\geq$ 900	$\geq$ 500	$\geq$ 700
Thickness	2 kPa	(mm)			according to producer	$\leq$ 10	$\geq$ 3	according to producer		$\geq$ 4	
	0.5 kPa									$\geq$ 5.5	
	20 kPa								$\geq$ 3		
	200 kPa		$\geq$ 1.7	$\geq$ 3.4		$\geq$ 4 mm	$\geq$ 1.9	$\geq$ 1.7	$\geq$ 3.4	$\geq$ 1.9	
Tensile strength		(kN/m)	$\geq$ 30	$\geq$ 50	$\geq$ 15	$\geq$ 25–30	$\geq$ 24	$\geq$ 30	$\geq$ 50	$\geq$ 30	$\geq$ 80
Tensile deformation		(%)	$\geq$ 50		$\geq$ 20	$\geq$ 50 (non-woven) $\leq$ 30 (woven)	$\geq$ 80	$\geq$ 50			$\geq$ 70
CBR resistance		(kN)			$\geq$ 2.5	$\geq$ 5.5 and <20					
Dynamic perforation (cone drop test)		(mm)	$\leq$ 13	$\leq$ 7	$\leq$ 10			$\leq$ 13	$\leq$ 7		
Puncture resistance		(kN)	$\geq$ 3	$\geq$ 7			$\geq$ 4	$\geq$ 3	$\geq$ 7	$\geq$ 5	$\geq$ 5
Tear strength		(kN)					$\geq$ 1.4				$\geq$ 1.5
In plane permeability	20 kPa	(m^2/s)			$\geq 10^{-4}$	$\geq 10^{-3}$	$\geq 9\ 10^{-6}$			$\geq 5\ 10^{-6}$	$\geq 10^{-1}$ cm/s
	100 kPa									$\geq 1.5\ 10^{-6}$	
	200 kPa		$\geq 2\ 10^{-6}$		$\geq 10^{-5}$		$\geq 6\ 10^{-7}$	$\geq 2\ 10^{-6}$			$\geq 10^{-2}$cm/s
Fire resistance			Class E			B2		Class E			

Table 5.8: Required properties for waterproofing geomembranes

Source			OBV Guidelines		Fascicule67		SIA272	DB853		ANAS	BBT	RFI		Metro Milano	
Material			PVC-P	TPO	PVC-P	ECB		PVC-P	PE	PVC-P	PVC-P	PVC-P	FPO	PVC-P	FPO
Thickness	without pressure	(mm)	2	2	2		2	2		≥ 2	2	2	2	2	2
	with pressure		3	3			3	3			3				
Tensile strength		(N/mm^2)	≥ 12	≥ 15	≥ 12	≥ 7	according to producer	≥ 12	≥ 15	≥ 15	≥ 12	≥ 15	≥ 15	>17	>11
Tensile deformation		(%)	≥ 250	≥ 500	≥ 270		≥ 200	≥ 300	≥ 500	≥ 250	≥ 250	≥ 250	≥ 500	>300	>500
E modulus between 1–2 %		(N/mm^2)	≤ 20	≤ 65			≤ 80 (FPO) ≤ 20 (other)	<20	<100		≤ 20				
CBR static puncture		(kN)					≥ 1.2–2.5								
Puncture resistance		(kN)	>2.5	>2.8	0.6–1.7						>2.5				
Tear resistance		(N/mm^2)								≥ 100		≥ 50	≥ 100	>120	
Resistance to impact load		(mm)	750 (2.1 mm) 1250 (3.5 mm)				≥ 700 ≥ 1250				750			800	
Foldability at low temperature		(°C)	-20		-20		-20	-20		-30	-20	-20	-30		-50
Dimensional stability		(%)	≤ 2												
Fire resistance			Class E				Class E or F			B2	Class E	Class E	B2	B2	

Table 5.9: Required properties for layer with high drainage

Source			ÖBV (2015)	BBT	RFI
Material					HDPE (+PP 180 g/m^2)
Thickness	2 kPa	(mm)		according to producer	
	20 kPa				≥ 8
	200 kPa		≥ 4 and ≤ 12	≥ 4 and ≤ 12	≥ 5.7
Tensile strength		(kN/m)	≥ 10	≥ 10	≥ 15
Tensile deformation		(%)			≥ 60
Puncture resistance		(kN)			≥ 5
In plane permeability	100 kPa	(m^2/s)			$\geq 3.9\ 10^{-3}$
	200 kPa		$\geq 10^{-4}$	$\geq 10^{-4}$	
Fire resistance			Class E	Class E	

Table 5.10: Required properties for sprayed waterproofing membrane

Source		Fascicule67 -10 °C	23°C	50°C	RFI
Thickness	(mm)				≥ 3
Tensile strength	(N/mm^2)		≥ 4	≥ 1	≥ 15
Tensile deformation	(%)	≥ 8	≥ 60		≥ 100
Adherence to concrete	(N/mm^2)		≥ 1.5		≥ 1
Hardness Shore A	(-)		60		

5.7 Conclusions

From the analysis of all the loads acting on the waterproofing system and from the laboratory tests performed it is possible to estimate qualitatively, and in some cases quantitatively, the required properties on each element of the system along the life of the underground structure. Table 5.11 summarizes the actions on the geomembrane during its life.

In Figures 5.24, 5.25 and 5.26 the mechanical and thermal actions on the geomembrane during the whole life are reported. Some of the actions are defined on the basis of evaluations and computations reported in this chapter. Others are not quantitatively defined since they depend on project specific properties, such as the hydraulic and geostatic pressure acting on the final lining, influencing the compression on the membrane, the puncture actions during operation and the protection and drainage requirements for the geotextile. The possible clogging of the drainage system is considered in the compression action and consequently on the puncture requirement.

Compression stresses are almost limited to the operation phase, and are depending on the long-term efficiency of the primary lining and of the drainage system. Pure compression can not induce failure of the geomembrane, therefore there is not

Table 5.11: Actions on the geomembrane

	Transport and storage	Installation	Casting	Operation
Traction	-	Low (35 N/m^2 of dead load)	Traction from shrinkage (about 1.8 N/mm^2)	Expansion joints: maximum 50% elongation Earthquake Shear due to relative movement between primary and final lining: 0.4 MPa at 1 MPa of pressure
Compression	-	-	Pressure of fresh concrete (50–100 kPa)	Compression due to degradation of primary lining: value depends on the specific boundary conditions of the project Hydraulic load (in undrained tunnels or in case of ineffective drainage system): value depends on the specific boundary conditions of the project Vibrations due to traffic (railway tunnels): 1.3 10^{-2}–1.6 10^{-5} mm (negligible)
Puncture	-	Variable, random actions: irregular substrate incorrect design of the protection layer tools fall rebar installation	Irregular substrate in association with casting pressure (negligible from laboratory tests results)	Irregular substrate in association with pressure Defects of the cast concrete (e.g. honey combs, voids) in association with pressure: no holes for pressure up to 6 MPa
Chemical	Negligible	Welds	-	Depending on the environment (pH, dissolved salts)
Fire	Negligible	Fire on the jobsite	-	Not relevant
Temperature	Negligible	Burning during welding	Hydration heat: low temperature increment (T_{max} =45°C) with possible influence on shrinkage (-1% – 0.7 %) and possible folds formation	Only for hot environment and water (e.g. deep tunnels)

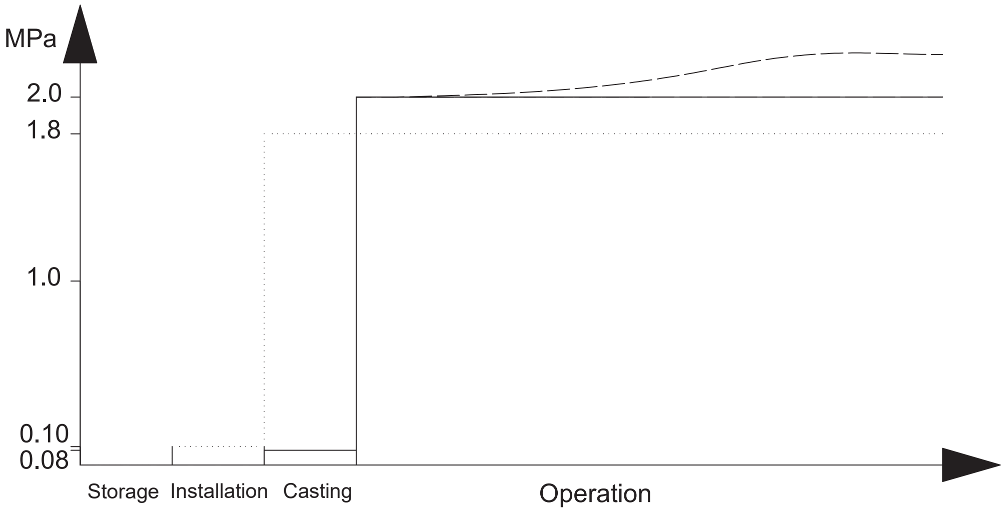


Figure 5.24: Mechanical actions on the geomembrane. Solid line compression, dashed line compression in case of clogging of the drainage system, dotted line tensile stress

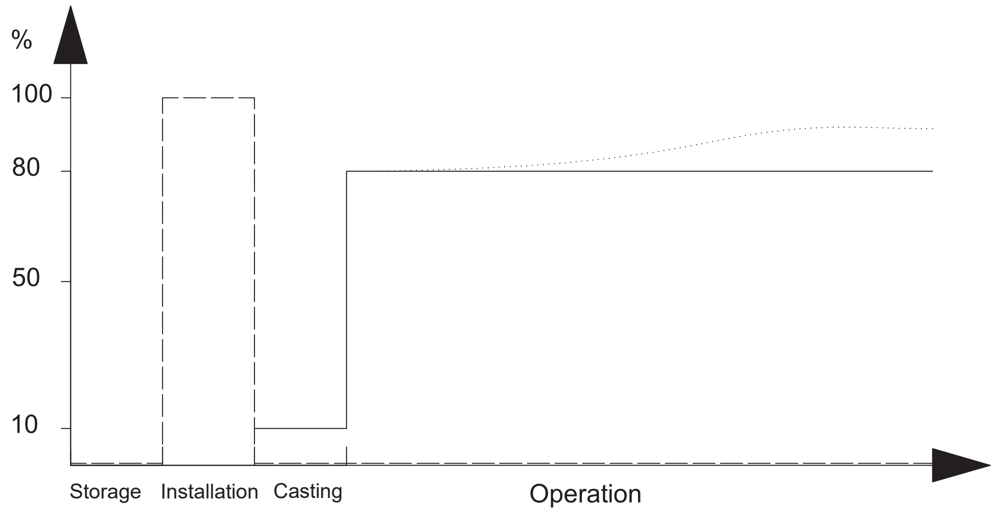


Figure 5.25: Puncture resistance required to the geomembrane. Dashed line in the case of perfectly smooth substrate, solid line for uneven substrate, dotted line in case of uneven substrate with clogging of the drainage system

a specific required property related to this value.

Nevertheless, if the substrate or the cast concrete surface are not sufficiently

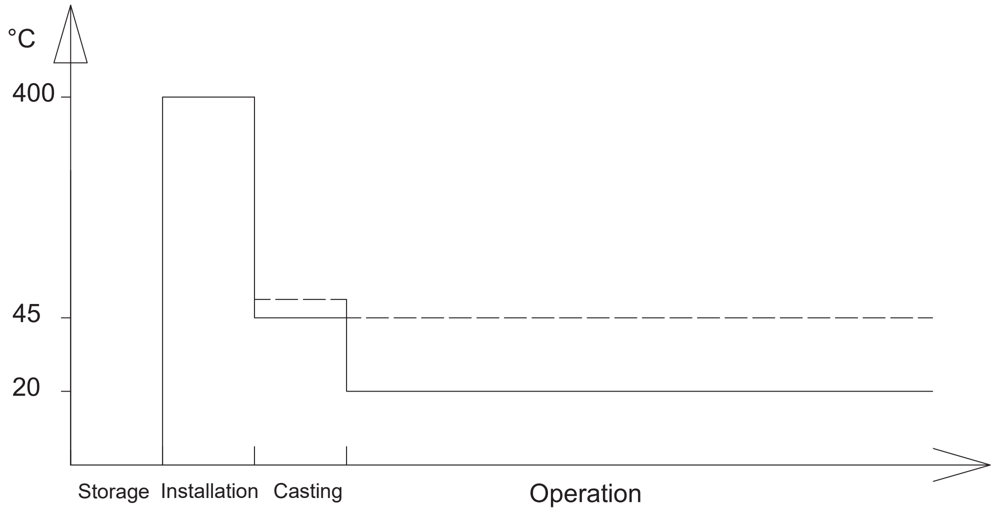


Figure 5.26: Temperature action on the geomembrane. Solid line in normal conditions, dashed line in the case of hot water or environment (deep tunnels and/or hydrothermal)

smooth, the value of compression is linked to the damaged due to puncture, increasing the penetration. The failure is reached if the combination of compression and roughness causes the total penetration of the irregularities through the membrane. For pressures up to 6 MPa and crushed gravel on the surface of 4 mm, not any hole appeared on the membrane. Moreover, the presence of regularization and protection layer highly reduces the possible damage. From the compression tests with normalized spherical elements of different diameters up to 5 MPa not any hole appeared even for 10 mm spheres, that is in the range of the maximum dimension of aggregates for shotcrete. The effect of increase of pressure and of diameter has been analysed and reported in Figure 5.16: lower diameters result lower penetration.

Nevertheless, even if there is not a complete penetration, the reduction of thickness coupled with high values of water pressure can induce the failure of the membrane under high stresses. The puncture resistance required is therefore correlated to the compression, given the value of roughness.

Tensile stresses are due to incorrect installation and possible shrinkage for stress relaxation and loss of plasticizer. It has to be considered that the relaxation behaviour presented by polymeric membranes reduces the tensile stress with time.

The temperature has a pick during installation due to welding. However, it is to be noted that welding is a localized and short action that has lower influence on the behaviour of the membrane compared to permanent relatively high temperatures, such as those of deep tunnels or hot water during all the operation life of the work.

The effect of temperature is to reduce the hardness of the membrane and the tensile strength and of increase the degradation. Therefore, when high temperatures are foreseen, specific analyses have to be done.

The protection requirements on the geotextile are directly dependent on the compression and puncture actions on the membrane.

The drainage requirements on the drainage system are limited to the operation phase and are constant for all the life span at the value of the maximum foreseen water flow.

These graphs and considerations are the basis for the definition of the required properties for the specific project. To perform a durability assessment on the waterproofing system the variation of the properties with time will be analysed in the following chapters.

Chapter 6

Waterproofing materials

6.1 Waterproofing systems materials

Almost all the materials used for waterproofing systems are geosynthetics. A geosynthetic is defined as 'a product, at least one of whose components is made from a synthetic or natural polymer, in the form of a sheet, a strip, or a three-dimensional structure, used in contact with soil and/or other materials in geotechnical and civil engineering applications' (EN ISO 10318-1, 2015). Therefore, in this chapter the main properties of geosynthetics used in tunnel waterproofing systems are summarized. In the following chapter the durability of the materials used is analysed with a particular attention to polyvinyl chloride because it is the most used material for underground waterproofing geomembranes.

6.1.1 Geotextiles

Geotextiles are permeable planar textile material. The properties of the geotextiles are depending on the polymer used, on the type of fibre and manufacturing technique.

The polymers used are mainly polypropylene (about 95% of the market) and in some cases polyester (about 2%) and polyethylene (about 2%) (Koerner, 2012). The fibres may be monofilament, multifilament, staple, staple yarn. The manufacturing can be woven or non-woven, the latter being the most used for underground applications.

Geotextiles cover many functions (e.g. separation, reinforcement, filtration, drainage) and in the case of waterproofing systems are used with two aims: protection of the geomembrane from uneven substrate (regularization layer) and drainage of groundwater (drainage layer). The principal design parameters for those functions are analysed in the following.

Thickness

Thickness is not a design parameter, since it is function of the pressure applied on the geotextile (ASTM D5199, 2012; EN ISO 9863-1, 2016). The variation of thickness with applied pressure is defined by the compressibility of the geotextile, that is high for non-woven needle-punched geotextiles, the most used in tunnel waterproofing. In technical documents, thickness is usually required at 2 kPa and at 200 kPa. The first value is not so useful in design since such a pressure is too low for real applications, while the second one can be somehow more realistic. Figure 6.1 shows the correlation between pressure and thickness for a geotextile.

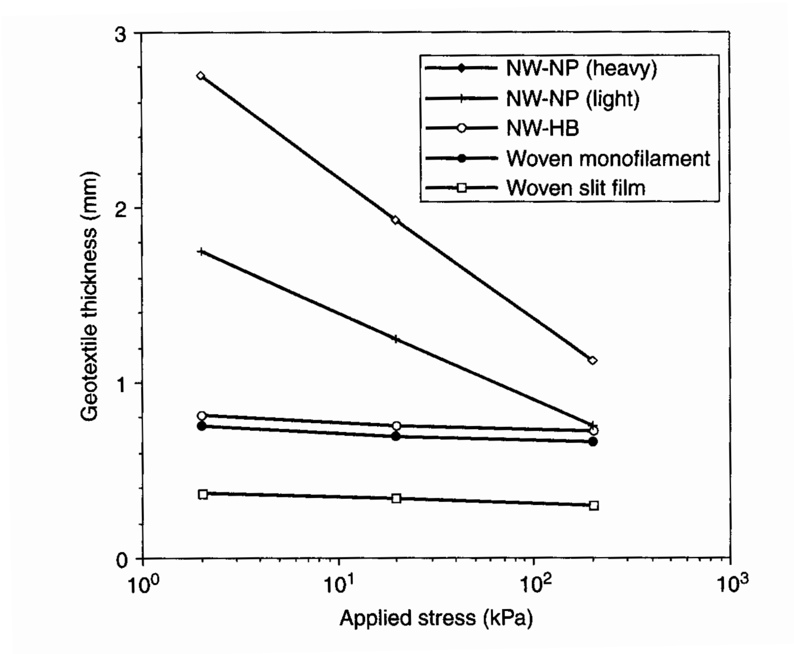


Figure 6.1: Geotextile thickness dependence on applied pressure, for different types of geotextiles (non-woven needle-punched (NW-NP) and non-woven heat-bonded (NW-HB). From Koerner (2012)

Mass per unit area

Mass per unit area, usually expressed in g/m^2, is the most common identification of geotextiles even though this vale is not able to describe the characteristics of the material. Indeed, the mass per unit area is dependent on the material and diameter of the fibres.

Nevertheless, it is widely used because it is easily measurable also on site. Values of commercial geotextiles ranges from 150 to 1000 g/m^2, but higher values can been applied, up to 2000 g/m^2.

Porosity

The porosity is defined as the ratio of the voids volume on the total volume. It is computed indirectly as

$$n_{GT} = 1 - \frac{m}{\rho_F t_G} \tag{6.1}$$

where n_{GT} is the porosity, m the mass per unit area, ρ_F the fibre density and t_G the thickness of the geotextile. From the definition and from equation (6.1) it is clear that porosity is depending on thickness and, consequently, on the applied pressure.

Permeability

Permeability of a geotextile is a key parameter for filtration and drainage applications such as those of tunnel waterproofing systems.

Two permeability parameters can be defined for geotextiles: cross-plane permeability, known as permittivity, influencing the filtration behaviour, and in-plane permeability, known as transmittivity, governing the drainage function.

Since geotextiles are used also as drainage layers, the latter parameter is of greater interest in tunnel waterproofing . Transmittivity ϑ is defined as

$$\vartheta = k_p t_G \tag{6.2}$$

where t_G the thickness of the geotextile and the in-plane permeability k_p is defined as

$$k_p = \frac{Q}{t_G \cdot i \cdot w} \tag{6.3}$$

where Q is the in-plane flow rate, i the hydraulic gradient and w the width of the geotextile.

From equation (6.3) it is evident that the flow rate is a function of thickness, and, therefore, of the applied pressure on the geotextile (Cazzuffi et al., 2016). Gerry and Raymond (1983) report 2.0 10^{-6} m^2/s as a typical value of transmittivity for a non-woven needle punched geotextiles at 40 kPa.

In drainage applications permeability is also depending on the roughness of the concrete or soil layers in contact because it influences the filtration paths. Murillo et al. (2014) study the permeability of a non-woven needle-punched geotextile for different roughness values and show a variation up to one order of magnitude of the permeability. This phenomenon is more evident for relatively high pressures.

6.1.2 Geomembranes

Geomembranes are used as a barrier for soil and fluids in many geotechnical applications since their permeability is very low. Geomembranes are divided in polymeric, bituminous and clay geomembranes on the basis of the material.

Polymeric geosynthetic barriers are the most used in waterproofing systems for underground structures. The polymers commonly used are polyvinyl chloride (PVC) and thermoplastic polyolefins (TPO) such as polyethylene (HDPE, LLDPE) and flexible polypropylene (fPP). These geomembrane are produced from raw material (polymer and additives) through extrusion (e.g. HDPE, LLDPE, fPP) or through calendaring (e.g. PVC) in order to obtain sheet of various thickness and width. The installation of this kind of geomembranes is done mechanically by thermal bonding, fusion or chemical bonding. Their permeability ranges between 1 10^{-11} m/s and 1 10^{-14} m/s (Koerner, 2012).

Bituminous geosynthetic barriers are sometimes used for cut-and-cover waterproofing and are obtained dipping geotextiles in bitumen or polymer modified bitumen (e.g. styrene-butadiene-styrene bitumen, SBS). The bonding is done by heating the geomembrane.

Clay geosynthetic barriers consist of a clay layer composited with geotextiles or polymeric geomembranes. It is seldom used in underground waterproofing, while is more used in foundations and retaining walls. The permeability is about 1 10^{-9} m/s (Koerner, 2012).

6.1.3 Other geosynthetics used for waterproofing systems

Geocomposites

Geocomposites are a combination of one or more geosynthetics in order to achieve multiple aims. For example, in waterproofing applications, geomembranes and geotextiles can be combined in a single element by bonding the geotextile on the extruded geomembrane permitting a faster installation due to less working phases on site. Care has to be taken in the coupling phase to avoid that the hot geomembrane damages the geotextile.

Moreover, geocomposites can be used to create high permeability drainage layers using geogrids and geomembranes.

Gaskets

Gasket are used for sealing the joints between concrete slabs or segments. They are made mainly of EPDM. Different geometries can be studied to take into account the compression behaviour of the material and the specific geometry of segments.

6.2 Materials composing geosynthetics

6.2.1 Polyester

Polyesters are a group of polymers containing the ester functional group.

Polyethylene terephthalate (PET) (Figure 6.2) is the most used polyester for geotextile production. It is a thermoplastic polymer formed by the condensation polymerization between ethylene glycol and terephthalic acid. Since for geotextiles it is used below the glass transition temperature and it is highly oriented (i.e. it is produced as a yarn), it has good chemical resistance and low creep-strain rate (ISO/TS 13434, 2008).

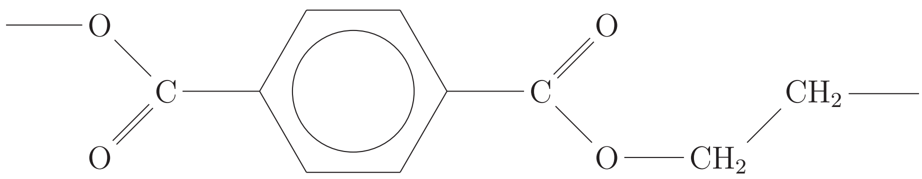


Figure 6.2: Polyethylene terephthalate (PET) monomer

6.2.2 Polyolefins

Polyolefins are a family of polymers with olefin monomers. Among polyolefins the most commonly used for geosynthetics are polyethylene (PE), polypropylene (PP) and flexible polypropylene (fPP). All these are thermoplastic polyolefines (TPO) with a semi-crystalline structure.

Polyethylene

Polyethylene (Figure 6.3) is used mainly for geomembranes, but it has applications also for geotextiles and geogrids.

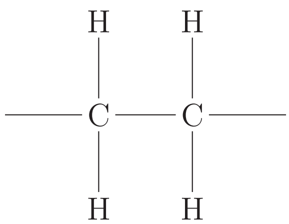


Figure 6.3: Polyethylene (PE) monomer

Based on its density it is categorized in different classes (EN ISO 17855-1, 2014):

- high density polyethylene (HDPE) with ρ=0.941–0.960 g/ml;
- medium density polyethylene (MDPE) with ρ=0.926–0.940 g/ml;
- Linear low density polyethylene (LLDPE) with ρ=0.912–0.925 g/ml.

The properties of PE are strongly dependant on density. LLDPE has excellent flexibility but is permeable and has low resistance to chemicals. On the contrary, MDPE has higher mechanical properties, chemical resistance and low permeability. Therefore, MDPE is more suitable for geomembranes. It is to be noted that the HDPE geomembranes commonly used for waterproofing are made of MDPE that reaches a density higher than 0.940 g/ml by addition of carbon black (Hsuan et al., 2008).

Polypropylene

Polypropylene (Figure 6.4) is the most used material for geotextiles, since it has good tensile properties, resistance to many chemicals and it is inert and hydrophobic.

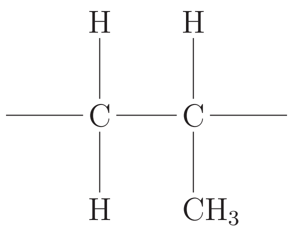


Figure 6.4: Polypropylene (PP) monomer

Flexible polypropylene is used for geomembranes. It is a copolymer of polypropylene and polyethylene, with higher flexibility than PP and a wide melting range that permits thermal seaming.

6.2.3 Polyvinyl chloride

Polyvinyl chloride (PVC) (Figure 6.5) is an amorphous polymer obtained from the polymerization of vinyl chloride.

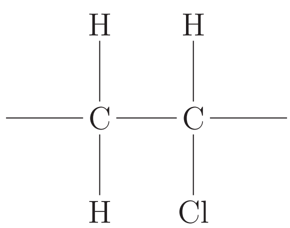


Figure 6.5: Polyvinyl chloride (PVC) monomer

Although the monomer is an inflammable gas that has been recognized as carcinogenic (World Health Organization, 1999), PVC is not carcinogenic or toxic.

The polymerization of PVC is started using initiators that create radicals from the vinyl chloride and proceeds as an auto-accelerating and highly exothermic reaction. Since the polymer is not soluble in the monomer, the former precipitate and the monomer swells the polymer giving to PVC the structure of porous grains (Wypych, 2015). This porosity is important for the ability of the polymer to absorb additives and plasticizers.

Typically, PVC is not used pure but several types of chemicals are added to enhance the properties of the polymer and to adapt them to different uses. The most common additives are:

- plasticizers: this is a big group of more than 1000 different materials used to obtain from the pure rigid PVC a semi-rigid or flexible material, known as plasticized PVC (PVC-P). Plasticizers are polymers with low molecular weight and glass transition temperature (lower than those of PVC). The most common plasticizers used in PVC-P are phthalates (92%) and among these di-2-ethylhexyl phthalate (DEHP, also known as DOP) (Hsuan et al., 2008). Concerns have been raised up for possible toxic effects of some plasticizer if released from the PVC-P, especially for medical and food packaging applications (Magdouli et al., 2013; Ventrice et al., 2013). These concerns led to the ban of some of these additives in some Countries. The effect of plasticizers is to reduce the glass transition temperature of the polymer from about 80–100 °C (Wypych, 2015) to values lower than the environment temperature. This effect implies higher flexibility and elongation at break, that are important parameters for the application of PVC-P for waterproofing. The relatively small particles of plasticizer increase the free volume in the matrix and consequently the mobility of the polymer chains. Since plasticizers are not chemically bonded to the PVC chain, they diffuse in PVC matrix and they are absorbed in the porosity of the grains.

  The effectiveness of plasticizers depends on the chosen molecule, on its size, on its molecular mass and on the percentage on the PVC mass. For geomembranes applications, the content of plasticizer ranges between 25–35% in weight on the PVC resin;

- fillers: to add fillers is common to reduce the price, but also to enhance the abrasion resistance and flame retarding properties of PVC. On the other hand, the use of fillers reduces the mechanical performances and increases the density of the material. Moreover, fillers affect the transparency of PVC. The most widely-used filler is calcium carbonate. The typical content of filler in PVC ranges between 5–15% for unplasticized PVC and 20–30% for PVC-P;

- stabilizers: these molecules are used to reduce the effect of thermal and UV ageing on PVC chains. Thermal stabilizers are added to all PVC formulation, even if thermal ageing is not a real issue during the operation life of the material, because thermal degradation occurs also during the mixing and calendaring of the material at relatively high temperatures (about 160 °C). At the contrary, UV stabilizers are usually added only for products for outdoor applications. The content of stabilizers is about 2%;

- flame retardants and smoke suppressants: unplasticized PVC does not require the use of flame retardants and smoke suppressant because the high chlorine content (56.8%) permits PVC to do not contribute to fire propagation (Levchik and Weil, 2005). Conversely, PVC-P flammability depends on the plasticized used and flame retardant and smoke suppressant can be necessary to achieve the required properties;

- biocides and fungicides: these classes of additives are used if there is the potential of degradation of the product due to bacteria of fungi. Particularly, fungi have been proved to be important colonizers of PVC (Kırbaş et al., 1999);

- pigments: pigments are used both for colouring the PVC and for UV protection. The most used molecules are titanium dioxide (for UV protection) and carbon black (Wypych, 2009). The content of pigments ranges between 5–10% of the weight.

6.2.4 Ethylene Vinyl Acetate

Ethylene Vinyl Acetate (EVA) is a copolymer of ethylene and vinyl acetate with a wide range of applications in different industrial fields (adhesives, coatings, paintings, photovoltaic modulus) and used in tunnel waterproofing for sprayed membranes.

Its properties depend on the proportion between the two components of the copolymer. It behaves as an elastomeric polymer, waterproof, flexible and with good adhesion properties.

6.2.5 Ethylene propylene diene monomer rubber

Ethylene propylene diene monomer (EPDM) is a synthetic rubber composed by the copolymerization of ethylene, propylene and small amounts of a diene that gives the chemical base for vulcanization. To increase the UV resistance, carbon black is usually added to the resin. It is applied in automotive industry and for O-rings and gaskets. In tunnel waterproofing is the most common material for gaskets for segmental linings.

6.2.6 Bitumen

Geomembranes with bitumen are made of geotextiles covered with bitumen often modified with polymers (e.g. styrene-butadiene-styrene) to increase the elasticity of the bitumen and to reduce its sensibility to fatigue and ageing. Additives can be used to increase the resistance to UV and oxidation. Bitumen geomembranes are used in underground for cut-and-cover excavation such as for the waterproofing of top slabs of metro stations.

6.2.7 Clay

Clay geomembranes are made from the combination of a geotextile or a geomembrane with a layer of clay or bentonite. The layers are kept together by needle-punching or chemical adhesives. This material is applied for the waterproofing of cut-and-cover with low hydraulic pressure (Mahuet, 2011).

Chapter 7

Degradation of waterproofing system

7.1 Geotextiles

The long-term capability of a geotextile of performing drainage and filtration is influenced by clogging that can occur by mechanical, chemical or biological phenomena (Too, 2015).

Mechanical internal clogging is due to the accumulation of fine particles within the voids of the geotextile reducing the permeability (Sabiri et al., 2017), while external clogging occurs on the upstream side of the geotextile with the formation of a filtercake at the interface between geotextile and soil (Veylon et al., 2016).

Biological clogging occurs when fungi or algae create biofilms and slimes on the fibres. However, this is not a common situation for tunnel applications.

Chemical clogging is caused by solutes that precipitate on the fibres due to the reduction of the speed of the flow in the geotextile. This is particularly the case of alkaline groundwater (i.e. calcium, sodium and magnesium solutions) and it is therefore important for tunnel waterproofing. A calcite crust affecting the permeability has been observed on the downstream side of 18 years aged geotextiles used as filters (Veylon et al., 2016). Halse et al. (1987) show that increasing the concentration of $Ca(OH)_2$ in the water, and therefore the pH, the flow time through the geotextile increases due to the formation of a filter of precipitate on the fabric.

Clogging can develop with time with two possible behaviours: an initial decrease of permeability to an asymptotic constant value or a continuous reduction to a null value. The former case can be considered acceptable as long as the final value ensures the design flow rate. On the contrary, the latter is an unacceptable situation because it implies the ineffectiveness of the drain.

The clogging of a geotextile is influenced by water solutes, by soil properties and by the properties of the geotextile. Higher porosity of the geotextile reduces the risk of clogging but at the same time reduces the filtration and protection effect.

Moreover, the percent of open area and the apparent opening size of the geotextile have to be considered for filtration purposes comparing them to the soil grain size distribution in order to avoid soil particles penetration in the geosynthetic. Non-woven geotextiles, used in tunnel waterproofing systems, have a lower tendency to clog because the irregular structure of the fabric creates many connected flow paths with great variation of nominal diameter and shape. Therefore, even if some particles are stopped in the geotextile, they do not stop completely the flow in that section. The applied pressure reduces the thickness of the geotextile and consequently the permeability (Farshad and Flüeler, 2004).

Consequently, specific tests have to be performed on the geotextile with the real soil and water to asses the compatibility to perform the filtration or drainage function for the time required by the project. For tunnel waterproofing applications, suspended particles can be the main issues, since the drainage layer is in between the shotcrete and the geomembrane and no soil particles should reach it. However, in some cases fine particles can pass through cracks in the primary lining and cause the clogging of geotextiles.

Therefore, geotextiles used in tunnel waterproofing systems as drainage layer have to be tested to evaluate the long-term clogging behaviour and the residual water flow. This flow has to be bigger than the design drained water flow. If the value of the designed water flow is too high, geotextiles can be not suitable as drainage layer and a high drainage capacity layer composed by a geocomposite or a geonet has to be adopted.

7.2 Drainage pipes

As for geotextiles with drainage function, also the long-term durability of drainage pipes is influenced by mechanical and chemical clogging: the sedimentation of fine particles transported by water and the precipitation of suspended particles. These phenomena are particularly relevant when the groundwater is rich in dissolved salts (e.g. $Ca(OH)_2$), that is often the case of rock tunnels. The clogging of drainage pipes causes the reduction of the flow and possibly the increase of hydraulic load on the lining.

In order to avoid this issue, the diameter of the pipe has to be correctly designed for the foreseen drained water flow with safety factors that take into account the clogging potential due to the composition of groundwater. Moreover, it is important to permit the inspection of the drainage pipes and to provide the possibility of cleaning the pipes during operation with regular schedule, in order to avoid clogging (Chen et al., 2019).

Furthermore, the effectiveness of drainage pipes can be affected by an incorrect design that causes, during casting, the partial closure of the section of the pipe due to the pressure of the fresh concrete. Specific design considerations on the section, material and thickness of the pipe have to be done (Masada, 2000; Touze-Foltz et al., 2008) and specifically designed elements can be installed before casting to avoid that the pressure of the concrete acts on the drainage pipe.

7.3 Degradation mechanisms of materials composing geosynthetics

7.3.1 Polyester

The main degradation mechanism affecting PET is hydrolysis. Two different and independent reactions can occur, known as internal and external hydrolysis.

The former reaction occurs in presence of acid or neutral pH and water. In these condition water is absorbed by PET and hydrolysis take place throughout the cross-section of the fibre as the reverse reaction of condensation causing the progressive reduction of strength.

Whereas, in alkaline environments the aggressive ions (i.e. OH^-) can not penetrate the fibres and the hydrolysis takes place on the surface. The consequent strength reduction is due to the cross section reduction of the fibres (Allen, 2016).

Higher molecular weight and crystallinity of PET result in lower tendency to hydrolysis. Additives and copolymers can be used to reduce the effect of internal hydrolysis, while they are less effective for the external one (Greenwood et al., 2015).

The application of PET geotextile in direct contact with concrete, such as in tunnel waterproofing, is therefore often avoided due to the presence of water and of pH>9 in the concrete, that are the typical environment parameter inducing external hydrolysis.

7.3.2 Polyolefins

Polyolefins degrade by oxidation. Even if the exact process of oxidation in solid state of polyolefins is complex and still under analysis, the principal steps of the reaction are well known.

Oxidation is initiated by the formation of a free radical. This phenomenon requires energy, that is provided by temperature, high energy radiation or UV rays (this last case is also known as photoxidation). Since the oxidation products act as initiators for other chains, once the process is initiated it proceeds rapidly as a chain reaction if oxygen is present and it is auto-accelerated (Allen, 2016). The result of oxidation is the breakage of polymer chains and consequently the reduction of strength. In PE the oxidation can also induce cross-linking, leading to lower flexibility (Greenwood et al., 2015).

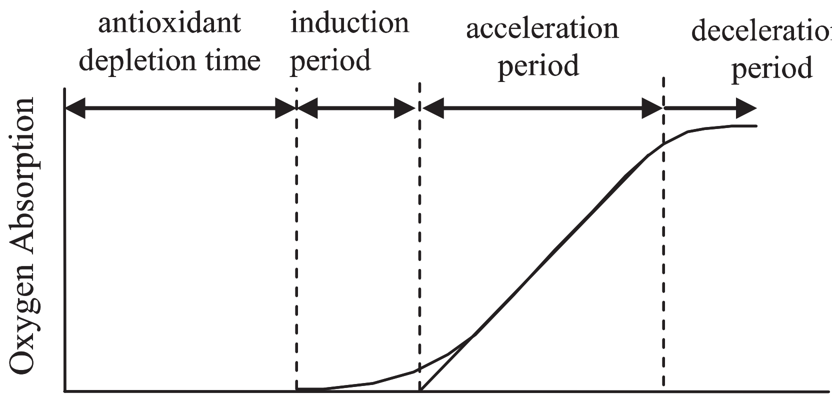


Figure 7.1: Development of oxidation of PE when antioxidants are used (from Hsuan et al. (2008))

Oxygen concentration, temperature, surface-volume ratio and the kind of polymer influence the oxidation resistance of the material. Another important factor is crystallinity of the polymer because oxygen propagation is easier in the amorphous phase.

Antioxidants and carbon black (for UV exposure) are used in small quantity (2–5%) to reduce the effect of oxidation, preventing the formation of free radicals or trapping them.

Hsuan et al. (2008) describe the long-term oxidation behaviour of HDPE. The authors identify 4 stages (Figure 7.1): a depletion time of antioxidants, when the antioxidant avoids the onset of oxidation, an induction period, when the initiation of the reaction occurs without reduction of polymer properties, an acceleration period, when oxidation occurs and the properties of the polymer degrades, and a final deceleration period.

Therefore, the effect of antioxidants is only that of delaying the onset of oxidation and the durability of the material is guaranteed until the antioxidants are completely consumed. To identify the amount of antioxidants presents in a geosynthetic the oxidative induction time (OIT) test is commonly used. This test is carried out using a differential scanning calorimeter (DSC) and measures the time interval to the onset of exothermic oxidation at a certain temperature with a fixed oxygen pressure. Knowing the original antioxidant content, this test gives an evaluation of the loss of antioxidants and of the time before the beginning of oxidation.

7.3.3 Polyvinyl chloride

Degradation of PVC is mainly due to dehydrochlorination. Dehydrochlorination is the loss from PVC of gaseous HCl and the formation of a double bond between the carbon atoms (Figure 7.2).

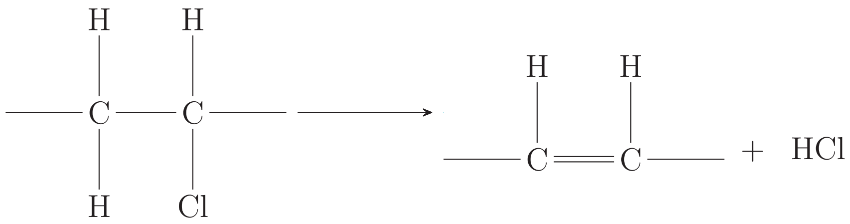


Figure 7.2: Dehydrochlorination reaction

Once the reaction is initiated in a monomer it propagates in the adjacent one with a chain reaction. Dehydrochlorination can be initiated in every monomer of the chain but structural irregularities in the PVC chain considerably increase the rate of degradation (Bacaloglu and Fisch, 1994). The starting energy for the first reaction can derive from a thermal source or from UV. The activation energy required for initiation ranges between 118 and 234 kJ/mol while propagation rate and activation energy are lower (Wypych, 2015). Van Krevelen and Te Nijenhuis (2009) propose an initial degradation temperature of 160 °C with an activation energy of 134 kJ/mol.

Thermal degradation results in the production of gaseous HCl from 160 °C (Jimenez et al., 1999) and of organic compounds over 200 °C. In UV degradation UV rays initiate dehydroclorination in PVC. The polyenes resulting from the loss of HCl are reactive in absorbing UV and induce yellowing of the PVC (Hsuan et al., 2008). The result of thermal and UV degradation is a more brittle material and crack formation (ISO/TS 13434, 2008).

Microbial attack can affect durability of PVC. Although the backbone of PVC is considered resistant to this phenomenon (Andrady, 2011), some studies have highlighted a degradation in PVC due to white rot fungi (Kırbaş et al., 1999). Conversely the influence of bacteria and fungi is recognized as important in PVC-P (Booth et al., 1968) . Sabev et al. (2006) analysed different PVC-P samples buried in ground and identified 42 fungal species while bacteria attack results not relevant. These fungi degrades the plasticizer and consequently induce a stiffer material with higher tensile strength.

In PVC-P, thermal degradation of plasticizer can occur but it is strictly depending on the plasticizer molecule. Plasticizers decompose in a range of temperature around 180–300 °C, that is the same range of PVC dehydroclorination.

7.4 Plasticizer loss from PVC-P

The most relevant phenomenon in PVC-P degradation is loss of plasticizer.

Since the plasticizer is not chemically bonded to the polymer, it can diffuse from the matrix to the surface. Once on the surface, it can be removed through:

- evaporation to the air;
- extraction by a liquid;
- migration to a solid in contact.

Since plasticizer loss is the composition of two mechanisms, the global rate of loss is given by the lower between the rate of the two.

7.4.1 Diffusion

The mechanism of diffusion can be analysed with Fick's first law (Fick, 1855)

$$J_x = -D\frac{\partial c}{\partial x} \tag{7.1}$$

where J_x is the flux in the x direction, D the diffusion coefficient and c the concentration. The driving force of this phenomenon is the difference of concentration between the material and the external environment. In order to keep in mind also the time coordinate t, neglecting any possible chemical reaction, the mass conservation equation can be used

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x}J_x \tag{7.2}$$

From equations 7.1 and 7.2 it is obtained

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \tag{7.3}$$

That, if D is a constant in time, space and concentration, reduces to Fick's second law

$$\frac{\partial c}{\partial t} = -D\frac{\partial^2 c}{\partial x^2} \tag{7.4}$$

Equation 7.4 describes one-dimension diffusion, that applies to geomembranes because the thickness is always negligible compared to the other dimensions. This equation can be solved with the boundary conditions of the geomembrane case: one-dimensional diffusion, initial uniform concentration c_0 in the membrane domain $-l < x < l$, constant concentration of the external environment of c_1. Under these conditions, the equation can be expressed as (Crank et al., 1979):

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}e^{-\frac{D(2n+1)^2\pi^2 t}{4l^2}} \tag{7.5}$$

where M_t is the mass uptake at the time t and M_∞ the mass uptake at infinite time. For short times this equation can be approximated to (Neogi, 1996)

$$\frac{M_t}{M_\infty} \simeq \frac{8}{\sqrt{\pi}}\sqrt{\frac{Dt}{l^2}} \tag{7.6}$$

From this relation it is evident that the variation in concentration is linear with $\sqrt{t}$.

However, in the case of polymeric geomembranes, D is not really a constant. Therefore, Equation 7.3 is the correct equation to be solved to study the diffusion of plasticizer in PVC. The main influencing factors of diffusion coefficient of plasticizer in PVC are:

- concentration: the presence of plasticizer in PVC matrix changes the behaviour of the material since it increases the mobility of polymer chains, reduces the glass transition temperature below the normal application temperature value increasing the free volume between the chains. All these phenomena permit to increase the diffusion coefficient (Storey et al., 1989). Therefore, a variation of the concentration of plasticizer in the matrix implies a variation of free volume and, consequently, of D. Higher concentrations result in higher D values;

- temperature: it is renown that increasing temperature the diffusion coefficient increases. This dependence can be described using Arrhenius'equation for D

$$D = D_0 e^{-\frac{E_A}{RT}} \tag{7.7}$$

  where D_0 is a constant, E_A the activation energy, R the universal gas constant and T the temperature in K (Griffiths et al., 1984);

- type of plasticizer: plasticizers with higher chain length and branching result in lower D values due to the higher difficulty in motion in the polymer (Storey et al., 1989);

Table 7.1 reports D values obtained for different plasticizers.

7.4.2 Evaporation

Evaporation of plasticizer from the surface of a PVC-P membrane is governed by the partial pressure of plasticizer in the air. The flux φ of gas molecules leaving the surface can be computed from Hertz-Knudsen equation

$$\varphi = \frac{p}{\sqrt{2MkT}} \tag{7.8}$$

where p is the partial pressure, M the molecular weight of plasticizer, k the rate constant of transfer of low molecular weight substances and T the reference temperature. At the typical site temperatures, the rates of evaporations of plasticizers are

Table 7.1: Diffusion coefficients (D) for plasticizer diffusion from Storey et al. (1989)

Plasticizer	T (°C)	C_0 (wt%)	D (cm^2/s)
DOP	80	0	$1.26 \cdot 10^{-9}$
	90	0	$3.74 \cdot 10^{-9}$
	100	0	$1.02 \cdot 10^{-8}$
DIDP	90	0	$4.58 \cdot 10^{-10}$
	90	11.6	$1.49 \cdot 10^{-9}$
	90	20.7	$5.55 \cdot 10^{-9}$
DUP	90	0	$3.29 \cdot 10^{-10}$
	90	11.6	$1.70 \cdot 10^{-9}$
	90	20.7	$4.36 \cdot 10^{-9}$
UDP	90	0	$2.60 \cdot 10^{-10}$
	90	11.6	$7.53 \cdot 10^{-10}$
	90	20.7	$9.65 \cdot 10^{-9}$

10 to 100 times lower that those of diffusion (Wypych, 2004), therefore, evaporation can be a limiting phenomenon in plasticizer loss for geomembranes applications.

7.4.3 Migration and extraction

Migration of plasticizer from PVC-P to another material in contact has been studied for its applications in medical and food packaging (Coltro et al., 2014) and for possible migrations to other polymeric materials (e.g. PVC, PS, PMMA) (Marcilla et al., 2004; Papakonstantinou and Papaspyrides, 1994; Papaspyrides and Papakonstantinou, 1995).

Theoretically, migration is composed of 3 phases: diffusion in PVC-P, interface phenomena and diffusion in the contact material. Interface phenomena have been shown to have no influence on the rate of migration (Marcilla et al., 2008; Wypych, 2004). Therefore, the migration is ruled by the diffusivity in PVC-P and in the contact material and by the compatibility of the plasticizer with it.

Extraction, i.e. the migration to contact liquid materials, follows the diffusion equations shown before. In this case a counterdiffusion of the liquid in the matrix occurs, with no effect on the diffusion of plasticizer. No surface barriers between liquid and plasticizers exists, unless the two are immiscible, that is not the case in many real applications (Wypych, 2004).

7.4.4 Effect of loss of plasticizer

The quantity of plasticizer in a PVC-P geomembrane can be described by the plasticizer content C_P, defined as

$$C_P = \frac{M_P}{M_M} \tag{7.9}$$

where M_P is the mass of plasticizer and M_M the mass of the geomembrane. This value can also be expressed as a percentage.

The loss of plasticizer can be described with the plasticizer loss ratio P_L (Benneton, 1994) defined as

$$P_L = \frac{M_{P_0} - M_P}{M_{P_0}} \tag{7.10}$$

where M_{P_0} is the initial mass of plasticizer.

When plasticizer is lost the material loses its flexibility and glass transition temperature and surface hardness increase.

Another effect of the loss of plasticizer is the loss of volume and consequently the shrinkage of the material. Due to the two-dimension shape of geomembranes, this effect is relevant only in the transversal and longitudinal direction, and not for the thickness. This phenomenon is well known in PVC-P membrane applications for roof waterproofing: in these applications technical solutions have been developed to avoid that the shrinkage of the membrane induces stresses in the material and cracks. Assuming that the porosity of the material is always equal to 0, i.e. the loss of plasticizer does not create voids in the material, Giroud (1995) derives the following theoretical equation to compute the shrinkage of the membrane

$$\frac{L_M}{L_{M_0}} = \left[1 - \frac{C_{p0} - C_p}{(1 - C_p)[C_{p0} + \frac{\rho_p}{\rho_{RA}}(1 - C_{p0})]}\right]^{\frac{1}{3}} \tag{7.11}$$

where L_M and L_{M_0} are the dimension at a specific plasticizer content C_p and the initial dimension respectively, C_{p_0} the initial plasticizer concentration, ρ_{RA} the density of the PVC resin and other additives and ρ_p the density of the plasticizer.

Under the same hypotheses, the density of the membrane can be evaluated: since plasticizer density is lower than that of PVC, the density of the material decreases with plasticizer loss as

$$\rho_M = \frac{(1 - n_M)\rho_{RA}}{1 + C_p(\frac{\rho_{RA}}{\rho_p} - 1)} \tag{7.12}$$

where ρ_M is the density of the membrane and n_M the porosity of the membrane (approximately 0) (Giroud and Tisinger, 1995).

7.5 Existing accelerated ageing tests on PVC-P

Since its great importance and large application fields, many studies have been developed on the durability of PVC-P. Great efforts have been made for industrial applications such as power cables (Ekelund et al., 2007; Jakubowicz et al., 1999), for the waterproofing of roof and buildings protection and for civil engineering works such as dams, water channels and artificial ponds (Blanco et al., 2012; Cazzuffi, 1995, 2016; Lambert et al., 1999; Newman et al., 2004; Stark et al., 2005). All these applications require different design life, in different environmental and operation conditions.

Therefore, several ageing tests have been developed to investigate long-term durability of PVC-P. These tests differ for the environment and the conditions of ageing, considering different degradation phenomena (e.g. loss of plasticizer, chemical effect of the environment, UV rays, biological degradation, electricity effect).

Tables 7.2 and 7.3 summarize some of the existing tests used for PVC-P.

The control requirements are usually elongation and resistance at break and weight change. These are not directly representative of chemical or compositional variations in the material and in many applications are not sufficient as parameters for a complete evaluation of the long-term performances. Nevertheless, these parameters, easy to be measured, give a qualitative assessment of the ageing and designer are more familiar with these mechanical characteristics than with chemical observations.

The existing tests can be divided considering the ageing environment and degradation mechanisms simulated in:

- Oxidation test, in an air environment accelerated by heat;
- Immersed test, in water environment accelerated by heat;
- Chemical resistance test, simulating the resistance to different chemical environment accelerated by emphasizing the chemical condition;
- Micro-organism test;
- UV weathering test.

Oxidation test

Oxidation tests are performed in air in an oven, usually with a forced air circulation, where ageing is accelerated with relatively high temperatures. The ageing mechanism is both the loss of plasticizer accelerated by temperature and the oxidation of the polymer chains in presence of oxygen. The ventilation should facilitate evaporation of plasticizer from the surface, thus avoiding that surface accumulation reduces plasticizer diffusion rate.

Table 7.2: Tests on the long-term properties of PVC-P (part 1)

Test	Standard	Medium	Temperature	Time	Specification	Requirements
Dimensional stability	EN 1107-2 (EN 1107-2, 2001)		80°C	6 hours	BBT	=<2.0%
	EN 1296 (EN 1296, 2000)		80°C	70 days	BBT OBV	Reduction of tensile strength =<20% Reduction of elongation to break =<20% No crack at -20°C
Oxidation resistance	EN 14575 (EN 14575, 2005)	oven	85°C	90 days	BBT OBV Gotthard	Reduction of tensile strength =<20% Reduction of elongation to break =<20%
Hot water immersion	EN 14415 (EN 14415, 2004) DIN 16726 (DIN 16726, 2017)	Water, flow rate 25–100% capacity per hour	50°C	8 months	BBT OBV	Reduction of elongation to break =<10–20% Mass variation =<4% Foldability at low temperature
Limewash immersion	EN 14415 (EN 14415, 2004) EN 1847 (EN 1847, 2010)	Limewash, test liquid 2	23°C	90 days	BBT OBV Gotthard	Reduction of tensile strength =<25% Reduction of elongation to break =<10–25%
Sodium bisulphite solution	EN 1847 (EN 1847, 2010)	5–6% soulphurus acid solution, test liquid 3	23°C	90 days	BBT OBV Gotthard	Reduction of tensile strength =<10–20% Reduction of elongation to break =<20% No crack at -20 °C
Acid and alkaline solutions	DIN 16726 (DIN 16726, 2017)	Acid and alkaline solutions		28 days	RFI	Reduction of elongation to break =<20%
UV resistance	EN 1297 (EN 1297, 2005)			5000 hours		

Table 7.3: Tests on the long-term properties of PVC-P (part 2)

Test	Standard	Medium	Temperature	Time	Specification	Requirements
Thermal ageing	EN 1296 (EN 1296, 2000) DIN 16726 (DIN 16726, 2017)		70°C	70 days	Gotthard	Weight loss =<2.0% Reduction of elongation to break =<10%
Storage NaCl(10%)	EN 1847 (EN 1847, 2010) DIN 16726 (DIN 16726, 2017)	NaCl(10%) solution	23°C	90 days	Gotthard	Reduction of elongation to break =<10% Weight loss=<1%
Storage N_2SO_4(5%)+ $MgSO_4$(1%)	EN 1847 (EN 1847, 2010) DIN 16726 (DIN 16726, 2017)	N_2SO_4(5%)+$MgSO_4$(1%) solution	23°C	360 days	Gotthard	Reduction of elongation to break =<10%
Micro-organism	EN 12225 (EN 12225, 2000) EN ISO 846 (EN ISO 846, 1997)		23°C	6 months	Gotthard	Weight loss=<1%

Immersed test

Many tests methods have been developed requiring the total immersion of PVC-P samples in water or liquid solutions, often in presence of water circulation and in some cases with relatively high temperature. Two mechanisms of ageing can be analysed:

- in case of water immersion with high temperature the loss of plasticizer is the main phenomenon occurring. The extraction of the plasticizer migrated from the surface is helped by the water circulation and therefore the diffusion is not slowed by accumulation on the surface. Great care has to be taken to the volume of water for each sample in order to avoid any influence of concentration of plasticizer in the liquid. With this aim the volume should be enough to consider negligible the quantity of plasticizer and for long-lasting tests the water should be changed periodically.
- in case of immersion in water solutions usually the test is performed at environment temperature (i.e. 23°C). In these situations, the chemical degradation due to the solute in the water is analysed. This is important for groundwater rich of dissolved salts. To enhance the degradation, the test liquids have solute concentration higher than those usually present in groundwater. The most common solutes are calcium hydroxide and sulphur composites (e.g. H_2SO_3, $NaHSO_3$, $MgSO_4$).

UV weathering test

UV rays are one of the most effective ageing factors for PVC. Accelerated UV ageing tests are performed in special ageing chambers with fluorescent UV lamps constantly lightening the samples for 5000 hours. In order to better simulate natural weathering, cyclically the samples are sprayed with water.

Micro-organism test

To evaluate the microbiological resistance of the material, it is buried in a microbiological active soil, in controlled conditions of temperature and humidity. The residual properties are evaluated both visually and with mechanical tests.

7.5.1 Methods for long-term extrapolation of accelerated ageing tests

The data obtained from accelerated ageing tests have to be extrapolated to the real site environmental conditions (i.e. temperature, chemicals, UV exposure). For thermal ageing tests one of the more diffused extrapolation technique is the use of Arrhenius'equation

$$k = k_0 e^{-\frac{E_A}{RT}} \tag{7.13}$$

where k is the rate constant, k_0 a constant, E_A the activation energy, R the universal gas constant (8.3145 kg m^2/s^2 K mol) and T the temperature in K. If the data are collected at different temperatures, the rate can be computed as the linear projection of the values of a parameter for different temperatures plotting $ln(k)$ versus $1/T$, and E_A and k_0 can be obtained from the equation:

$$ln(k) = ln(k_0) - \frac{E_A}{R}\frac{1}{T} \tag{7.14}$$

This method assumes that only one phenomenon is acting on the material, that its rate is constant along all the time of the test and that there is no difference in the mechanisms and behaviour of phenomena occurring at different temperatures. If the data fit a straight line in the log-plot, the hypotheses can be considered fulfilled.

In order to have a reliable prediction at least 3 temperatures have to be tested, with a range between the temperature values lower than 15°C and with the lower test temperature not exceeding the site temperature for more than 25 °C (EN ISO 2578, 1999).

Benneton (1994) analyses samples of different geomembranes aged for 10 years immersed in water and finds a good correlation to long-term extrapolations of accelerated ageing tests values of plasticizer loss using Arrhenius' equation.

Another possible technique for data extrapolation to the long term is the use of the principle of time-temperature superposition. The hypothesis of this approach is that the effect of a variation in temperature at a defined time can be correlated to the variation of time at a defined temperature. Therefore, the data of the variation of a property of the material with time at different temperatures can be shifted with some vertical and horizontal shift factors to superimpose to the data at the temperature of interest creating a master curve. This master curve, created by all the curves at different temperatures, permits the evaluation of the property for longer values. This approach is not suitable for all polymers since the base principle of the superposition is not always true.

For UV weathering the average quantity of UV acting on the membrane in the installation site conditions can be evaluated and compared to the same UV exposition in the accelerated tests.

7.6 Data from naturally degraded PVC-P

Some studies have reported data of tests performed on naturally aged samples in different applications.

Brebu et al. (2000) report data from 18 years outdoor aged PVC-P samples from electrical cables with few variation of the properties of the material from the original ones.

For membrane aged for 30 years buried in a basin at 3°C Newman et al. (2004) report that no relevant variation has been noticed even in presence of roots. Cazzuffi (1995) from the analysis of samples of 15 years old PVC-P membrane taken from an hydraulic canal concludes that although the material has became stiffer the permeability is not compromised and the geomembrane is still satisfactory for its aim. The same author (Cazzuffi, 2016) analyses samples of PVC-P geomembranes aged up to 29 years from dams. The study concludes that waterproofing properties increase with time due to a reduction of water permeability coefficient and that the decrease of mechanical properties is not affecting the barrier function. No relevant changes in mechanical behaviour have been reported also for PVC-P geomembrane used for a reservoir waterproofing after 19 years from the installation (Blanco et al., 2012).

At the contrary, Lambert et al. (1999) report damages and cracks on 3 years aged PVC-P geomembrane used for an artificial basin in an alpine environment. While the material constantly under the water level presents a small deviation from the original properties, the samples constantly above the water level have great variation both of plasticizer content and of mechanical properties. The authors remark that cracks have formed due to shrinkage and impact loads. This highlights the great influence of UV photo-oxidation, especially in high mountain environment.

7.6.1 Natural degradation of PVC-P geomembranes in underground structures

While many case histories are reported for dams and basin applications, underground and tunnel cases of naturally aged PVC-P membranes are rarely reported.

Usman and Galler (2014) report the analyses on ten samples from five different tunnels in Austria after about 30 years of operation. The material is in some cases stiffer than modern geomembranes and has a lower plasticizer content. However, the lack of informations on the original properties of the material does not permit to establish a correct correlation. The authors conclude that the degradation level does not compromise the serviceability of the membrane. It is worthy to be noted that the degradation of the membranes taken from different cross-passages is different even for similar ageing times. This confirms the high influence of the ageing environment on the development of degradation of PVC-P membranes. Moreover, the influence of the environment is also correlated to the water quality: from IR spectroscopy presence of calcium carbonate has been found in the geomembrane. This can be justified partially by the filler in the membrane and partially by the penetration in the geomembrane of the salts dissolved in the water.

Maehner et al. (2018) take samples of PVC-P geomembrane from a 43 years old railway structure in Germany. The PVC-P geomembrane has a thickness of 1.5 mm and was protected by a 1 mm rigid geomembrane and a non-woven geotextile. The original material has not been found and therefore no comparison has been possible with the original properties. Nevertheless, the mechanical properties of the aged membrane and of the welding fulfil modern requirements and no damage has been found. The tensile strength of the aged material result >12 N/mm^2 and the elongation at break >200 % in the 51% of cases and higher than 150% in all cases but one. The membrane withstood an applied water load of 1 bar for several days without leaking.

The clear lack of reported case histories and the shortage of information on the original properties and on the ageing environment for the reported ones do not permit to perform a deeper analysis of data coming from underground waterproofing naturally aged PVC-P geomembranes.

Therefore, at the state of the knowledge, accelerated ageing tests and data from other applications are the best available tools for long-term evaluation of durability of waterproofing systems, with the clear disadvantages due to the different ageing conditions.

Chapter 8

Tunnel waterproofing accelerated ageing test

The tests reported in the previous Chapter do not represent the real conditions of the membrane once it is installed in the tunnel. For PVC-P membranes, oxidation is negligible below 120°C, that means in all real tunnel applications. UV and weathering are only limited to the storage phase of the material before the installation and are therefore negligible, too. Moreover, the presence of fungi or micro-organisms is inhibited by the absence of air circulation and by the chemical conditions (i.e. pH>8.5) due to the concrete slabs.

Finally, immersed tests seem to be the most representative, simulating mostly the loss of plasticizer from the membrane, accelerated using warm water. It is important to consider that if the temperature is too high dehydrochlorination can occur (due to the higher activation energy) and the two phenomena will cooperate in degrading the material. This is not a realistic condition in the job-site, where the temperature is not enough to initiate dehydrochlorination. Nevertheless, also immersed tests are not simulating exactly the real conditions. In the immersed test small sample (some cm^2) are tested totally immersed in water only in some cases flowing. In the tunnel, only one side of the membrane is exposed to the water, while the intrados side is in direct contact with the final lining concrete. This means that the path of diffusion of the plasticizer can be different due to a non-uniform flow of the plasticizer and to the different surface condition. Moreover, due to the small size, the diffusion can be almost three-dimensional, while the membrane can be considered in mono-dimensional condition because thickness is small compared to the length and the high of the membrane (some mm compared to 2 to 10 m). Furthermore, the worst condition for the degradation of a real tunnel is when there is a constant flow of incoming water through the geotextile on the extrados side of the membrane, accelerating the removal of the plasticizer from the surface, and consequently the diffusion of plasticizer from the membrane to the surface. Finally, the presence of shotcrete and concrete creates a particular environment in terms of pH that can affect the membrane and that is not considered in the immersion tests. Therefore, a new test device has been developed to better simulate these conditions and to obtain a more realistic estimation of the long-term behaviour of PVC-P waterproofing membrane.

8.1 Apparatus

In order to better reproduce the real conditions of the waterproofing membrane in the tunnel, the tested samples have been created as a core drilling of the tunnel with 4 layers:

- a 5 cm slab of concrete to simulate the primary lining;
- a layer of PP geotextile simulating the protection layer;
- the PVC-P waterproofing membrane;
- a 15 cm slab of concrete to simulate the final lining.

A constant flow of water has been maintained through the geotextile to reproduce the flow of the drained water. Water is only flowing on the geotextile side and not on the surface between membrane and final lining. To facilitate the flow of the water the top edge is knocked off both on the 5 cm and on the 15 cm slab.

The sample dimensions are 150x150 mm. This dimension has been chosen to limit boundary interference on the test, to simulate the mono-dimensional behaviour of plasticizer flow and to allow mechanical tests on the aged samples. Bigger samples would result in difficulties due to the dimension of the test device and to the water flow needed, and would not have increased significantly the results. The samples have been installed on an aluminium structure. On the top of the samples a rigid PVC pipe is installed. This pipe has 150x2 mm hoses in the bottom where the PP geotextile is inserted. Therefore, the water flowing in the pipe flows along the geotextile through the sample and then in an U-shaped rigid PVC pipe positioned below the samples. This U-shaped pipe collects the water to the storage tank. A pump keeps the flow, pumping water from the storage tank to the inlet pipe (Figures 8.1 and 8.2).

The temperature of the water is kept constant by an electric boiler installed between the pump and the inlet pipe. For the tests at 75°C special layers of waterproof and warm keeping materials have been installed on the device in order to avoid loss of water and to maintain the temperature in the device.

The water flow is measured periodically at the end of the U-shaped pipe and for each sample. The temperature is measured in the electric boiler, at the end of the rigid PVC pipes and in the storage tank. Periodically the temperature is measured also on the geotextile just above the point of contact between the geotextile and the sample membrane.

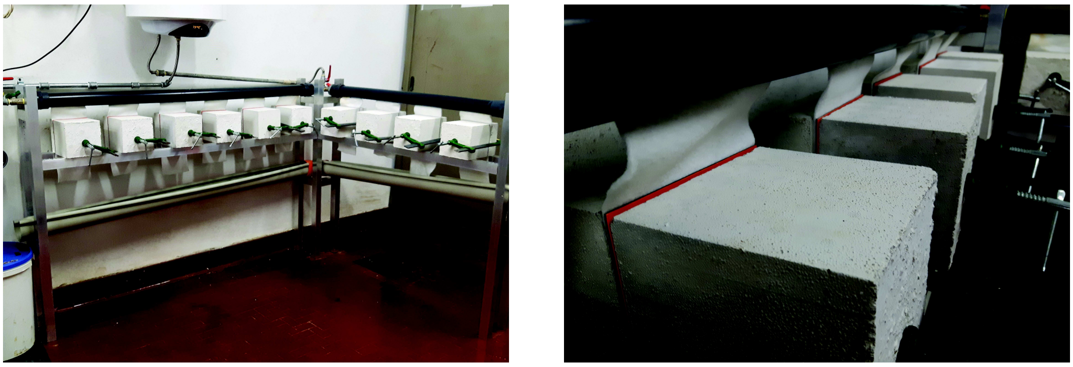


Figure 8.1: Photos of the developed device

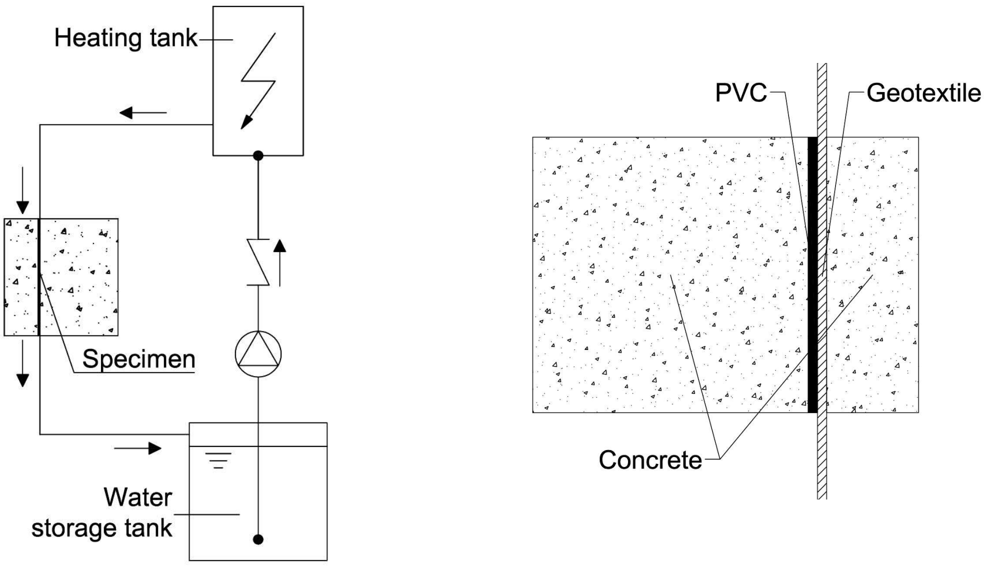


Figure 8.2: Schematic drawings of the plant of the device and of the section of one specimen

8.2 Materials

The two types of PVC-P commercial membrane used for the tests of Chapter 5 have been tested in the device:

- material A, a two-colour signal layer 2 mm co-extruded PVC-P membrane. This membrane has 20% of carbonate filler inside. This is a commercial entry-level waterproofing geomembrane;

Table 8.1: Parameters of the water used in the accelerated ageing tests

pH	Electrical conductivity (μS/cm)	TH (°f)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	Cl^{-} (mg/l)	$NO_3{}^{--}$ (mg/l)	$SO_4{}^{--}$ (mg/l)	$CO_3{}^{--}$ (mg/l)
7.68	544	26.08	77.7	16.2	29.8	62.6	61.7	233.0

- material B, a translucent 2 mm PVC-P membrane. This membrane has no fillers inside. This is a commercial high-quality waterproofing membrane.

Material A has a plasticizer content, expressed as percentage on the weight of the membrane, of 24.0% while material B of 26.7%.

The regularization layer is a commercial PP non-woven geotextile with mass per unit area of 500g/m^2.

The water used in the tests has been taken from the water supply system. In Table 8.1 the parameters of the water before the test are reported.

8.3 Test schedule

Three tests have been performed at different temperature of the water: 45°C, 60°C and 75°C. Tests at 60°C and 75°C lasted for 9 months.

In the test at 45°C after 3 months fungi appeared on the membrane significantly changing the ageing of the samples. Therefore, the test was stopped and the device cleaned and restored. The test was then restarted for 6 months at 45°C with 1 ppm of chlorine in order to avoid appearance of fungi.

Material A has been tested at all three temperatures while material B has been tested only at 75°C and at the second test at 45°C.

In order to compare the results obtained from the new device with standard tests available, material A and B have been tested in accordance with standard test procedures both by immersion in hot distilled water and by ageing in oven for 3 months at 75°C (EN 14415, 2004; EN 14575, 2005).

8.4 Test procedure

8.4.1 Sampling

The 150x150 mm specimens have been taken from the rolls of the membrane avoiding the 20 cm near the boundary of the roll. The square samples have been cut paying attention to have the sides parallel to the extrusion direction, in order to conserve the different behaviour of transversal and longitudinal direction. Samples have been checked to avoid the presence of any irregularity or surface damage before the test.

8.4.2 Physical and chemical properties

Visual check

Samples are visually checked and photos are taken before the ageing test, after the test, after cleaning and after weighting in order to find any possible visual change (e.g. colour, uniformity).

Weight

All samples are weighted before and after the ageing with a balance with an accuracy of ±0.1 mg.

In order to determine the initial dry mass, the samples are stored in a desiccator until a constant weight is reached (experimentally this procedure has result to last about 72 hours). Then the samples are weighted to the nearest 0.1 mg and the initial dry weight (M_1) is obtained. The samples are not dried in the drying chamber to avoid any ageing due to the heat before the test.

After the ageing test, the samples are cleaned with a cloth and alcohol to eliminate deposits and placed in the drying room at 60±2°C for 48 hours. Subsequently, the samples are cooled in the desiccator and weighted to the nearest 0.1 mg. This value is assumed as the final dry weight (M_2). The change in weight (C) is evaluated as a percentage as

$$C = \frac{M_2 - M_1}{M_1} \cdot 100 \tag{8.1}$$

Density

The density is evaluated on 5x5 mm samples. The samples are dried for 48 hours in oven at 60±2°C to eliminate the water, then they are weighted in air (M_{air}) and immersed in water (M_{water}) to the nearest 0.01 g.

Using the Archimedes' principle the density ρ can be evaluated as

$$\rho = \rho_{H_2O} \frac{M_{air}}{M_{air} - M_{water}} \tag{8.2}$$

with ρ_{H_2O} the density of water.

Three samples are tested for each of the materials and from each aged specimen and the mean of the three has been assumed as the value of density.

Size

The dimension of the sides of the samples is measured with a calliper with a precision of 0.01 mm before ageing (L_1) and after the weighting of aged samples (L_2). Thickness is not measured because the possible variation in this dimension is very low, due to the small thickness. The error and the variation of thickness are in the same order of magnitude of the precision of the measure. Moreover, the production tolerance on the thickness of geomembranes is bigger than the possible dimensional variation.

The change in size is computed in percentage as the variation of the single side

$$\Delta L = \frac{L_2 - L_1}{L_1} \cdot 100 \tag{8.3}$$

and as the variation of the area computed on the mean value of the longitudinal and transversal sides

$$\Delta A = \frac{A_2 - A_1}{A_1} \cdot 100 \tag{8.4}$$

with

$$A_i = \overline{L}_{i,transversal} \cdot \overline{L}_{i,longitudinal} \tag{8.5}$$

Water absorption

Water absorption tests are performed both on unaged membranes and on the aged samples in accordance with EN ISO 62 (2008). However, specimen of 50x50 mm instead of 60x60 mm are used because three square aged samples of 60 mm of width after the mechanical test are not available, while three 50x50 mm samples are available.

The samples are dried in an oven at 50°C until no change in weight occurs, then cooled at room temperature in the desiccator and weighted to the nearest 0.1mg (m_1). Afterword, the samples are completely immersed in distilled water at a temperature of 20±2°C. The determination of water absorbed is done after 24 hours, 72 hours, 7 days and then each week until the change in weight is less than 1%. At each interval, the sample is extracted from the water, the surface water removed with a dry cloth and the sample is immediately weighted (m_t). The water absorbed at time t is expressed as a percentage as

$$c = \frac{m_t - m_1}{m_1} \tag{8.6}$$

In accordance to EN ISO 62 (2008), from these tests it is possible to derive the water content at saturation c_s and the diffusion coefficient D, in the hypothesis that Fick's diffusion law can be applied, as stated in the standard.

The solution of Fick's second law for a plane sheet with the boundary conditions of constant concentration on the two surfaces and zero concentration inside can be expressed as (EN ISO 62, 2008)

$$c(t) = c_s - c_s \frac{8}{\pi^2} \sum_{k=1}^{20} \frac{1}{(2k-1)^2} e^{-\frac{(2k-1)^2 D \pi^2}{d^2} t} \tag{8.7}$$

where $c(t)$ is the water content at time t, and d the thickness of the membrane. Fitting this equation to the water absorption data, the value of D and c_s are obtained.

Plasticizer absorption

To compare the loss of plasticizer during the test with the theoretical diffusion behaviour according to Fick's law, absorption tests have been performed on the two original materials at the three test temperatures (45°C, 60°C and 75°C) and at room temperature (20°C). This procedure has been reported by several authors such as Griffiths et al. (1984), Papakonstantinou and Papaspyrides (1994), and Storey et al. (1989).

The aim is to estimate the diffusion coefficient at different temperatures from the integration of Fick's second law.

In the case of a membrane the specimen can be obtained with a geometry that permits to consider the thickness d negligible compared to the other dimensions. This allows to hypothesize that diffusion only occurs in the direction of thickness and that the diffusion through the lateral surface of the specimen is negligible.

Fick's law can be solved considering the boundary conditions of constant concentration c_0 on the two surfaces and uniform initial concentration c_b in the membrane equal to the concentration of plasticizer in the membrane (Crank et al., 1979). The equation of concentration $c(x,t)$ is

$$c(x,t) = c_b + (c_0 - c_b) \left[1 - erf \left(\frac{x}{2\sqrt{Dt}} \right) \right] \tag{8.8}$$

differentiating this equation and using Fick's first law the flux of plasticizer through the surface can be computed (Storey et al., 1989). Integrating the flux over time and multiplying it for the area A of the surface the total amount of plasticizer absorbed $p(t)$ at time t can be evaluated as

$$p(t) = 2A(c_0 - c_b)\sqrt{\frac{Dt}{\pi}} \tag{8.9}$$

From this relation the coefficient of diffusivity D can be obtained for each couple $p(t)$-t. A linear relationship exists when the values of plasticizer absorbed is plotted against $\sqrt{t}$. The slope m of this straight line can be used to evaluate D as

$$D = \frac{m^2 \pi}{4A^2(c_0 - c_b)^2} \tag{8.10}$$

Circular specimens with a diameter of 30 mm have been cut from the membranes with a metallic hollow cutter. The specimens have been dried in desiccator for 72 hours and weighted. Then they have been immersed in the plasticizer. Each 10 minutes a specimen is removed from the plasticizer, cleaned up with a clean cloth to eliminate plasticizer from the surface and weighted. Since the diffusion coefficient at lower temperature is small, for tests at 20°C the time interval has been increased to 4 hours with a duration of the test of 24 hours. The difference between the first and last weight gives the absorption of plasticizer. A layer of fibreglass net is put on the base of the tank and between one specimen and the other to guarantee the flux of plasticizer on both the surfaces. Since the absorption occurs on two surfaces, the mass of absorbed plasticizer is divided by two.

The plasticizer is kept at a constant temperature ±1°C. To guarantee the temperature constancy, the tank filled of plasticizer has been put in a bigger container with water at the desired temperature that gives the thermal inertia to small temperature variations. The test duration is of 1 hour, except for tests at 20°C.

There is an intrinsic time limitation in this method given by the limit of validity of the used equation. Indeed, the solution of Fick's second law used is valid for a semi-infinite medium. Therefore, it is valid only when there is no interference on the flow from one surface of that from the other one. Consequently, the test has to be stopped before the flux of plasticizer reaches the center of the surface of the membrane. Considering the obtained diffusion coefficients and the thickness of the membranes, this condition has always been respected.

8.4.3 Mechanical tests

Tensile test

Both the unaged and aged membrane are tested with a tensile test in accordance with EN ISO 527 (2012) (Figure 8.3). For the unaged materials 5 samples are tested in transversal direction and 5 in the longitudinal direction. From each aged sample 4 specimens are tested, 2 transversal and 2 longitudinal. The specimens are cut with a dumb-bell shape.

Before testing, the specimens are conditioned for 20 hours at 23±2°C, that is also the test atmosphere. The test is performed at a fixed deformation speed of 100 mm/min.

From these tests, three results are obtained, as defined in EN ISO 527 (2012):

- stress at break;
- strain at break (or elongation at break);

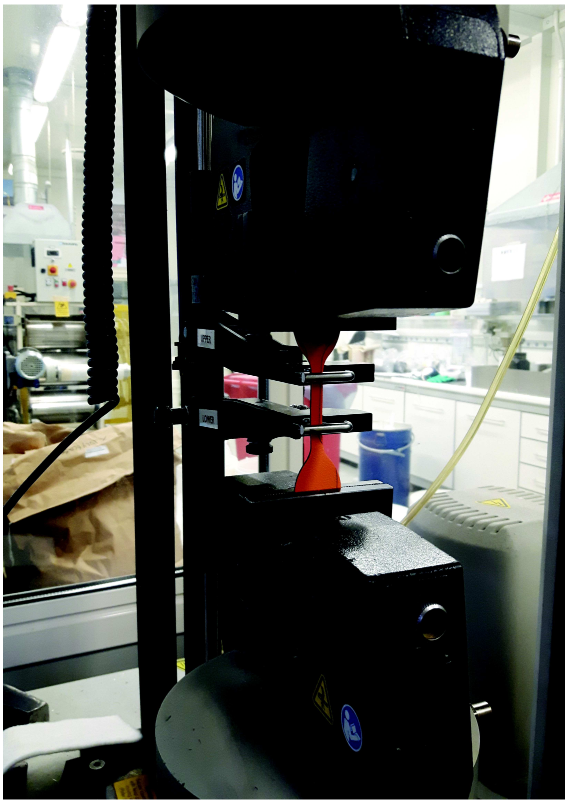


Figure 8.3: Photo of the device used for tensile tests

- elastic modulus in the range 0–1% of deformation.

Flexibility at low temperature

All samples are tested for the flexibility at low temperature in accordance with EN 495-5 (2013). From each sample a specimen of 50x100 mm is cut, folded of 180° and conditioned for 12 hours at -25°C. After the conditioning, the specimen is rapidly folded with the folding device (Figure 8.4). If any crack appears on the material, the test is not passed and the procedure has to be repeated at an higher temperature.

Shore A hardness

The surface hardness of the samples is measured with a Shore A durometer (ISO 48-4, 2018). Since the thickness of the membrane is of 2 mm and the Shore A test requires a minimum thickness of 6 mm, three layers of membrane are superimposed for the test, as suggested by ISO 48-4 (2018). For each sample 5 values are measured and averaged.

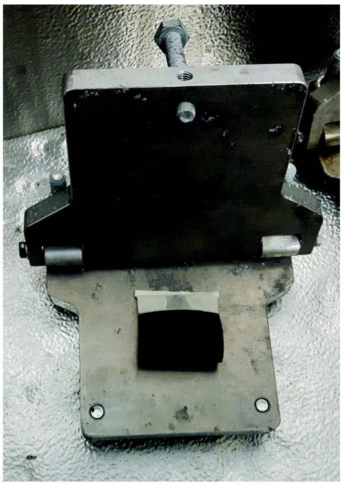


Figure 8.4: Photo of the tool for flexibility test

8.5 Results

8.5.1 Physical and chemical properties

Visual check

After the tests and before cleaning, the specimens result partially covered, on the side in contact with the geotextile, with calcium carbonate, due to the drying of the circulating water. This layer is more evident in the tests at 75°C while it seams to be not influenced by the ageing time. Indeed, the higher test temperature implies higher precipitation of salts and evaporation of water.

The specimens tested at 45°C where fungi appeared have the geotextile side covered with an opaque soft small layer, that is the microbiological environment. This layer becomes more uniform and thick with the increase of ageing time (Figure 8.5). When the specimen is left to dry up, this layers turns to dark green and becomes brittle.

Moreover, once the specimens are cleaned up with alcohol, some surface changes appear.

In material A, the orange side of the membrane with time becomes less bright and shows some local point turned red. This phenomenon does not occurs for the tests at 45°C and is more evident for the tests at higher temperatures and with longer ageing tests. This is due to the slow oxidation of the polymer and to water absorption, since the colour returns partially more bright after drying in oven.

For material B, the membrane becomes white and opaque for the water absorption and returns transparent after drying. The membranes aged for more time at the higher temperatures yellowed due to oxidation. The oxidation is much more evident for the specimens aged in oven according to EN 14575 (2005), where the

Figure 8.5: Photo of one of the specimens aged for 90 days at 45°C where fungi appeared

presence of oxygen accelerates the process.

Weight

Figure 8.6 reports the results of the changes in weight for the tested specimens. Due to the composition of PVC-P and to the relatively low temperatures it has been assumed that all the loss of mass is only due to plasticizer loss.

It is evident that the presence of fungi highly influences the loss of plasticizer inducing a very fast loss of weight that is out of the range of values of the other tests.

Material B shows a better behaviour if compared to the tests at the same temperature performed on material A. Obviously, higher temperatures induce higher loss rates, even if the loss rates seem to decrease with time.

Figure 8.7 shows the comparison of the results of the tests at 75°C in the developed device and in water and in oven according to EN 14415 (2004) and EN 14575 (2005). The loss of plasticizer is much higher in the developed ageing device, probably due to the constant flow of water on the specimens that enhances the removal of plasticizer from the surface, guaranteeing a zero external concentration and consequently increasing the flux of plasticizer.

Density

The densities of materials A and B are of 1.23 and 1.35 g/cm^3 respectively. The difference between the two values is due to calcium carbonate filler in the

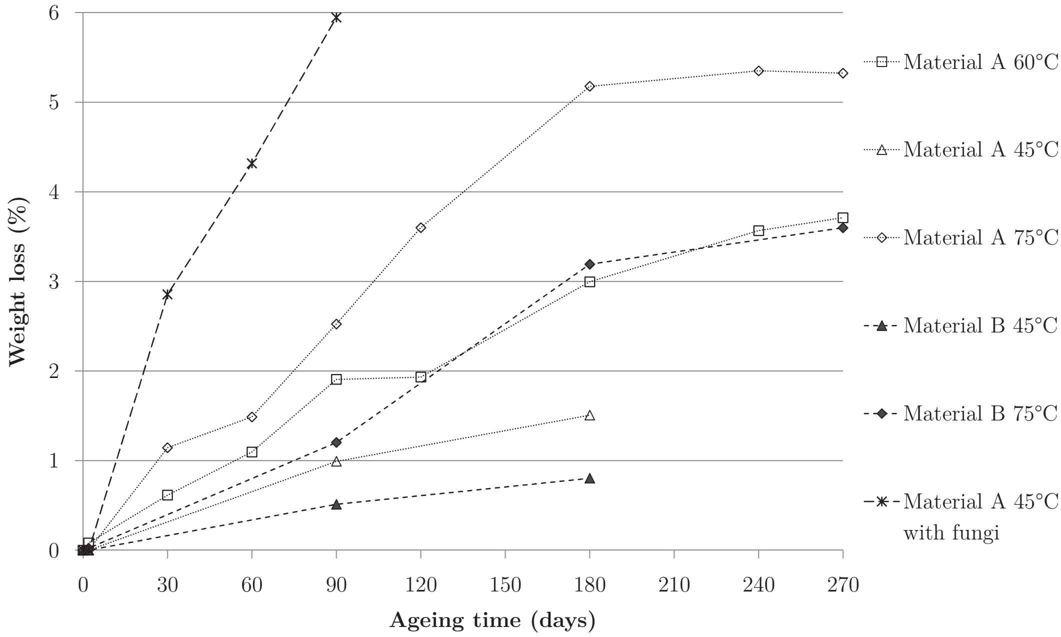


Figure 8.6: Weight loss of the aged specimens

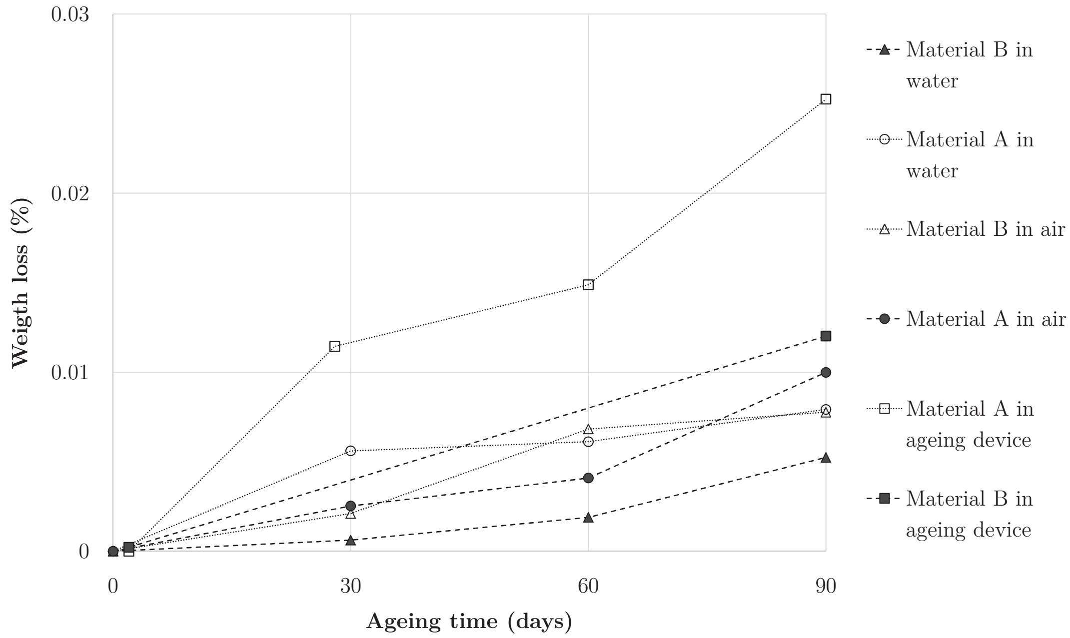


Figure 8.7: Comparison among the weight loss of the specimens aged in the developed ageing device, and in water and in air at 75°C

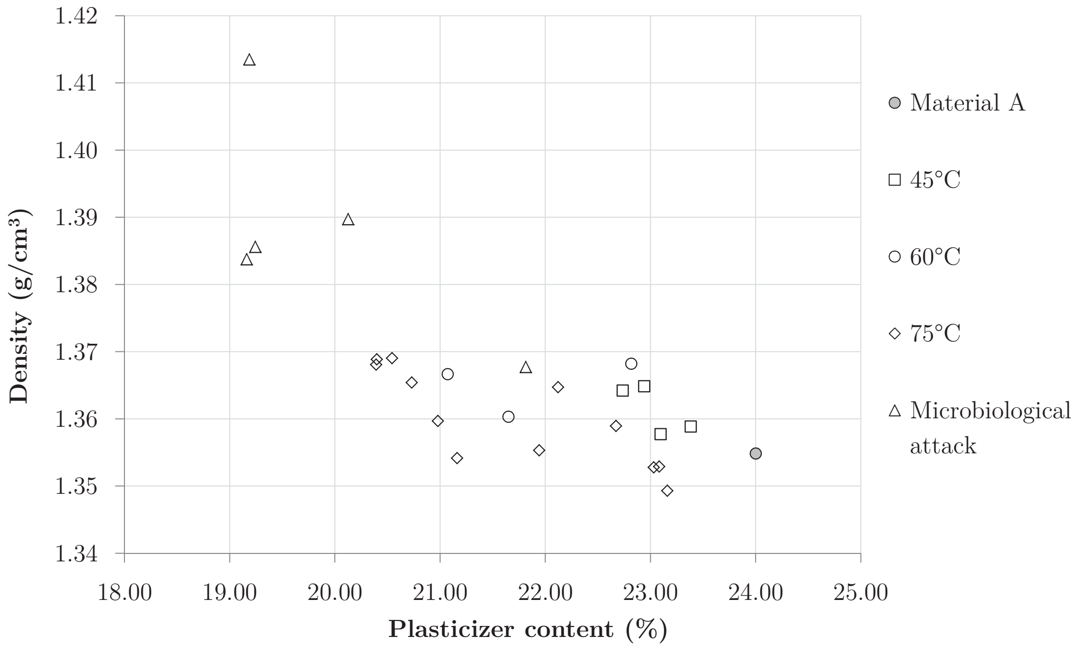


Figure 8.8: Variation of the density of the aged specimens of material A with the weight loss

formulation of material A. Indeed, the density of calcium carbonate (~ 2.93 g/cm^3) is higher than that of the pure PVC-P membrane.

The values of density for aged specimens of materials A and B is reported in Figures 8.8 and 8.9 respectively.

As plasticizer is lost, density increases because plasticizer has lower density (~ 0.96 g/cm^3 for the one used in these commercial membranes) than the PVC resin (~ 1.50 g/cm^3).

Size

In Figure 8.10 and 8.11 the dimensional variation of the specimens aged respectively at 45°C, and 75°C are reported. The variation is averaged on the values obtained on the two parallel sides of the specimen.

Since the analysed membranes are extruded, there is a small amount of residual stresses in the material. This induces, when heated, stress relaxation and therefore the membrane shrinks in the longitudinal direction and enlarges in the transversal one.

In order to remove this phenomenon from the analysis of the shrinkage due to loss of plasticizer, three specimens of both material A and B have been kept in an oven at the three temperatures analysed and the dimension of the sides have been measured with a calliper until dimensional stability is reached. The stability has

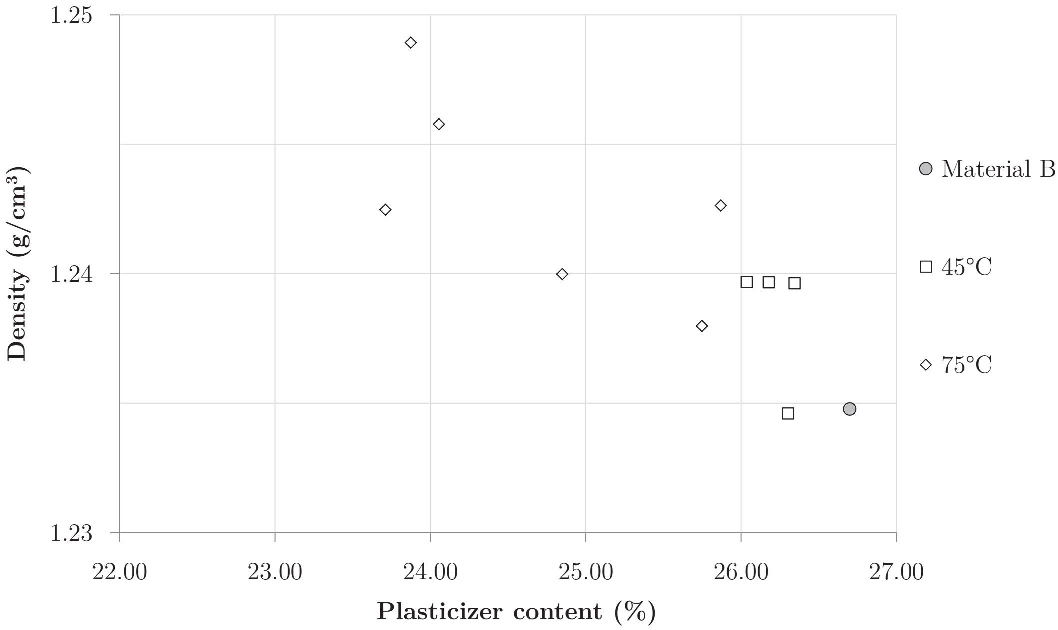


Figure 8.9: Variation of the density of the aged specimens of material B with the weight loss

been always obtained within seven days. As an example, the results of these tests performed at 45°C are reported in Figure 8.12 for materials A and B.

The average values of dimensional variation at stability is then removed from the values of variation obtained from the aged specimens. In this way, the change of dimension is not influenced by residual stresses and is only a function of plasticizer loss.

Materials A and B exhibit the same shrinkage for the same loss of plasticizer, that means that it is not dependent on the formulation.

Figures 8.13 and 8.14 compare these results with the theoretical relationship proposed by Giroud (1995) (Equation 7.11) in terms of side dimension variation for the test at 45°C and 75°C. The residual area follows the same behaviour. The theoretical equation results an overestimation of the shrinkage for the tests at 75°C while for the tests at 45°C there is no evident discrepancy. This different behaviour can be due to the fact that, for lower temperatures, there is less loss of plasticizer and the difference between the theoretical relationship and the real behaviour is small and can not be appreciated. The discrepancy from the theoretical equation implies that the hypothesis that all the volume of the lost plasticizer is compensated by a decrease of volume of the membrane is not correct in this case.

The loss of plasticizer causes a reduction of the dimension of the specimens that reaches 3% in the longitudinal direction and 11% of the area for the specimens aged

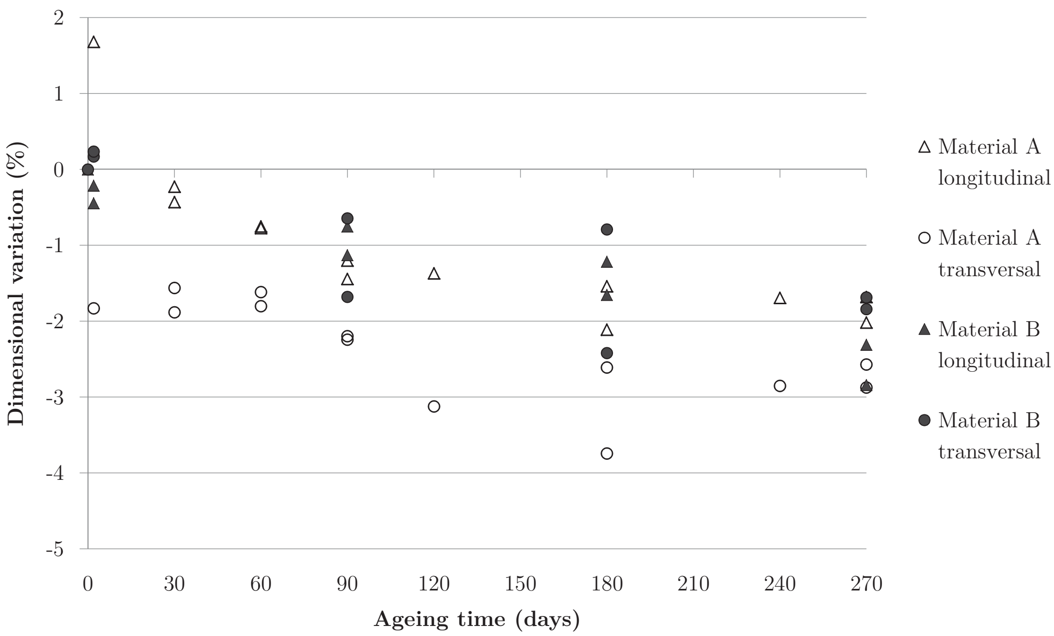


Figure 8.10: Dimensional variation in the longitudinal and transversal direction of specimens of materials A and B aged at 75°C

at 75°C for 9 months.

Water absorption

Figure 8.15 reports the water absorption of material A with a thickness of 2.0 mm and 1.5 mm, material B and some of the aged specimens of material A. Material A shows higher water absorption due to the presence of calcium carbonate filler in the membrane. The reduction of the thickness increases the rate that brings the material to saturation because the lower thickness facilitate the diffusion.

Table 8.2 reports the values of diffusion coefficient D and water content at saturation c_s obtained using Equation 8.7 and the ageing parameters of the aged specimens.

The water absorption slowly decrease in speed as ageing increases, that means that the diffusion coefficient becomes smaller. However, there is not a clear relationship between D and c_s values obtained for water at 21°C and the plasticizer content.

Plasticizer absorption

For each temperature the increase in weight after immersion in plasticizer has been plotted versus the square root of time and the linear relation fitting the data

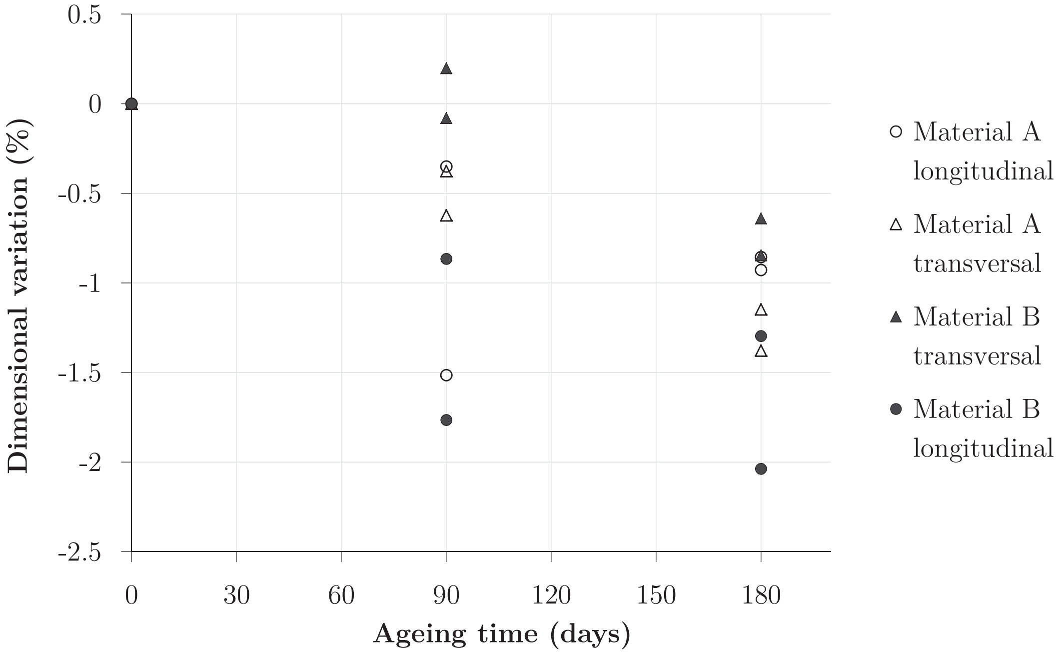


Figure 8.11: Dimensional variation in the longitudinal and transversal direction of specimens of materials A and B aged at 45°C

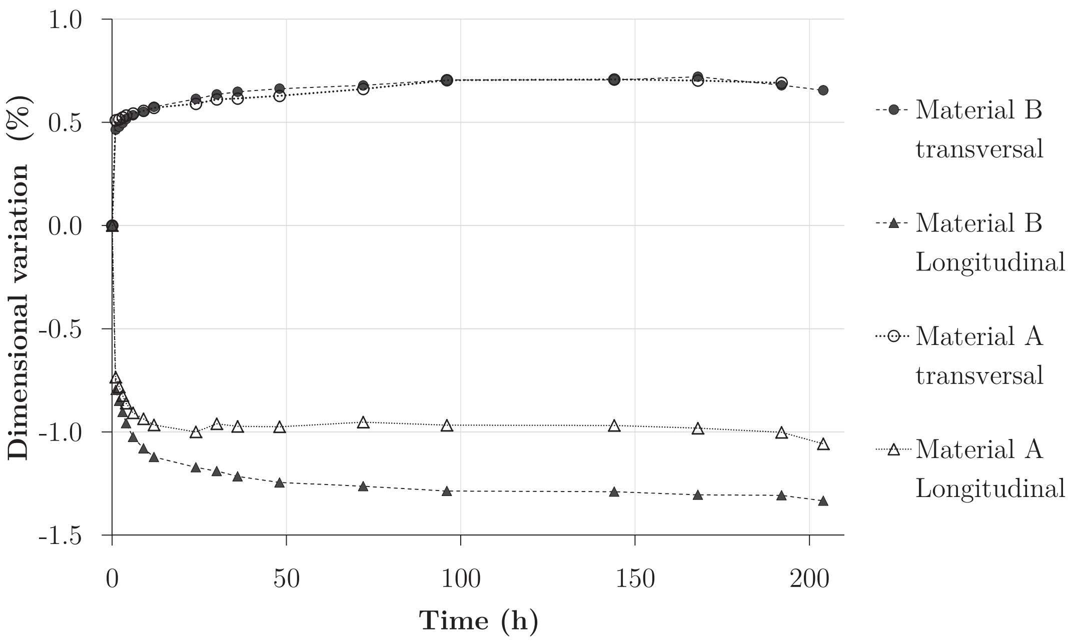


Figure 8.12: Dimensional stability of specimens at 45°C

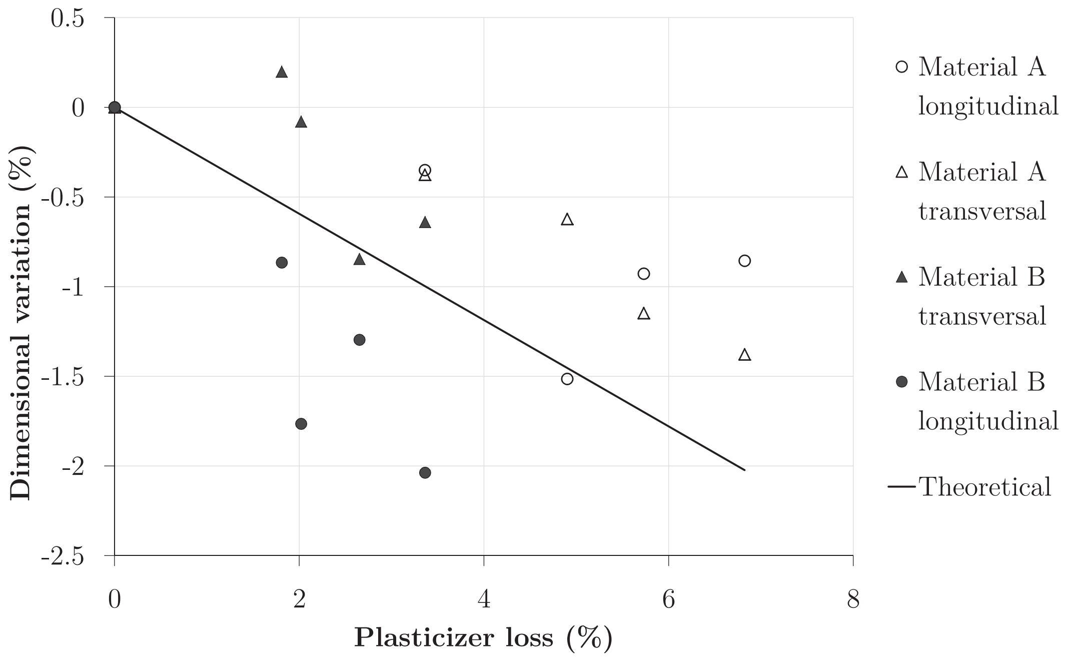


Figure 8.13: Comparison of the results at 45°C with the theoretical relationship by Giroud (1995)

Table 8.2: Water absorption parameters

Specimen	D (mm^2/s)	c_s (%)	Ageing time (days)	Ageing temperature (°C)	Plasticizer loss (%)
Material A 2.0 mm	1.0 10^{-7}	2.7	0	-	0
Material A 2.0 mm	1.0 10^{-7}	2.7	0	-	0
Material B 2.0 mm	4.6 10^{-7}	0.8	0	-	0
5	1.1 10^{-7}	2.4	90	60	6.13
13	8.3 10^{-8}	2.7	180		12.00
4	9.0 10^{-8}	2.8	270		14.84
29	8.5 10^{-8}	2.3	30	45 (with fungi)	11.18
28	9.8 10^{-8}	2.0	60		19.40
32	9.5 10^{-8}	2.1	90		23.94
33	9.0 10^{-8}	2.3	90		23.56

has been defined (Figure 8.17). From Equation 8.10 the value of D has been defined. The results are summarized in Table 8.3. The diffusion coefficients of material B

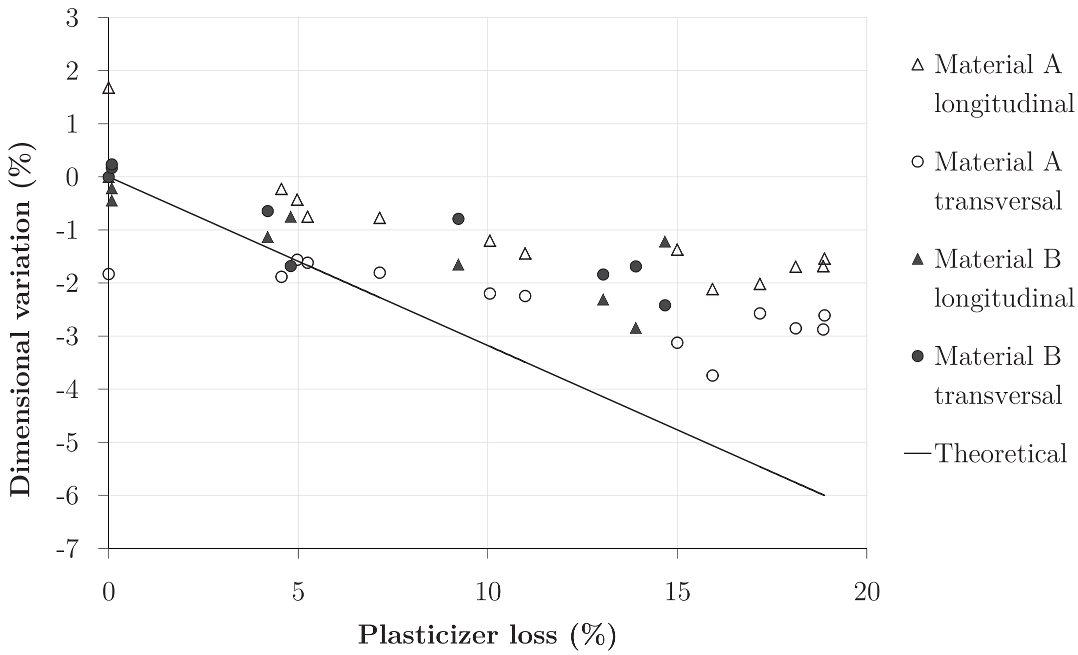


Figure 8.14: Comparison of the results at 75°C with the theoretical relationship by Giroud (1995)

Table 8.3: Diffusion coefficients D obtained for materials A and B in mm^2/s

	Temperature (°C)			
	20	45	60	75
Material A	1.49 10^{-9}	3.13 10^{-8}	2.51 10^{-7}	1.21 10^{-6}
Material B	1.36 10^{-10}	2.74 10^{-9}	9.74 10^{-8}	6.64 10^{-7}

are one order of magnitude lower than those of material A.

The diffusion coefficient D decreases with temperature T, with a behaviour that can be described using Arrhenius' equation because the data fit well a straight line in a plot $lnD - t^{-1}$(Figure 8.18).

Arrhenius' equation can be rewritten as

$$D = D_0 e^{-\frac{E_A}{RT}} \tag{8.11}$$

where D_0 is a constant and T is expressed in Kelvin. Table 8.4 reports D_0 and E_A for materials A and B.

Material B has higher parameters, resulting in lower diffusion coefficient and therefore slower plasticizer loss.

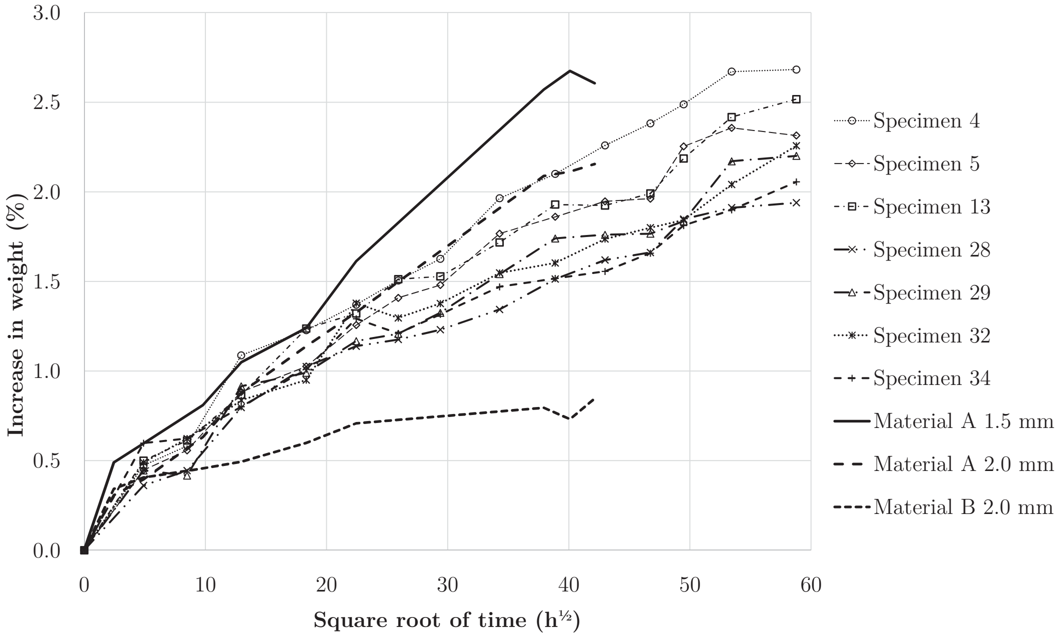


Figure 8.15: Comparison of the water absorption of materials A and B and some of the aged specimens of material A

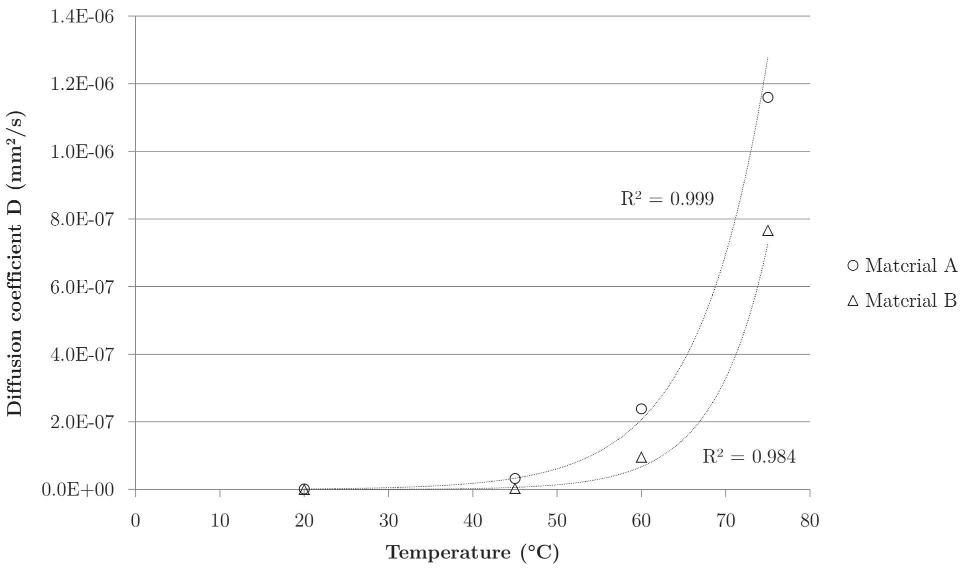


Figure 8.16: Variation of the diffusion coefficient D with temperature for materials A and B

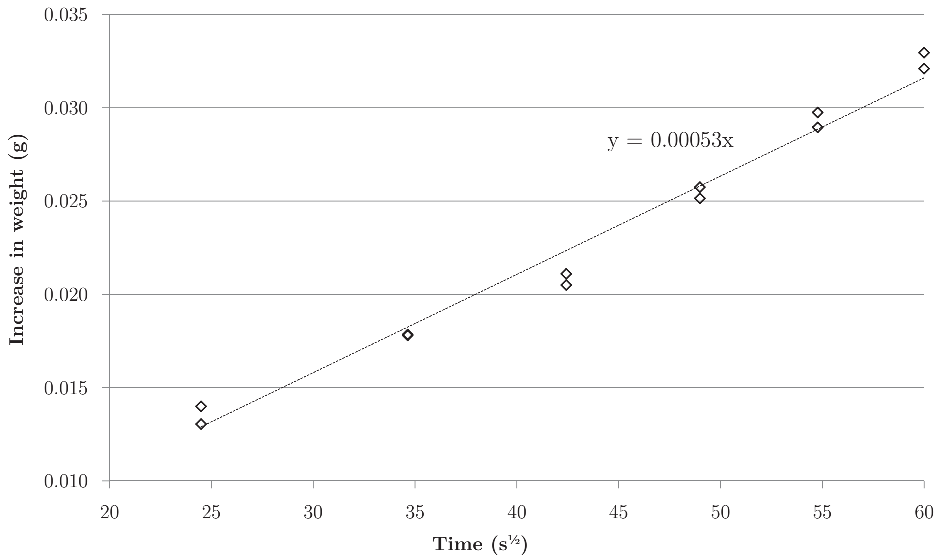


Figure 8.17: Example of the results of the plasticizer absorption test for material A at 75°C

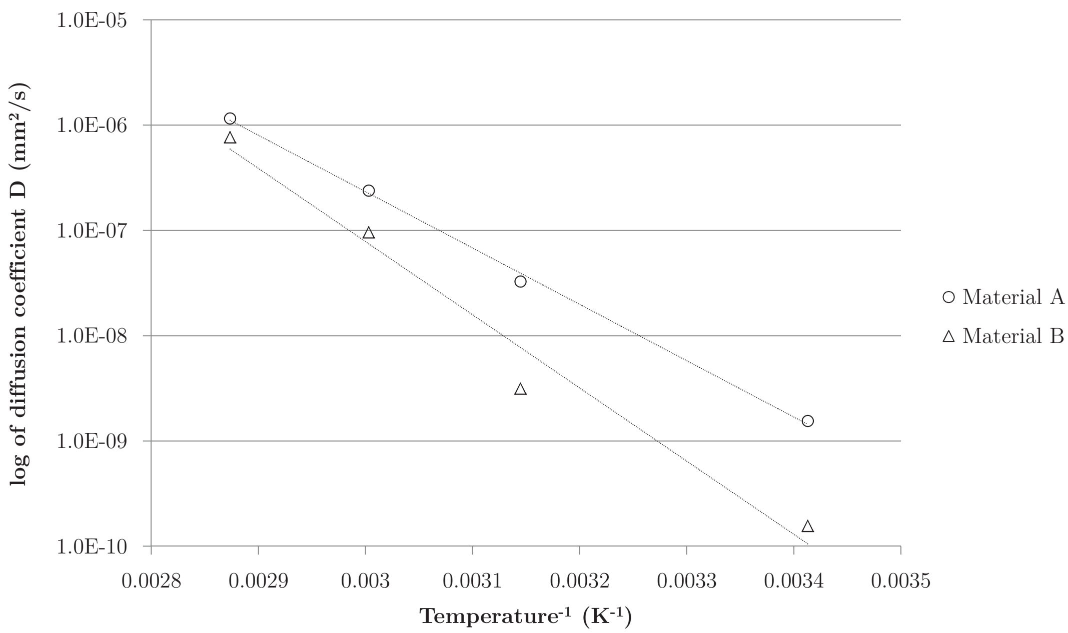


Figure 8.18: Plot of $lnD - t^{-1}$ for materials A and B

Table 8.4: Values of D_0 and E_A for materials A and B

	D_0 (mm^2/s)	E_A kJ/mol
Material A	$4.83\ 10^{9}$	104.1
Material B	$6.64\ 10^{13}$	133.8

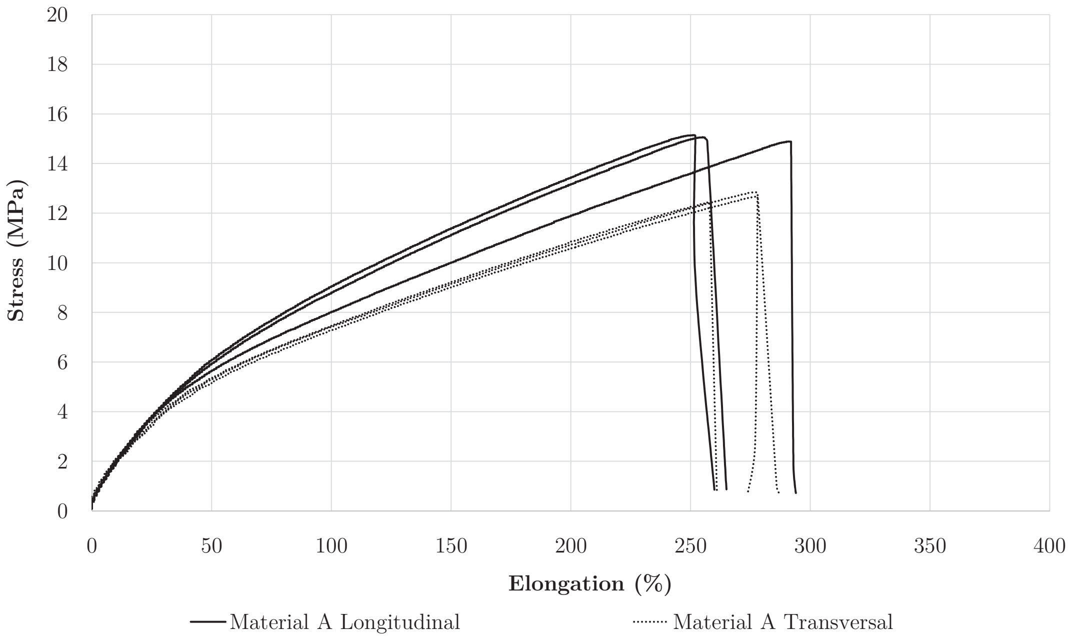


Figure 8.19: Tensile tests on material A

8.5.2 Mechanical tests

Tensile test

Figures 8.19 and 8.20 report respectively the tensile behaviour of materials A and B. Two sets of plots exist for each material: the ones in the longitudinal direction have higher elongations at break and lower tensile strength than that in the transversal direction. This is due to the residual stresses induced by the extrusion of the membrane.

Figures 8.21, 8.22 and 8.23 summarize the results of tensile tests on the specimens aged at 75°C both for material A and B in terms of stress at break, elongation at break and elastic modulus. The tests at 45°C and 60°C are analogous and are not reported since the weight loss is lower and consequently also the variation in the mechanical properties is low.

The quite big dispersion of the results does not permit to establish a clear relation on the variation of the mechanical properties with the loss of plasticizer.

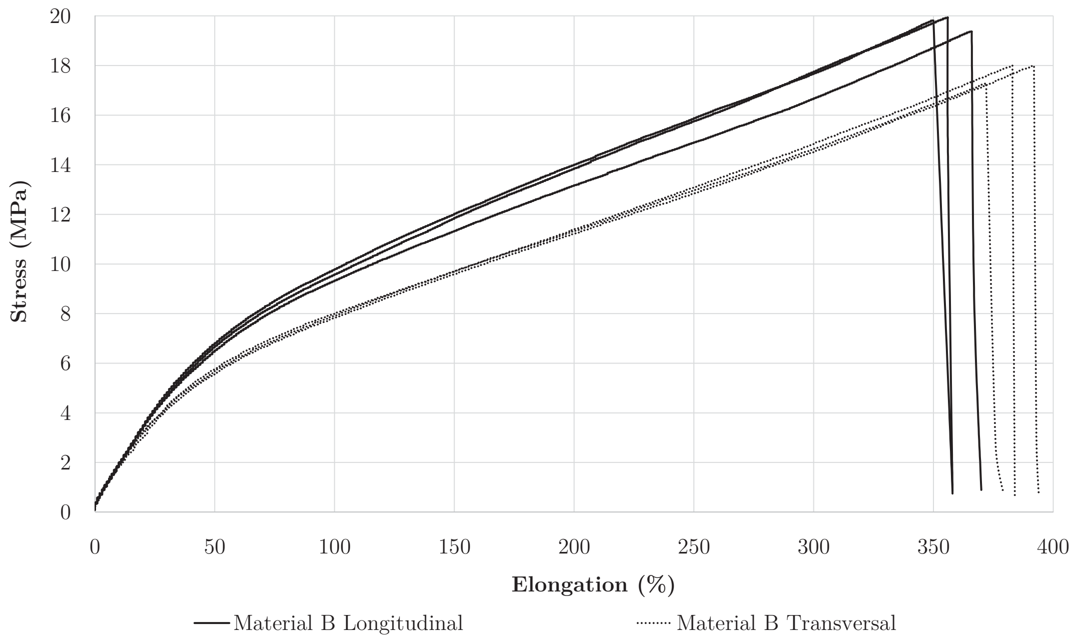


Figure 8.20: Tensile tests on material B

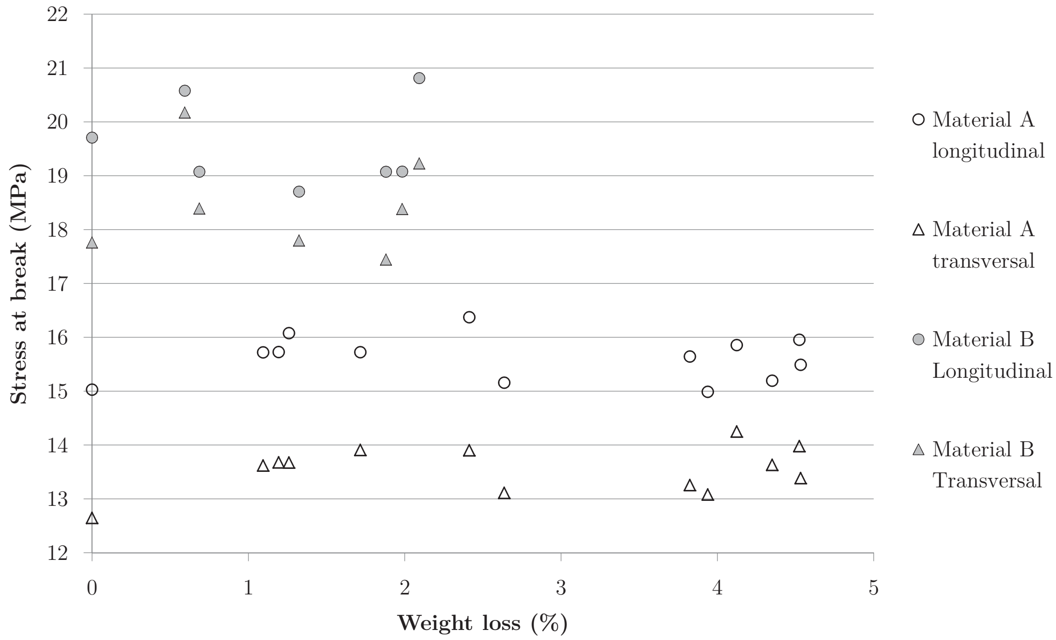


Figure 8.21: Stress at break of specimens aged at 75°C

The stress at break and the elastic modulus slightly increase in the analysed range of variation, while elongation at break reduces.

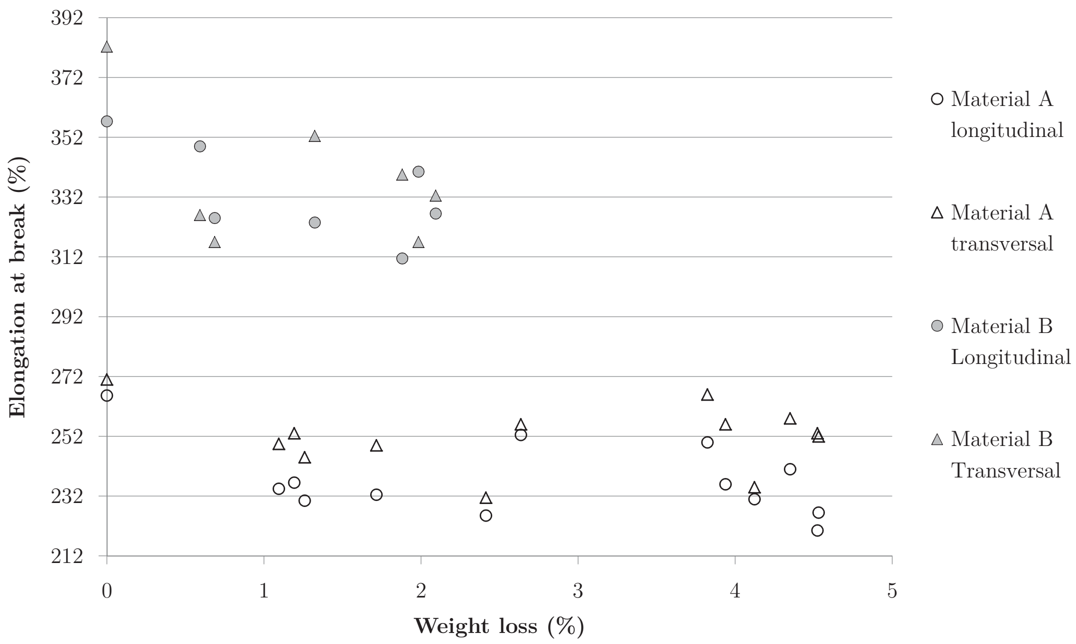


Figure 8.22: Elongation at break of specimens aged at 75°C

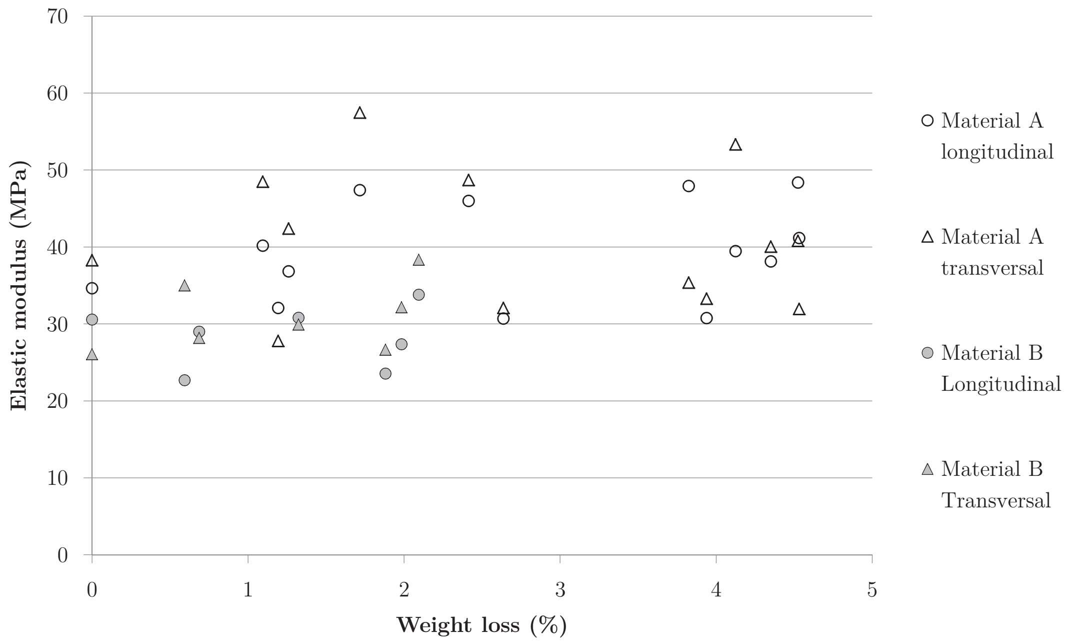


Figure 8.23: Elastic modulus of specimens aged at 75°C

Material B has higher values both of stress and of elongation at break, due to the absence of filler. The elastic modulus is comparable with that of material A.

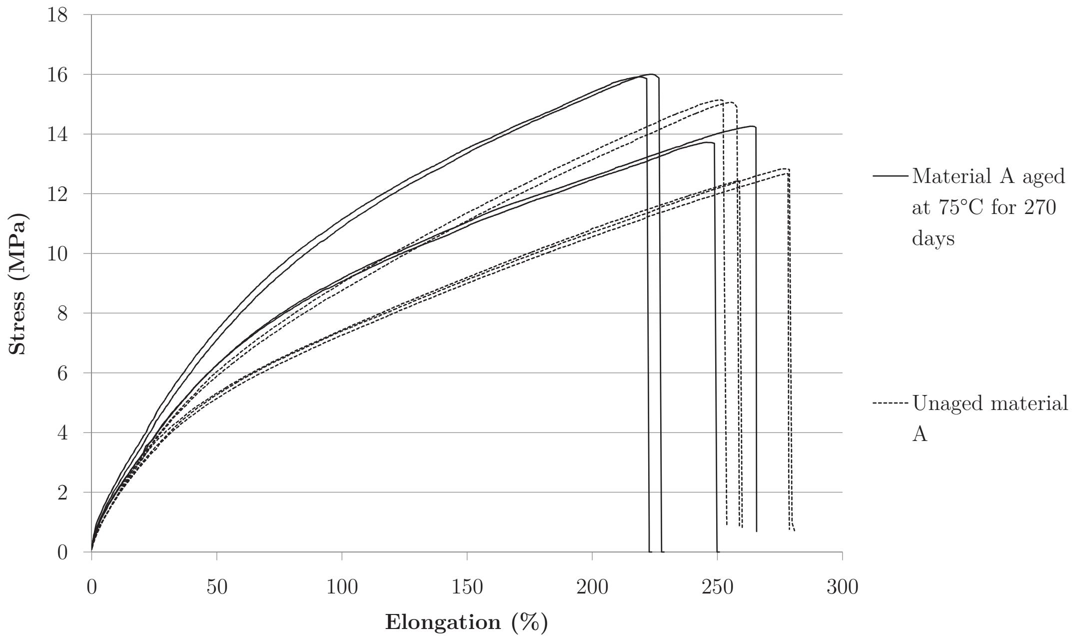


Figure 8.24: Comparison between the tensile behaviour of material A before and after ageing

To analyse the differences between the mechanical behaviour before and after ageing, Figure 8.24 compares the tensile test on the original material A and on a specimen aged for 270 days in the tests at 75°C.

Both transversal and longitudinal specimens shows a more rigid behaviour after ageing with higher tensile strength and elastic modulus and lower elongation at break.

Flexibility at low temperature

All the specimens passed the test of flexibility at -25°C without break and cracks.

Shore A hardness

Figures 8.25 and 8.26 report the Shore A hardness for aged and unaged specimens of material A and B respectively.

With the loss of plasticizer, the surface hardness increases linearly. The results of the different tests superimpose quite well, showing that there is the same trend of change with loss of plasticizer at different temperatures.

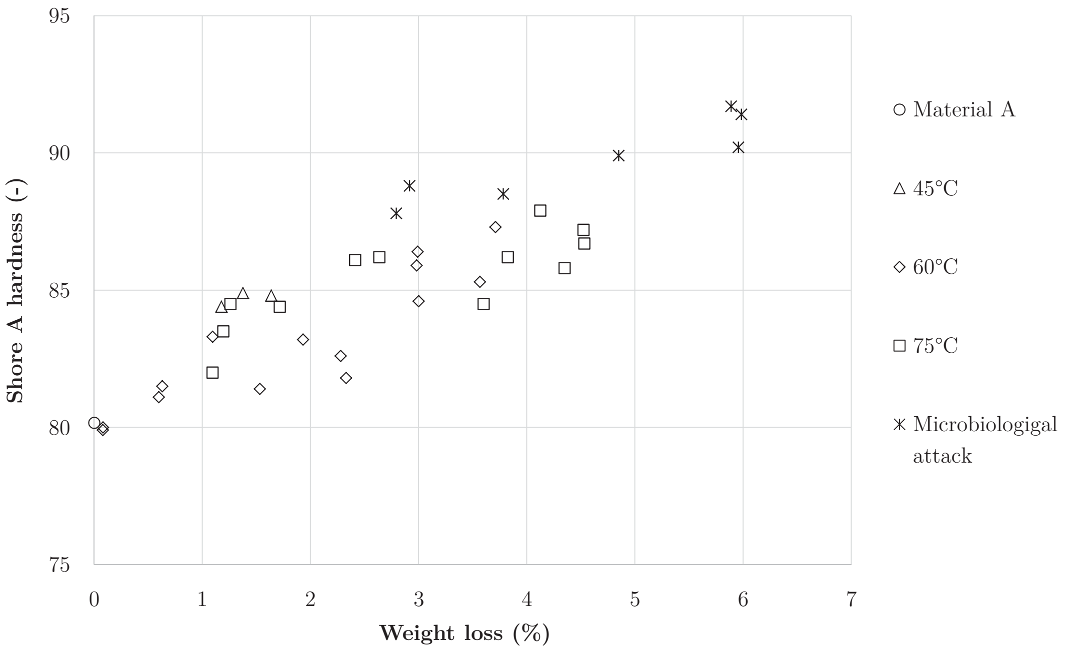


Figure 8.25: Shore A hardness of aged and unaged specimens of material A

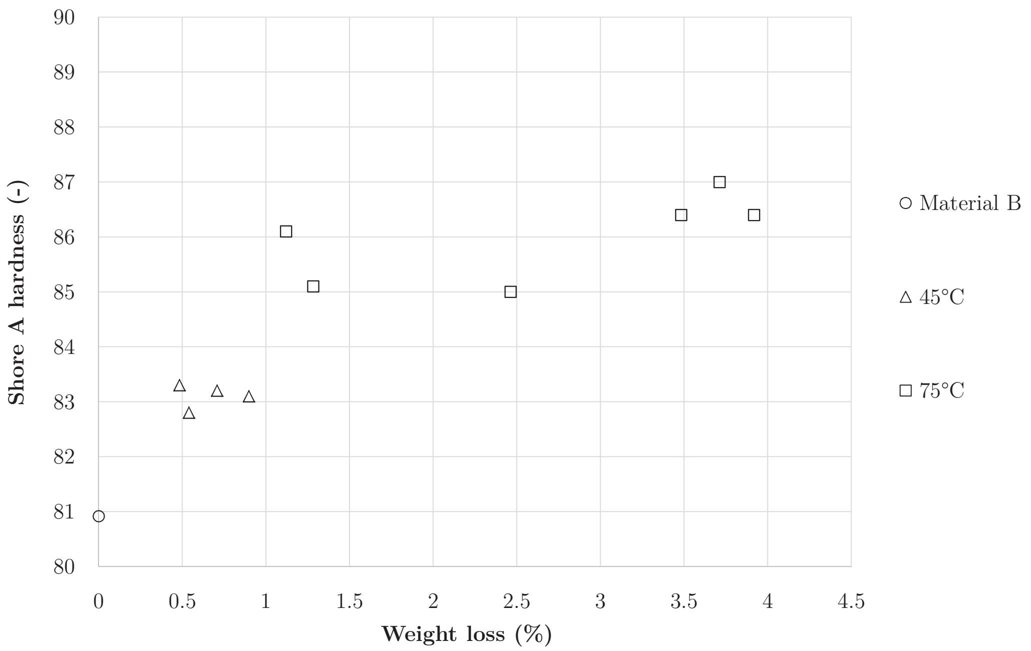


Figure 8.26: Shore A hardness of aged and unaged specimens of material B

8.6 Discussion

8.6.1 Considerations about the developed accelerated ageing test

The accelerated ageing test proposed in this Chapter aims to simulate the real conditions of installation of the geomembrane in a tunnel to better analyse the degradation behaviour in underground structures. A constant flow of water has been kept on one side of the geomembrane through a geotextile and the system is between two concrete layers.

From the comparison with the accelerated ageing tests in hot water and hot air, the proposed test shows higher loss of plasticizer. This can be justified by the constant flow, that guarantees the removal of the plasticizer from the surface and the consequent higher difference between internal and external concentration.

8.6.2 Mechanical properties variation with time

Translucid membrane has better mechanical properties: the tensile strength and elongation at break are higher than those of material A. Moreover, the lower diffusion coefficient (about one order of magnitude) of plasticizer in the translucid membranes implies lower loss of plasticizer and, therefore, higher durability. This is also confirmed by the ageing tests, where material B shows lower weight (and consequently plasticizer) loss than material A.

The loss of plasticizer causes an increase of tensile strength and hardness of the membrane, while the elongation decreases. However, the quantity of plasticizer lost in the accelerated ageing tests is low and, therefore, it is impossible to clearly define the variation of the mechanical behaviour.

To better study the problem longer ageing tests or tests at higher temperature should be performed. However, longer tests will result in very long test programs, keeping in mind that in order to have a relevant variation of plasticizer content at least 2 years tests have to be performed, on the basis of the results of the presented tests. Moreover, it is not possible to reduce the duration of ageing test further increasing the tests temperature because as we move close to 100–120°C the effect of dehydrochlorination of PVC increases and the ageing is no longer simulating only the degradation mechanism occurring on the job-site.

The unwanted occurrence of microbiological attack on the membrane at 45°C permits to analyse the effect of this kind of degradation. The loss of plasticizer is one order of magnitude higher than that of diffusion. Consequently, the lifecycle of the geomembrane is shorter and surely lower than 100 years, that are the standard for underground structure. Therefore, the absence of any possibility of microbiological attack has to be established in the design. Where this phenomenon is possible (e.g. for very shallow tunnels, near vegetate soil) specific additives have to be included in the geomembrane formulation to avoid fast loss of plasticizer.

8.6.3 Needs for further investigations

From the considerations of the variation of the mechanical properties of the aged geomembrane, the need of study PVC-P membranes with higher loss of plasticizer raises. This will allow to define how the content of plasticizer influences the mechanical properties of the material.

However, very long accelerated tests (e.g. up to 3 years) are very demanding in therms of time and consequently the way of performing longer accelerated ageing tests has not been followed.

Conversely, in the next Chapter, eight PVC-P membranes with different formulations and different content of plasticizer will be studied, in order to obtain the required information on materials with up to 50% less plasticizer.

Chapter 9

Effect of plasticizer content on PVC-P waterproofing membranes

To define the life-cycle of the waterproofing membrane the effect of the loss of plasticizer has been analysed with accelerated ageing tests. However, from those tests it has not been possible to obtain samples with high loss of plasticizer due to the low speed of the phenomenon, and consequently it was impossible to analyse the mechanical effect of loss of plasticizer on the behaviour of the material. Therefore, samples of PVC-P with different contents of plasticizer have been created and mechanical tests have been performed on these samples.

9.1 Material preparation

9.1.1 Formulations

Eight PVC-P formulations have been designed with different percentages of plasticizer, as reported in Table 9.1. All the percentages are expressed as weight on weight.

Table 9.1: Composition of the produced materials

Sample	PVC (%)	Plasticizer (%)	Stabilizer 1 (%)	Stabilizer 2 (%)	Stabilizer 3 (%)	Filler (%)	Plasticizer reduction (%)
1	67.4	30	0.5	2	0.1	0	0
2	72.4	25	0.5	2	0.1	0	-17
3	77.4	20	0.5	2	0.1	0	-33
4	82.4	15	0.5	2	0.1	0	-50
5	47.4	30	0.5	2	0.1	20	0
6	52.4	25	0.5	2	0.1	20	-17
7	57.4	20	0.5	2	0.1	20	-33
8	62.4	15	0.5	2	0.1	20	-50

Figure 9.1: Photos of the turbo mixer and of the obtained PVC-P blend

Materials from 1 to 4 do not have filler and therefore represent a formulation similar to that of translucent PVC-P membranes (material B). On the other hand, materials from 5 to 8 have a 20% of filler ($CaCO_3$) representing a formulation similar to that of coloured PVC-P (material A). Materials 1 and 5 have a 30% of plasticizer, while in the other materials plasticizer has been reduced with steps of 5% on the weight of the total formulation, until the value of 15%. All the components are commercial products, used in the industrial production of PVC-P.

9.1.2 Extrusion procedure

The powder components (PVC, Stabilizer 1 and 2 and filler) are inserted in an industrial turbo mixer tank (Figure 9.1), while the liquid components (Plasticizer and Stabilizer 3) are inserted in the liquid tank. The inclusion of the various components in the PVC grains is possible when the temperature increases up to 60°C opening the porosity of the grains. In PVC technology, this heating is obtained by friction through the rotation of the powder in the turbo mixer. The liquid components are automatically added in the turbo mixer at steps at different temperatures as reported in Table 9.2.

Once the maximum temperature of 105°C is reached, the mixer is cooled through water circulation to 40°C while the rotation is kept at 500 rpm. The PVC blend is

Table 9.2: Times of injection during the mixing of PVC

Temperature (°C)	Injection time (s)
25	1.5
50	5
75	10

then removed from the rotating mixer and put in the extruder (Figure 9.2). The parameters of extrusion are reported in Table 9.3.

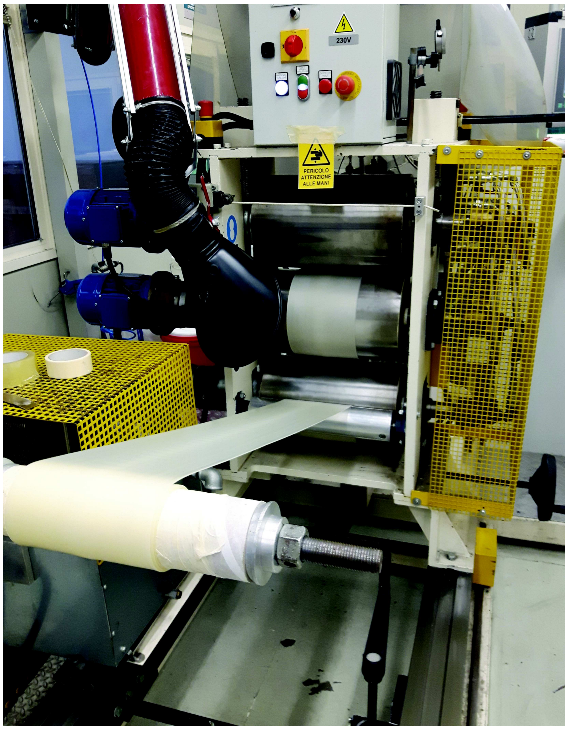


Figure 9.2: Photo of the extrusion device

Extrusion pressure and temperature increase with the reduction of plasticizer in the material for the higher viscosity of the material. Moreover, materials 5 to 8 have lower extrusion pressure than 1–4 because the presence of filler reduces the viscosity.

Table 9.3: Extrusion parameters

Sample	Extrusion speed	Pressure (Bar)	Temperature (°C) 1	2	3	4	5	6	7	8	9	Melting temperature (°C)
1	15	42	150	150	155	160	165	155	175	155	175	162
2	15	54	150	150	155	160	165	155	175	155	175	163
3	15	67	150	160	165	168	170	160	178	160	178	168
4	15	87	155	165	165	170	175	160	178	160	178	173
5	15	30	150	150	155	160	165	155	175	155	175	163
6	15	41	150	150	155	160	165	155	175	155	175	163
7	15	55	150	160	165	168	170	160	178	160	178	167
8	15	72	155	160	165	170	175	160	178	160	178	173

9.2 Results

On the extruded materials the same tests performed on materials A and B have been done, in order to compare the behaviour of the eight formulations with the commercial materials and to analyse the variation of the properties of PVC-P with the variation of plasticizer content.

9.2.1 Weight

The extruded materials have been tested according to EN 14415 (2004) for loss of plasticizer at 75°C for 56 days. Figure 9.3 shows the results of these tests and the comparison with the same test developed on the commercial membranes.

The materials with higher values of plasticizer (formulations 1 and 5) result in higher loss of plasticizer. The commercial materials behave better, with a lower loss of plasticizer. Since the tests lasted only 56 days, there are not enough data to define, from these tests, the diffusion coefficient of the extruded membranes.

9.2.2 Density

Figure 9.4 reports the density values obtained from the extruded materials. The density is slightly higher than that of the commercial membrane both for those with filler and for those without it and increases with the reduction of the content of plasticizer.

The difference between the two sets of materials is due to the presence of filler that increase the density of formulations 5–8 (ρ_{CaCO_3}=2.93 g/cm^3).

9.2.3 Water absorption

Water absorption tests have been performed in accordance to EN ISO 62 (2008) on samples of 50x50 mm at a temperature of 20±1°C. Figure 9.5 and 9.6 report

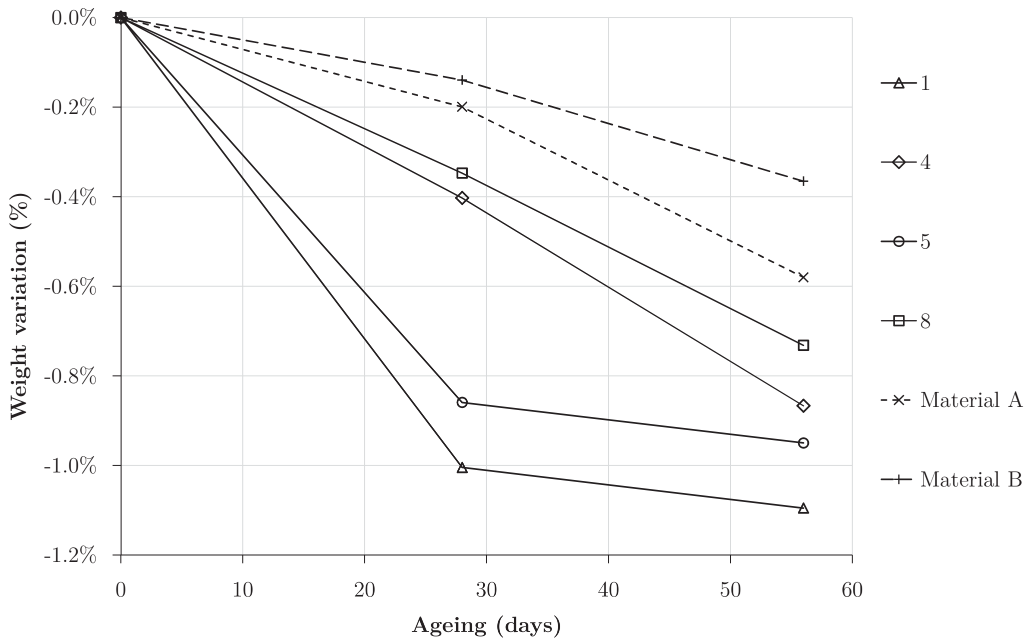


Figure 9.3: Plasticizer loss for the extruded materials

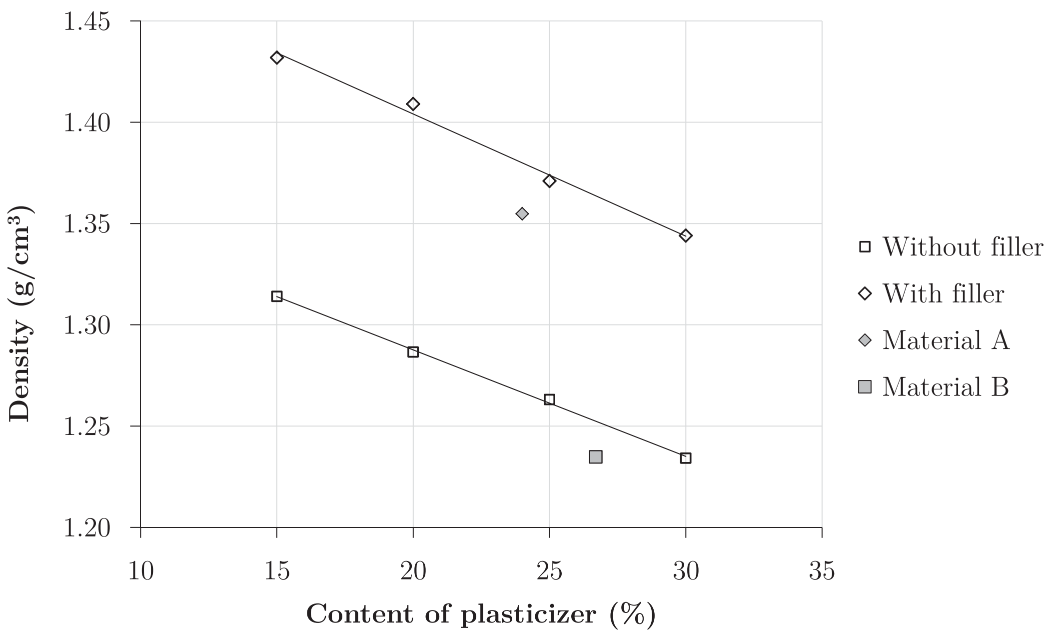


Figure 9.4: Density of the extruded materials

the results of these tests.

From these data, it is possible to obtain the diffusion coefficient of water at

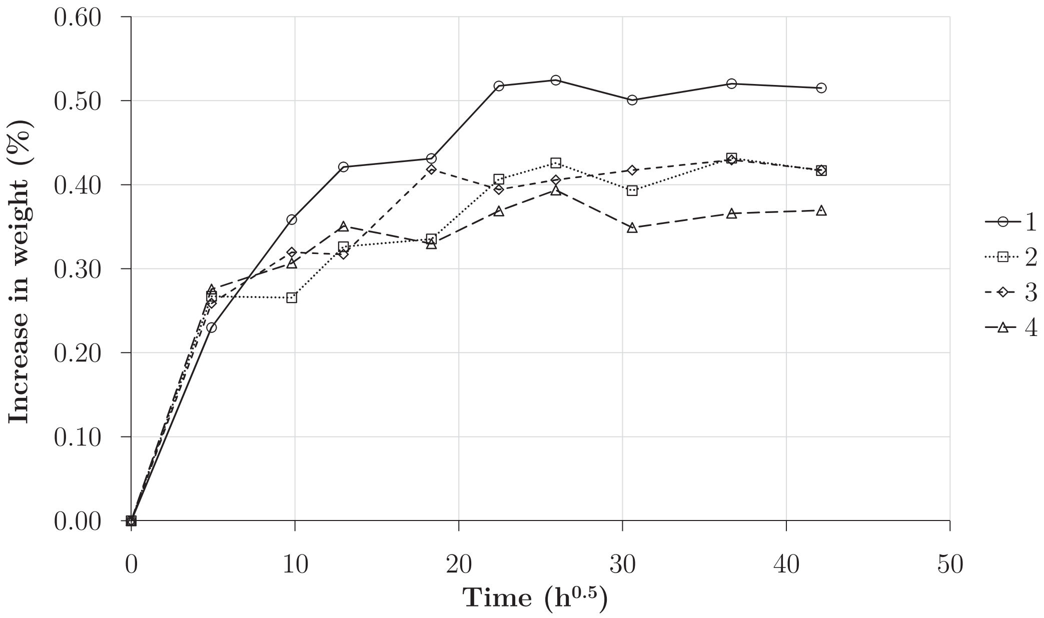


Figure 9.5: Water absorption for formulations 1–4 without filler

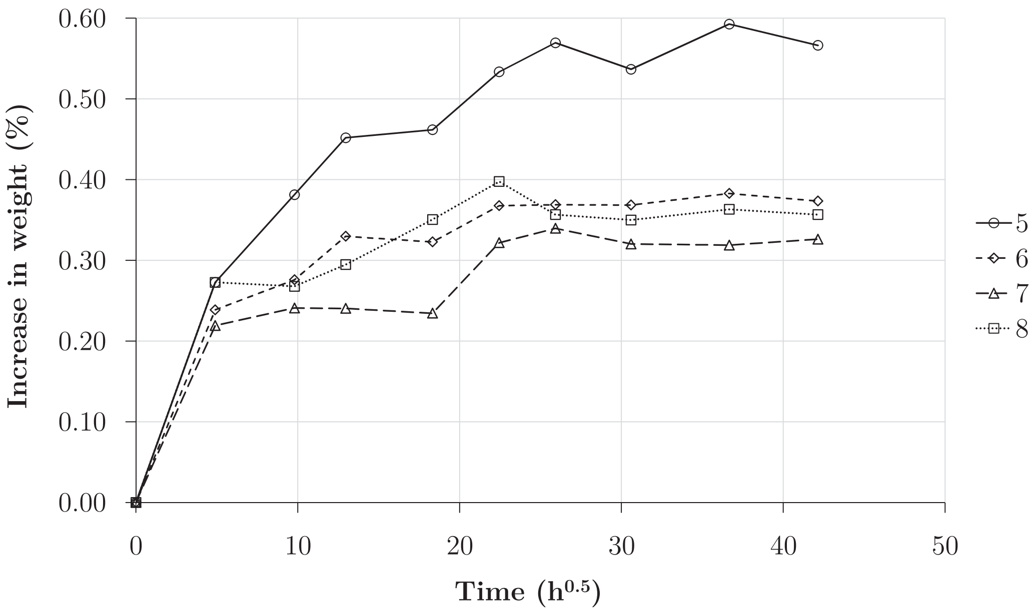


Figure 9.6: Water absorption for formulations 5-8 with filler

room temperature and the value of saturation (ASTM D570) (Table 9.4).

These values are lower than those obtained for commercial PVC-P membranes

Table 9.4: Diffusion coefficients and saturation concentration of water at 21°C for the commercial materials (A and B) and for the extruded materials

Material	D (mm^2/s)	c_s (%)
A	1.0 10^{-7}	2.70
B	4.6 10^{-7}	0.80
1	1.0 10^{-6}	0.51
2	9.0 10^{-7}	0.42
3	9.0 10^{-7}	0.42
4	2.0 10^{-6}	0.37
5	8.0 10^{-8}	0.57
6	1.2 10^{-6}	0.37
7	1.5 10^{-6}	0.33
8	1.3 10^{-6}	0.35

used in the tests of Chapter 8 (Figure 9.7). This can be due to the higher density materials coming from the different machinery used for the extrusion. Moreover, in the extruded materials a stabilizer containing carbonates has been used that is more sensible to water absorption, while in the commercial one a different stabilizer has been used. This implies higher water absorption by extruded membranes, but is not affecting the other properties of these materials.

9.2.4 Plasticizer absorption

The plasticizer absorption test has been performed as described in the previous Chapter. The aim is to estimate the diffusion coefficient for each material at different temperatures (20°C, 45°C, 60°C and 75°C).

Figures 9.8 and 9.9 show the variation of diffusion coefficient with temperature for the eight extruded materials compared to those of the commercial membranes.

As established for the commercial materials in Chapter 8, the diffusion coefficient follows an exponential behaviour with the variation of temperature that can be described by Equation 8.11. Table 9.5 summarizes the parameters of this relationship for the extruded materials. Material A superimposes very well to the behaviour of material 6, while material B superimposes to that of material 2 even if with lower precision.

The diffusion coefficient reduces with the reduction of the content of plasticizer in the membrane and is one order of magnitude higher for the materials with filler.

The variation of the diffusion coefficient with the content of plasticizer in the membrane has been studied. As an example, Figures 9.10 and 9.11 report the results of plasticizer absorption tests at 75°C and 20°C in therms of diffusion coefficient

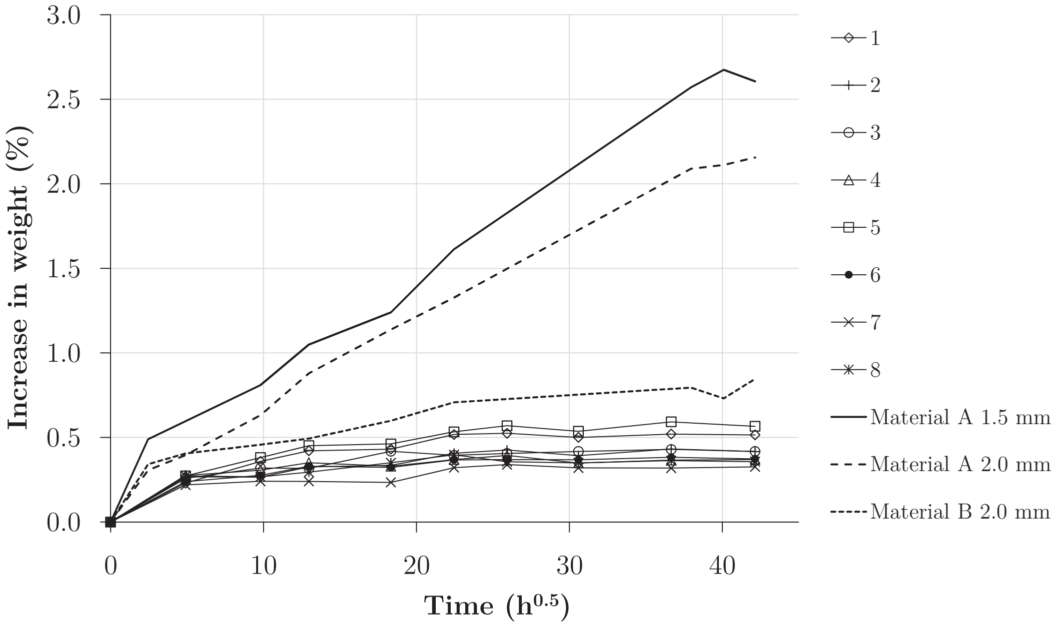


Figure 9.7: Comparison with water absorption of commercial membranes

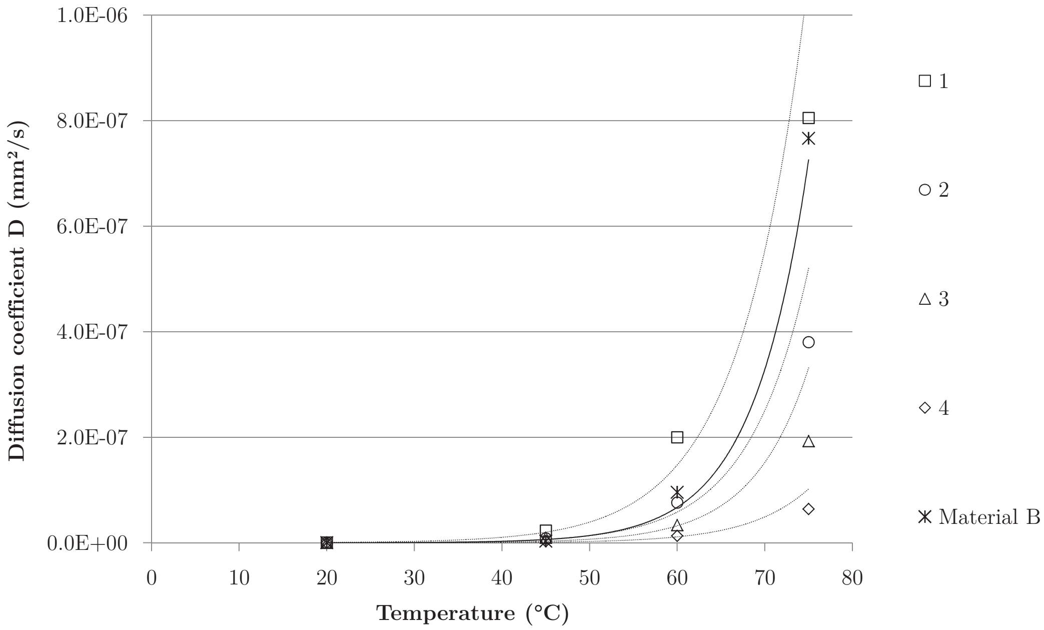


Figure 9.8: Diffusion coefficient of the materials 1–4 and B

for the eight extruded materials with reference to plasticizer content in weight on the membrane.

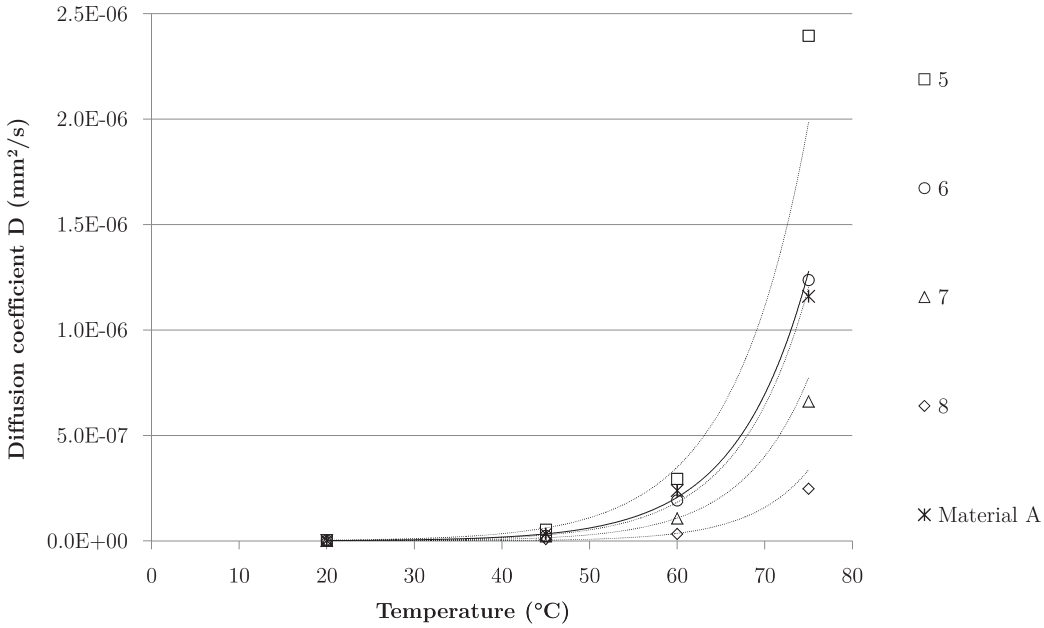


Figure 9.9: Diffusion coefficient of the materials 5–8 and A

Table 9.5: Parameters of Equation 8.11 for the extruded and commercial materials

Material	D_0 (mm^2/s)	E_A kJ/mol
A	$2.66\ 10^{9}$	102.47
B	$5.60\ 10^{13}$	133.08
1	$6.00\ 10^{10}$	112.00
2	$1.56\ 10^{12}$	123.55
3	$2.07\ 10^{13}$	132.32
4	$4.73\ 10^{11}$	124.78
5	$6.71\ 10^{8}$	97.22
6	$7.10\ 10^{9}$	105.52
7	$3.11\ 10^{10}$	111.04
8	$3.33\ 10^{12}$	127.00

The diffusion coefficient follows a potential law with concentration, that can be described as

$$D = D_1 {C_P}^b \tag{9.1}$$

where C_P is the plasticizer content expressed as mass of plasticizer over mass of membrane, b is a constant exponent and D_1 is a constant. D_1 represent the

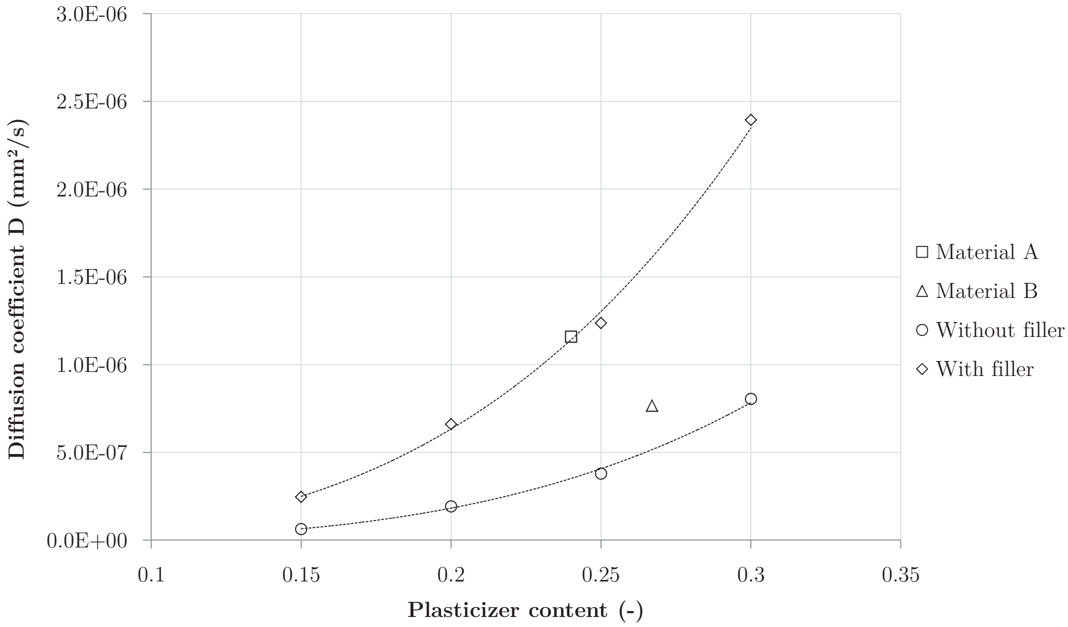


Figure 9.10: Diffusion coefficients at 75°C

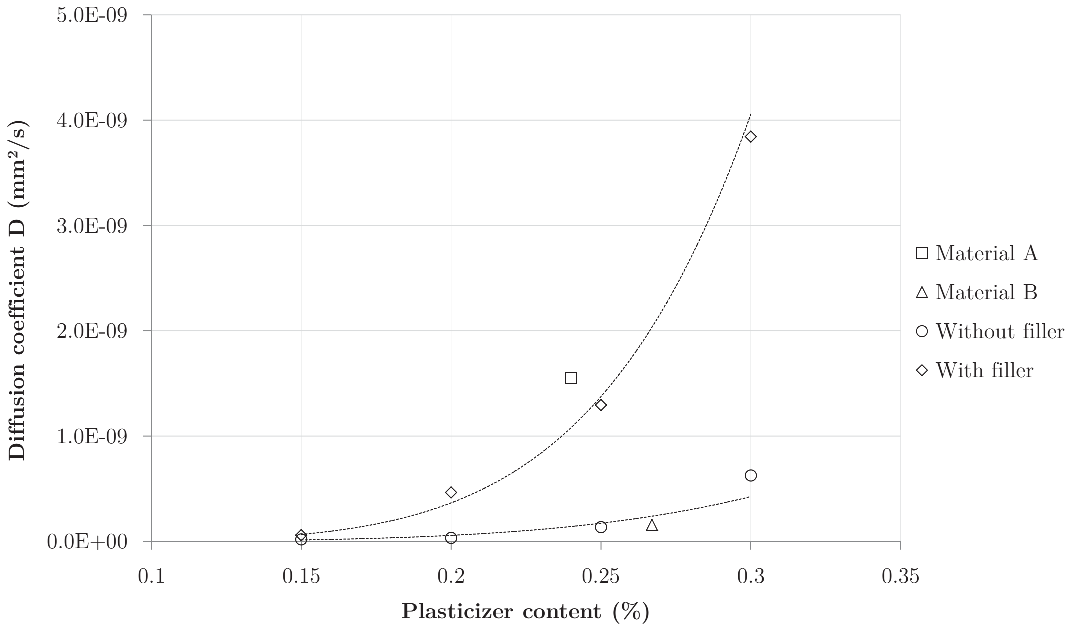


Figure 9.11: Diffusion coefficients at 20°C

theoretical diffusion coefficient when C_P=1. Table 9.6 summarizes the obtained parameters for the four test temperatures.

Table 9.6: Parameters of Equation 9.1 for the test temperatures

Material	Temperature (°C)	D_1 (mm^2/s)	b (-)
Without filler	20	$1.62\ 10^{-7}$	4.94
	45	$5.77\ 10^{-7}$	2.77
	60	$1.79\ 10^{-5}$	3.85
	75	$5.92\ 10^{-5}$	3.59
With filler	20	$5.13\ 10^{-6}$	4.94
	45	$1.34\ 10^{-6}$	2.63
	60	$1.46\ 10^{-5}$	3.16
	75	$1.15\ 10^{-4}$	3.23

9.2.5 Tensile tests

Three samples of each mix have been tested in a tensile test according to EN ISO 527 (2012). Due to the geometry of the extruding device, it has been possible to test only longitudinal samples.

Figures 9.12 and 9.13 compare the results of the different mixes in terms of stress and elongation at break.

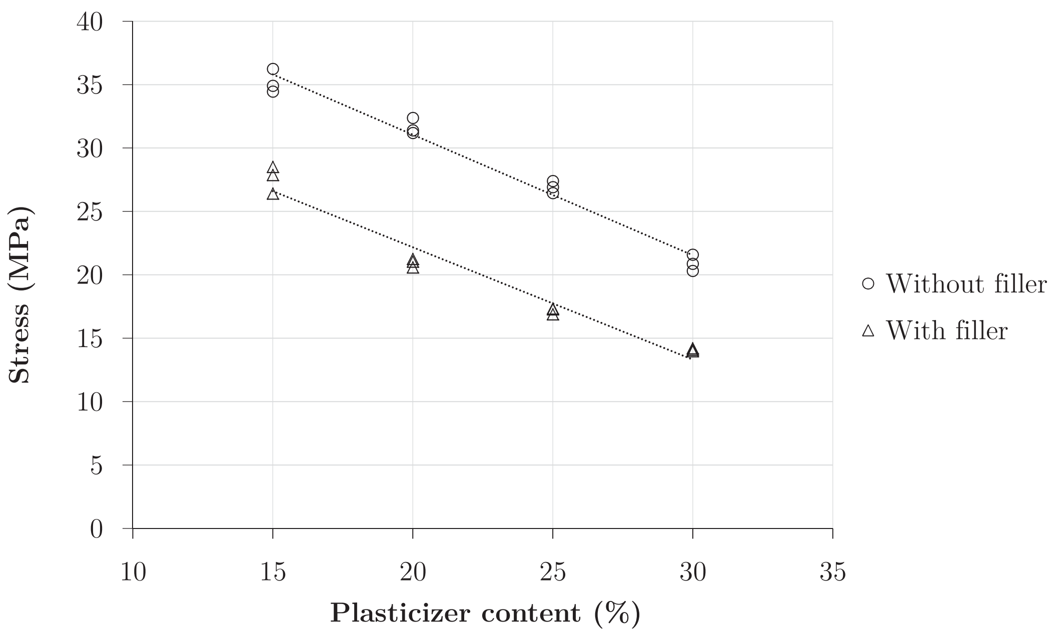


Figure 9.12: Tensile strength values of the extruded materials

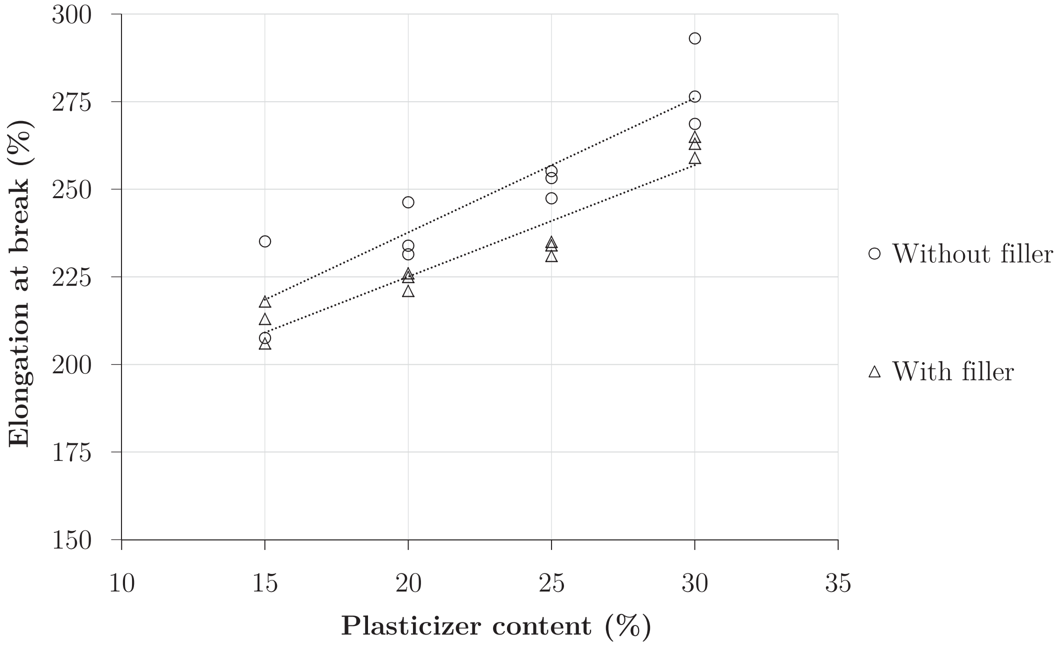


Figure 9.13: Elongation at break of the extruded materials

Tensile strength decreases with the increase of plasticizer percentage, while the elongation at break increases. The materials without filler behave better, especially in terms of tensile strength that is about 8 N/mm^2 higher than that of the materials with filler.

However, tensile strength and elongation at break are not enough to fully describe the different behaviour of the samples. Figure 9.14 reports the graphs of tensile tests on materials from 1 to 4. It is clear from these graphs that the materials have different mechanical behaviours. Material 1 has a soft rubber-like behaviour, typical for PVC-P membranes. On the contrary, material 4 has an elasto-plastic behaviour, with a clear yielding point. Materials 2 and 3 have intermediate behaviours.

Materials with filler show the same trend, but the change in the behaviour is less evident (Figure 9.15). In this case the material with 15% of plasticizer does not have a clear yielding point but has a clear elasto-plastic behaviour.

In order to better analyse this difference, the elastic modulus has been evaluated in accordance with EN ISO 527 (2012). Figure 9.16 reports the trend of variation of the mean elastic modulus at the variation of plasticizer content. The modulus increases exponentially with the reduction of plasticizer content. The effect of filler in the mix is of reducing the elastic modulus. This effect is not so evident with 30% of plasticizer but becomes more evident with the reduction of plasticizer content.

These results can be compared to those of the commercial membranes. In

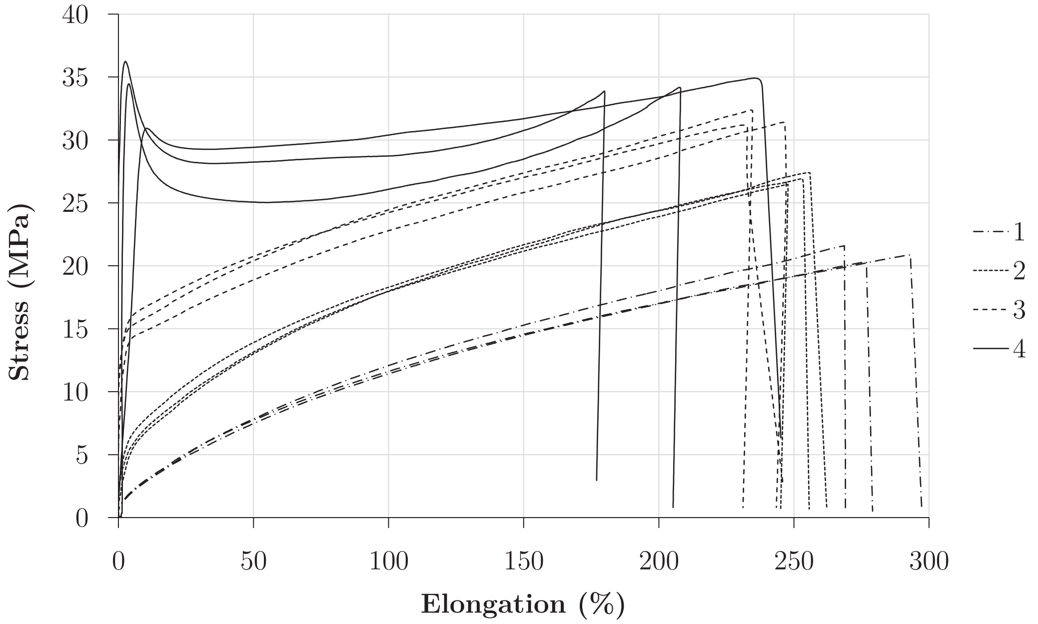


Figure 9.14: Tensile tests results for the materials without filler

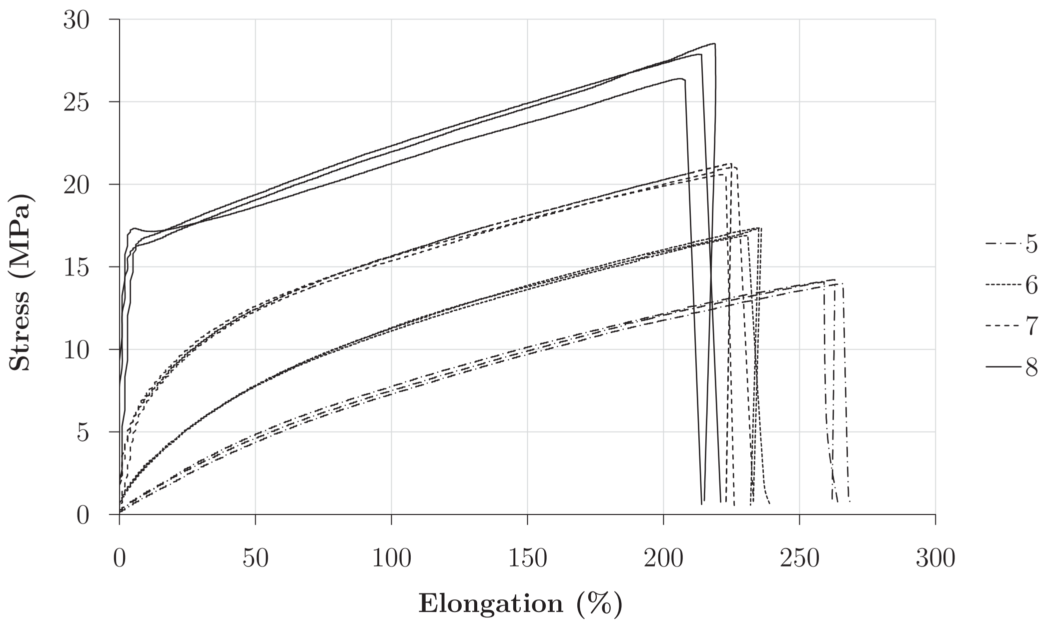


Figure 9.15: Tensile tests results for the materials with filler

terms of tensile strength, the longitudinal behaviour of material A is in quite good agreement with that of material 6 that has a similar plasticizer content, while

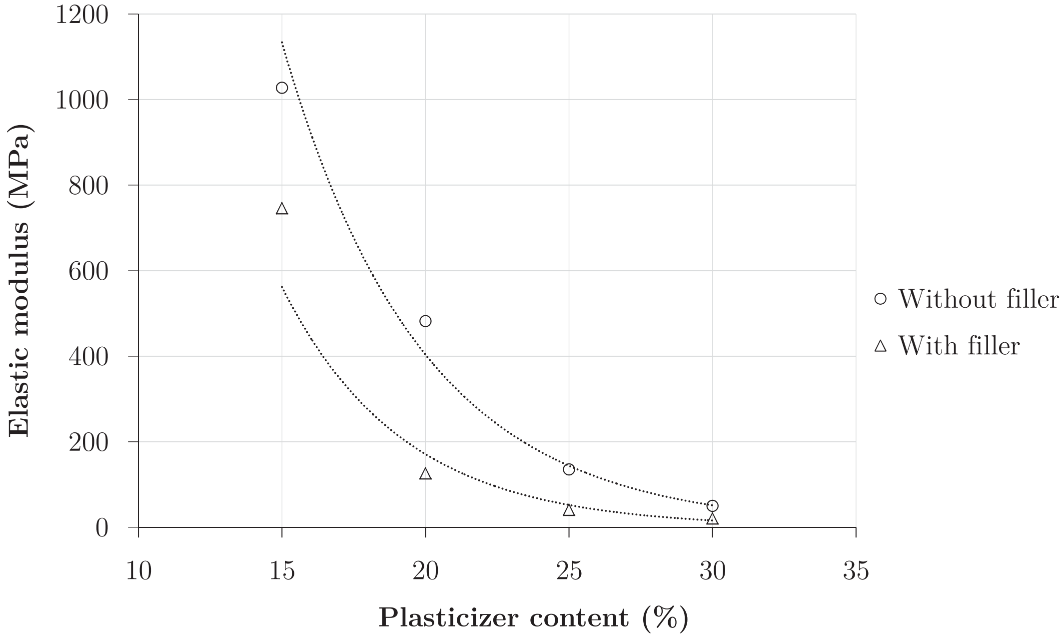


Figure 9.16: Elastic modulus of the extruded materials

material B, that has a plasticizer content of 26.7%, behaves more similarly to the extruded membrane with 30% of plasticizer, having a lower stress at break than material 6. The elongation at break is higher for the two commercial membranes than that of the corresponding extruded ones. In particular, material B has an elongation at break of about 360% while materials 1 and 2 have values about 275% and 260% respectively. As a consequence of the differences in stress and elongation, the elastic modulus of the commercial membranes is lower than that of the extruded membranes with similar plasticizer content: 28.3 MPa and 36.5 MPa for materials A and B and 40.9 MPa and 135.5 MPa for materials 6 and 2.

9.2.6 Foldability at low temperature

All samples do not break or present cracks after the low temperature flexibility test at -25°C according to EN 495-5 (2013). However, the behaviour of the samples is very different: samples 2, 3, 4, 7 and 8 are very stiff a -25°C even if they do not break.

9.2.7 Shore A hardness

Figure 9.17 reports the trend of Shore A hardness of the materials compared with that of the commercial materials and aged commercial materials.

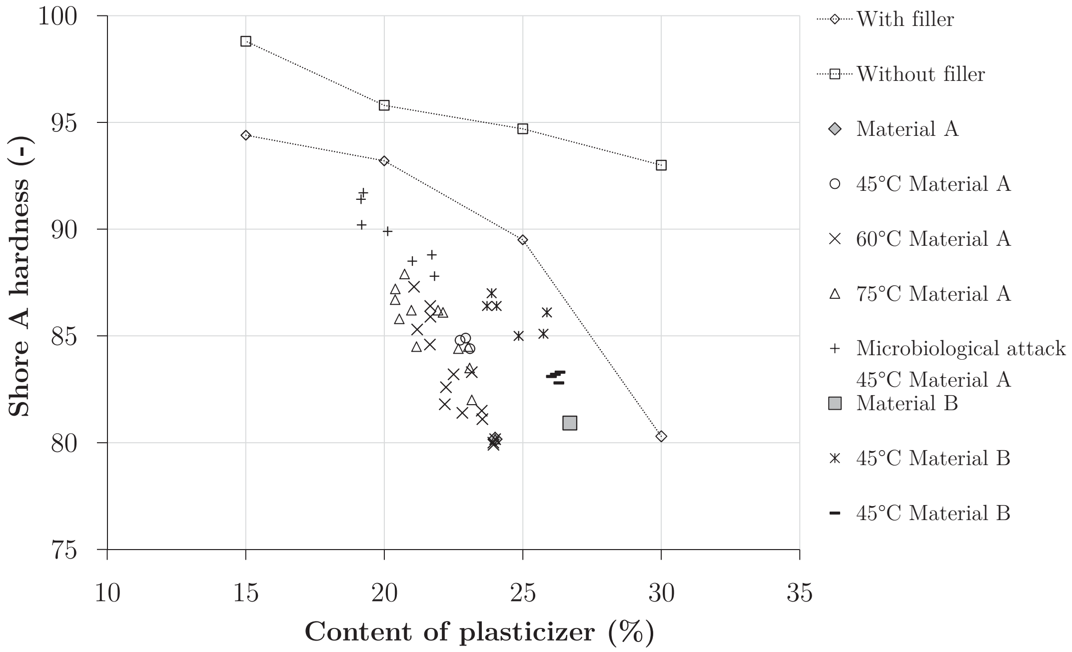


Figure 9.17: Shore A hardness of the eight formulations

The materials with filler have lower hardness than the others. Hardness decreases linearly with the increase of plasticizer content for materials without filler, while the reduction for the materials with filler increases with the increase of plasticizer content.

For the same plasticizer content, the commercial materials have lower surface hardness and shows a more rapid hardness increase with the loss of plasticizer due to ageing.

It is to be noted that Shore A hardness test is less effective for values above 95, that is the case of some of these results. However, in these tests the values over 95 have been considered in order to compare them to the other.

9.2.8 Compression test

The compression test with spheres described in Chapter 5 has been performed on the eight extruded materials in order to better analyse the mechanical effect of the variation of plasticizer content. Figures 9.18 and 9.19 compare the results of the tests with spheres of 10 mm of diameter for the eight extruded material with the two commercial membranes analysed in the previous Chapters.

At the contrary of what occurred for material A and B, in this case the extruded materials without filler have lower penetration than the once with filler with the same plasticizer content. As plasticizer content reduces, the materials without filler exhibit lower variation of the penetration while for the materials with filler

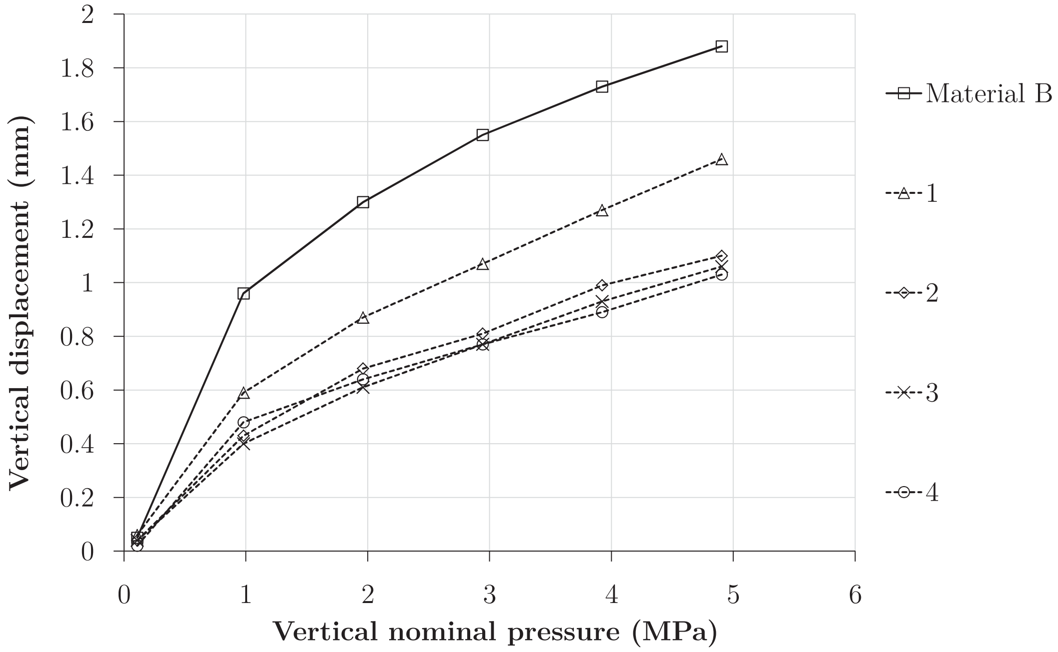


Figure 9.18: Vertical displacement of the tests with spheres of 10 mm of diameter for the materials without filler

the variation is almost constant. Material A behaves similarly to material 5 while material B shows a very different behaviour compared to the onces of the other materials without filler.

These differences in the behaviour between commercial and extruded materials and between those with filler and those without filler can be correlated to the surface hardness of the membranes. Figure 9.20 reports the penetration at 5 MPa of vertical pressure with spheres of 10 mm of diameter plotted against the Shore A hardness of the membranes.

The difference in the behaviour between material B and 1, that have similar compositions, is correlated to the difference of surface hardness. For the same value of surface hardness the membranes without filler show higher penetration of about 0.2 mm.

9.3 Discussion

9.3.1 Effect of variation of plasticizer content on the mechanical properties of PVC-P membranes

The mechanical behaviour of the PVC-P membrane is strongly influenced by the content of plasticizer in the material.

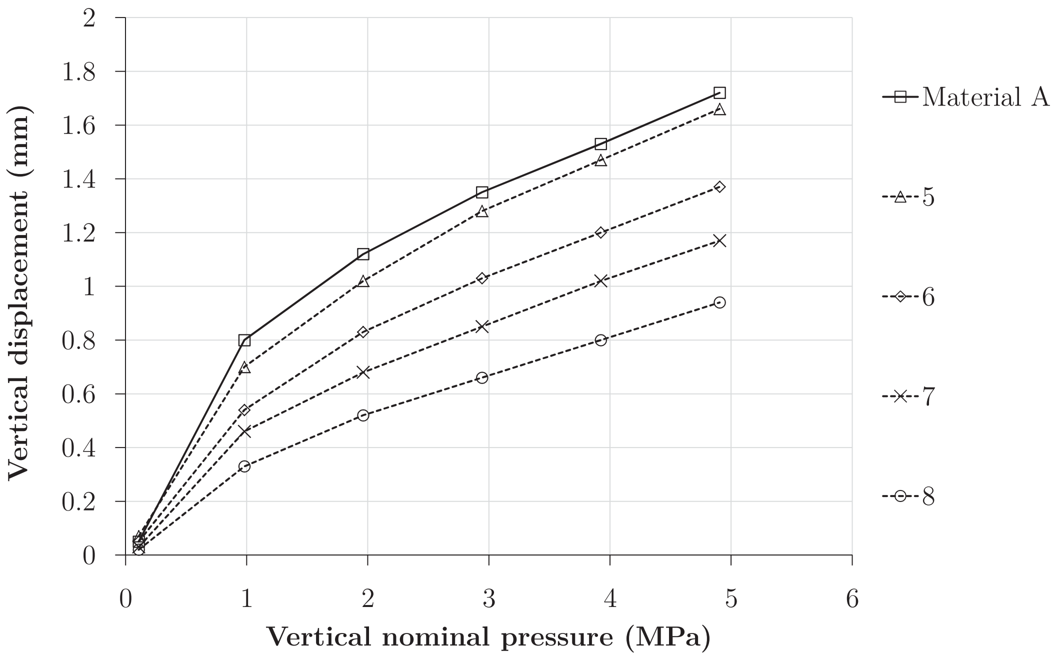


Figure 9.19: Vertical displacement of the tests with spheres of 10 mm of diameter for the materials with filler

With the reduction of plasticizer content the elongation at break reduces: materials with 15% of plasticizer have 79% of the elongation of those with 30% of plasticizer for the materials without filler and of about 81% of the value for those with filler. At the contrary, the tensile strength increases with the reduction of plasticizer of 68% of the value of the material with 30% of plasticizer for samples without filler and of 95% for those with filler.

However, not only the failure values are influenced by the content of plasticizer but the whole behaviour of the material. The higher the plasticizer percentage the more the PVC-P behaves like a viscoelastic material. Otherwise, with lower values of plasticizer, the material shows an elasto-plastic behaviour. In this case, the material still has a high value of elongation at break but it is due to the plastic deformation after yielding that is irreversible. This behaviour is also evident from the variation of the elastic modulus of the membrane, that increases exponentially with the reduction of plasticizer. Therefore, even if the final response of the material is similar, it behaves differently for small deformations (that are the most interesting in the case of tunnels where deformations are limited by the cast concrete).

The filler in the mix reduces the mechanical performances of the membrane. On the other hand, it reduces the temperature and pressure of extrusion and the effect of plasticizer reduction on the behaviour of the membrane. Moreover, materials with filler have lower surface hardness than equivalent formulation with the same

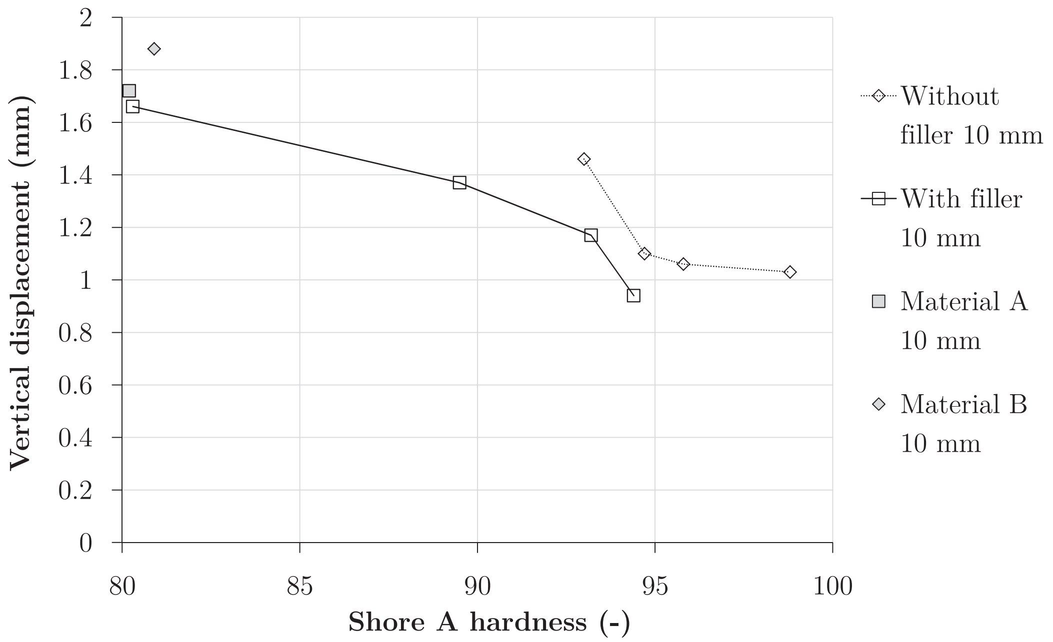


Figure 9.20: Vertical displacement of the tests with spheres of 10 mm of diameter compared to the surface hardness of the membranes

amount of plasticizer and lower values of penetration by external elements than membranes without filler with the same surface hardness.

The results cannot be directly linked to the aged material behaviour because the tested materials have been originally extruded with a lower value of plasticizer, while the aged materials loss a part of the plasticizer. The loss of plasticizer can result in voids in the structure of the material and consequently in lower mechanical properties. However, from density tests on the aged membranes reported in the previous Chapter and from the theoretical considerations of Giroud and Tisinger (1995), the void ratio in the membrane while plasticizer is lost can be considered low or negligible. Therefore, the developed tests give an evaluation of how the membrane parameters change due to the plasticizer loss during the life of the material.

9.3.2 Comparison between commercial and extruded membranes

The eight extruded membranes cover the range of variation of the plasticizer content in the PVC-P geomembranes (25–30%) and lower values simulating the potential loss of plasticizer.

In order to define the feasibility of using those materials to study the behaviour of the long-term aged commercial membranes, a comparison among the physical and mechanical properties should be done with the extruded materials with similar plasticizer content (material 6 for material A and material 1 and 2 for material B).

The density of the commercial membranes fits quite well with that of the materials studied in this Chapter. At the contrary, in terms of mechanical properties, the commercial membranes have lower tensile strength and elastic moduli and higher elongation at breaks. This results in a more soft behaviour of the commercial membranes, confirmed also by the lower value of surface hardness. As a consequence of the higher hardness, the extruded materials are less susceptible to the penetration in the performed compression tests.

Therefore, the mechanical properties of the extruded materials cannot be directly correlated to those of the commercial membranes when, due to loss of plasticizer, the same plasticizer content is reached. Nevertheless, the trend of variation of the mechanical properties with the variation of plasticizer content is representative of the behaviour of PVC-P geomebranes and can be rescaled on the original values of the mechanical properties of the commercial membranes to have a qualitative evaluation of their change in performances with the loss of plasticizer.

At the contrary, the plasticizer absorption tests shows a good correlation of the behaviour of the commercial materials with the extruded ones and therefore permits to use the obtained laws of dependence of D on the plasticizer content for the commercial membranes.

9.3.3 Effect of plasticizer content on the long-term plasticizer loss

From the tests of loss of plasticizer according to EN 14415 (2004) the formulations with higher plasticizer content show higher rates of loss of plasticizer. Moreover, the materials with filler confirm to be more susceptible to plasticizer loss.

The plasticizer absorption tests confirm these observations and permit to obtain a relationship between the diffusion coefficient D and the plasticizer content in the membrane. Material A fits well the behaviour of the formulations with filler, while material B has a less good fitting.

The reduction of plasticizer in the membrane results in the reduction of the free volume and consequently of the mobility of the polymer and plasticizer chains. Therefore, for lower plasticizer contents the diffusion is harder and the diffusion coefficient lower.

The outcomes of the plasticizer absorption tests can be used to have a better long-term extrapolation of the plasticizer loss in a membrane taking into account the dependence of D from the concentration. This dependence will induce a self-reducing phenomenon: as the plasticizer is lost, the diffusion coefficient reduces and consequently the speed of plasticizer loss decreases.

Chapter 10

Long-term extrapolations and durability assessment

10.1 Extrapolation through Arrhenius' equation

In order to establish a correlation between the accelerated ageing tests developed and the natural ageing that can occur in underground structures, Arrhenius' equation can be used. This is one of the most used correlations in literature for long-term extrapolations. The weight loss graphs of Figure 8.6 are fitted by a straight line in order to define the rate k of the phenomenon at the three tests temperatures. Figure 10.1 shows the variation of $ln(k)$ with T^{-1}. Using Equation 7.14, from this graph it is possible to define the constant A and the activation energy E_A of the phenomenon (Table 10.1) and with these values extrapolate the results to the jobsite temperature.

Table 10.1: Parameters of Arrhenius' equation for materials A and B

	A (%/day)	E_A (kJ/mol)
Material A	109.18	24.81
Material B	2425.03	34.79

Therefore, assuming a jobsite temperature of 15°C (that is the case of an urban tunnel), it is possible to define the relation between the accelerated ageing time and the ageing time on the jobsite for material A and B. Table 10.2 reports the corresponding natural ageing time and the acceleration factor expressed as natural days over accelerating ageing days. The result in terms of natural ageing days is low compared to the lifespan of underground structures.

From the same relation, it is possible to compute the time before all the plasticizer is lost from the geomembrane: 20 years for material A and 69 years for

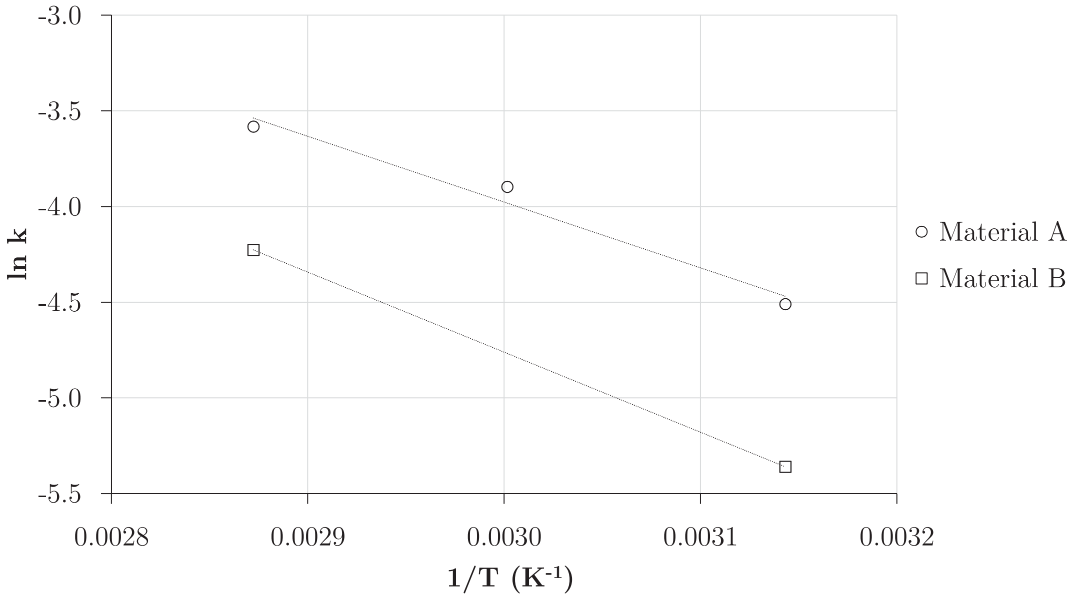


Figure 10.1: Values of rate of the phenomenon for material A and B

Table 10.2: Correspondences between accelerated ageing tests and ageing at 15°C

	Material A (years)	Material A (days/days)	Material B (years)	Material B (days/days)
45°C 180 days	1.3	2.64	1.84	11.11
60°C 270 days	3.0	4.06	-	-
75°C 270 days	4.4	5.95	8.22	3.73

material B.

These results give unrealistically low times for the complete loss of plasticizer, even compared to the values reported in literature on natural aged membranes analysed in Chapter 7.

The problem with this extrapolation comes from Arrhenius' hypotheses: this method is based on the assumption that the studied phenomenon has a constant rate with time, but this is not the case for plasticizer loss from PVC-P geomembranes. This is clear from the weight loss results of the accelerated ageing tests: the graphs can hardly be fitted by a straight line while they are better fit a curved line that reduces its slope with time. This is more evident for the tests where higher plasticizer loss occurs.

Repeating the Arrhenius' extrapolation on the weight loss data considering different durations of accelerating ageing test the loss rates results higher as the time basis shorts. As an example, Figure 10.2 reports the extrapolation of plasticizer loss computed with Arrhenius' equation for material B considering both the data of 270 of accelerating ageing tests and the data of 90 days of tests. The difference between the two extrapolation is of about 100%.

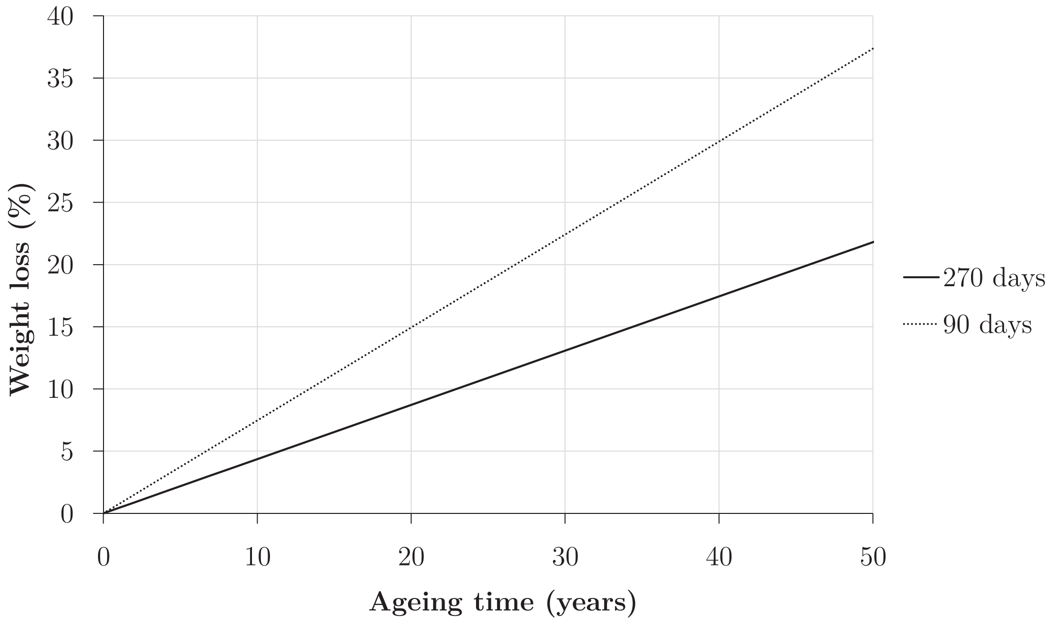


Figure 10.2: Extrapolation of weight loss through Arrhenius' equation based on different data

Therefore, the results of the performed tests highlight that Arrhenius' equation is not suitable to describe the long-term behaviour of plasticizer loss form PVC-P geomembrane. A not constant rate of plasticizer loss in natural ageing has been reported already by Stark et al. (2005). Benneton (1994) reports the study of 10 years natural ageing tests on PVC-P geomembranes and assesses that the results fit Arrhenius' equation. This can be due to the relatively short test and low loss of plasticizer, that can justify a linear interpretation of the data. However, to perform long-term extrapolations this method seems to be not well performing.

10.2 Extrapolation using Fick's law

The loss of plasticizer can be better analysed considering that the phenomenon is describable as diffusion. Therefore, the data are analysed using Fick's law, where the diffusion rate decreases as the concentration gradient between inside and outside the material decreases and, consequently, the loss has a path that is more similar to that of the accelerated ageing test results.

Fick's second law solution for semi-infinite space is reported in Equation 8.8. However, the model can be better refined taking into account the real geometry of the phenomenon. This result can be achieved solving Fick's second law (Equation 7.1) in the domain $0<x<x_{max}$ with the initial condition

$$c(x, t=0) = C_0 \tag{10.1}$$

where x and t are respectively the space and time coordinates, c the concentration in the membrane and C_0 the initial uniform concentration.

The boundary conditions are

$$c(0, t) = 0 \tag{10.2}$$

$$\left.\frac{c(x,t)}{x}\right|_{x=x_{max}} = 0 \tag{10.3}$$

The resulting solution is

$$c(x,t) = -\sum_{n=1}^{\infty} C_0 \frac{2x_{max}}{(2n-1)(1-x_{max})\pi} e^{-D\left(\frac{2n-1}{2x_{max}}\pi\right)^2 t} \sin \frac{2n-1}{2x_{max}}\pi x \tag{10.4}$$

Assuming the diffusion coefficient D equal to those obtained from plasticizer absorption tests, Fick's equation can be computed for the three test temperatures. Figures 10.3, 10.4, 10.5, 10.6 and 10.7 report the comparison among the results of the accelerated ageing tests and this model.

The results of Equation 10.4 using the D values obtained from the plasticizer absorption tests do not fit the experimental data and overestimates the plasticizer loss.

A better definition of the model can be achieved taking into account the dependence of the diffusion coefficient on the plasticizer content. From the plasticizer absorption tests, a potential law has been obtained in Chapter 9 and can be used to compute the diffusion, assigning for each time step a D value computed from Equation 9.1. The D_1 and b values for materials A and B are those obtained in Paragraph 9.2.4. At each time step, the value of C_P is that computed as the result of the previous step.

In Figures 10.8, 10.9, 10.10, 10.11 and 10.12 the results of this correction are compared to those of the other models and to the experimental data. The plasticizer loss has reduced but the experimental data are still not represented by this model.

The residual discrepancy between the model and the experimental data can be due to several conditions:

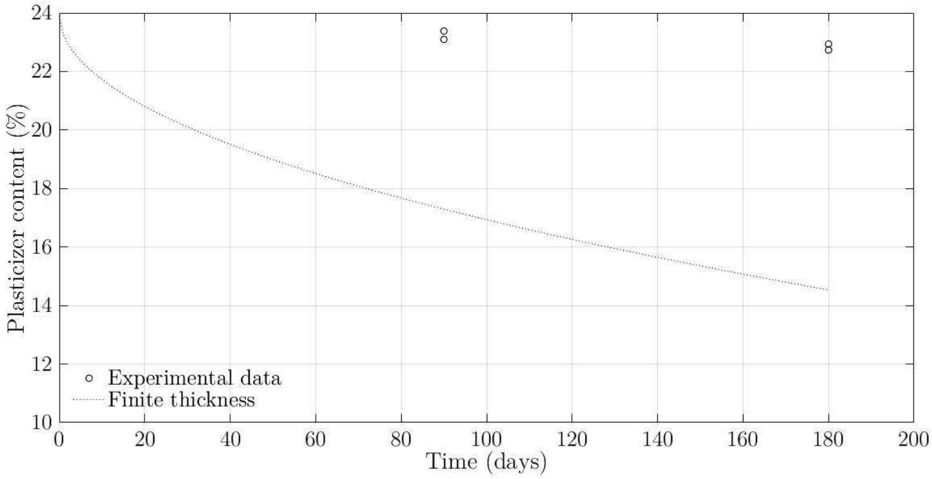


Figure 10.3: Comparison between experimental data at 45°C and the model according to Fick with the diffusion coefficient obtained from plasticizer absorption tests for material A

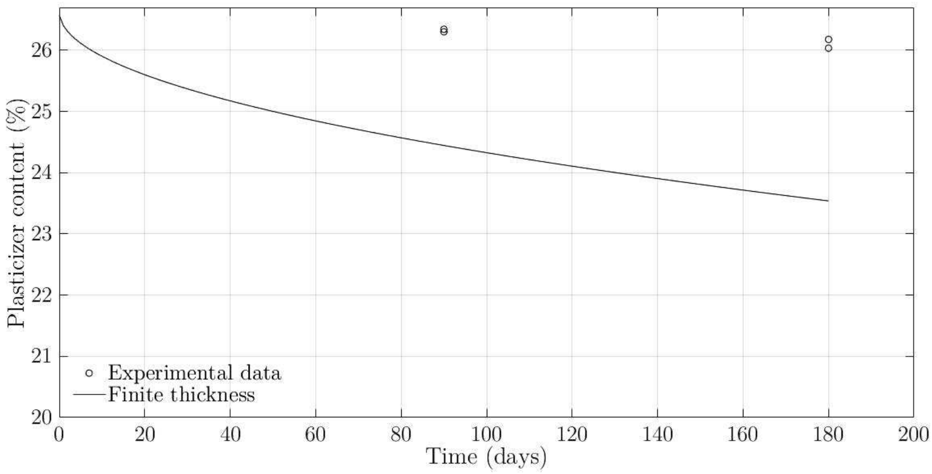


Figure 10.4: Comparison between experimental data at 45°C and the model according to Fick with the diffusion coefficient obtained from plasticizer absorption tests for material B

- the experimental conditions of the plasticizer absorption tests are artificially created: the membrane is totally dry and the surface cleaned, the plasticizer is the only external substance in contact with the PVC-P. This can result in higher diffusion coefficients than those occurring on the jobsite, where the membrane is wet (saturated with water after a certain time) and the surface not perfectly clean;

- the presence of salts dissolved in the water flowing in the accelerated ageing

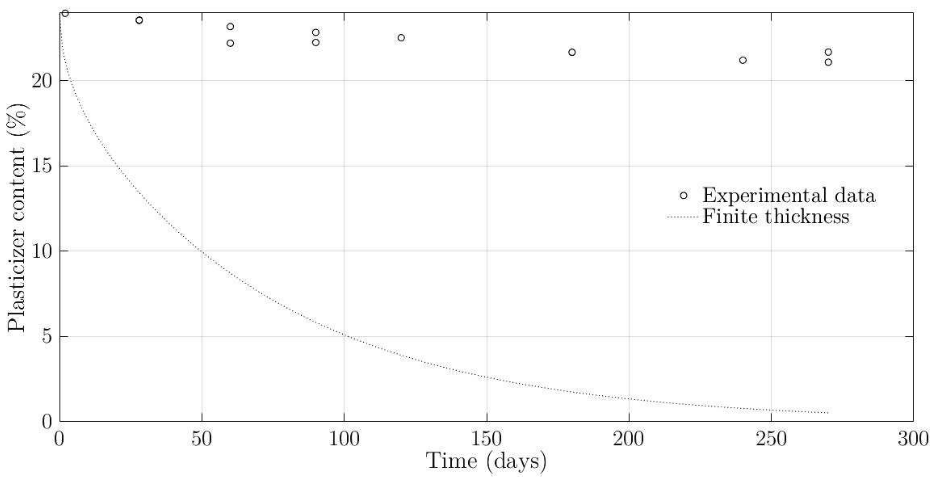


Figure 10.5: Comparison between experimental data at 60°C and the model according to Fick with the diffusion coefficient obtained from plasticizer absorption tests for material A

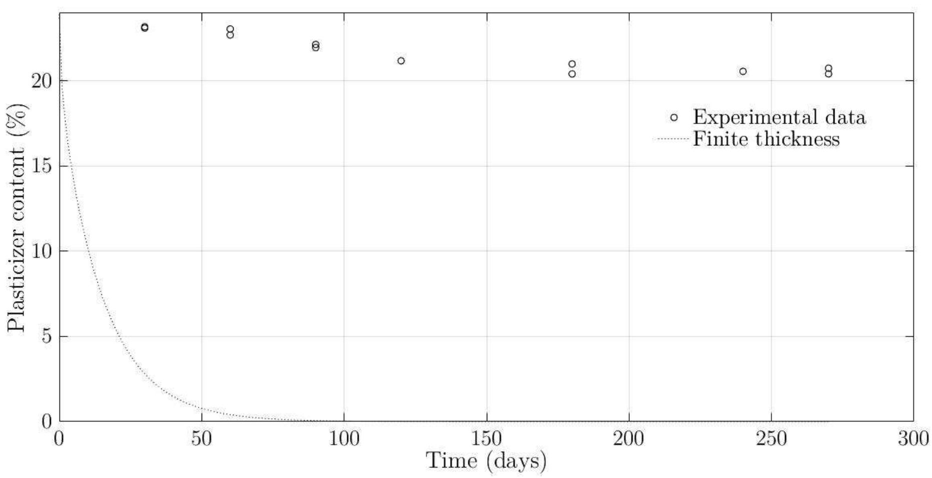


Figure 10.6: Comparison between experimental data at 75°C and the model according to Fick with the diffusion coefficient obtained from plasticizer absorption tests for material A

tests can reduce the ability of water of taking plasticizer from the membrane;

- since the flowing water is in contact with concrete, it is reach in calcium carbonates that partially deposited on the surface. However, the deposition of calcium carbonates can not justify on his own the difference in diffusion coefficient: in order to fit the experimental data with the diffusion coefficient obtained from plasticizer absorption tests, the accumulation of plasticizer on the surface, due to the obstacle given by calcium carbonates deposits should

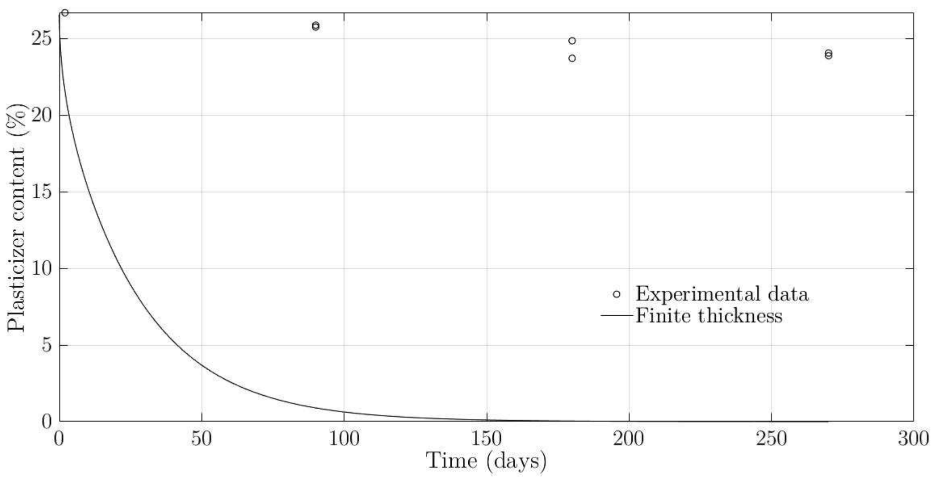


Figure 10.7: Comparison between experimental data at 745°C and the model according to Fick with the diffusion coefficient obtained from plasticizer absorption tests for material B

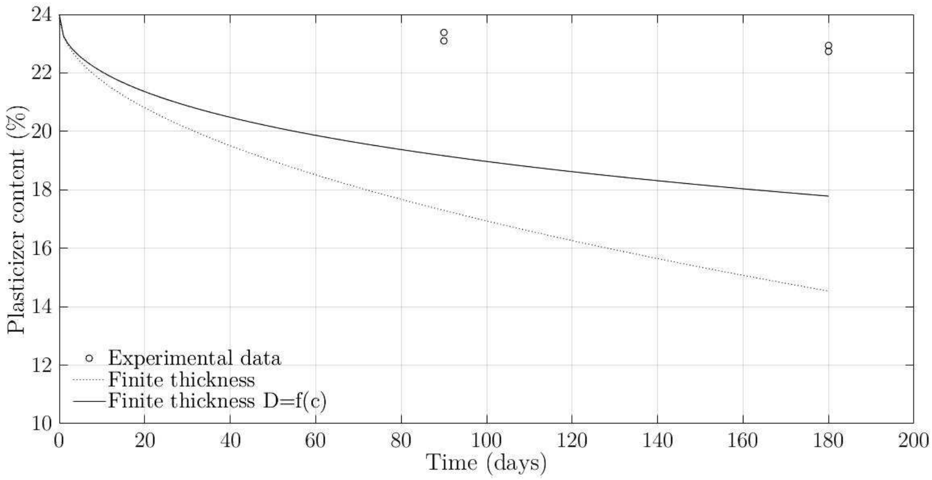


Figure 10.8: Comparison between experimental data at 45°C and the model according to Fick with the diffusion coefficient obtained function of the concentration for material A

be the 85% of the concentration inside the membrane, that is unrealistically high;

- some of the dissolved salts in the water may have partially entered the membrane reducing the diffusion coefficient. This condition has been reported by Usman and Galler (2014) for 30 years aged membranes in underground with water rich in $CaCO_3$. Moreover, the tested specimens extracted from the accelerated ageing test where partially covered with a thin layer of calcium

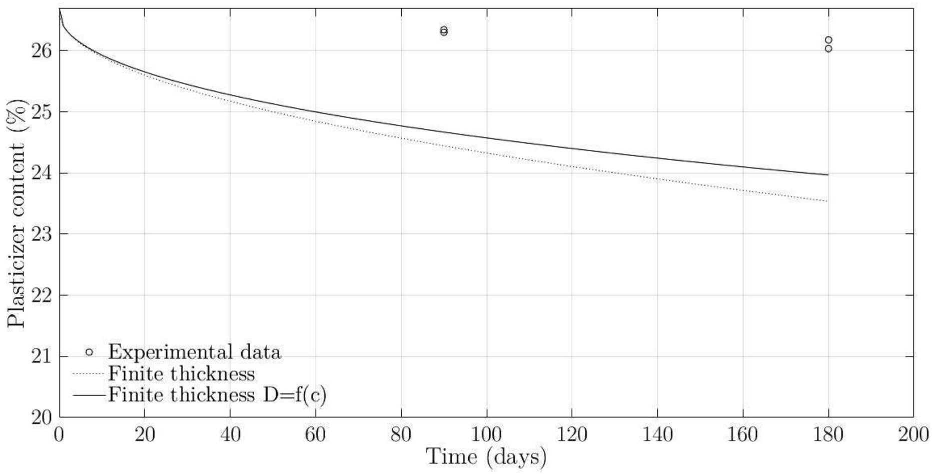


Figure 10.9: Comparison between experimental data at 45°C and the model according to Fick with the diffusion coefficient obtained function of the concentration for material B

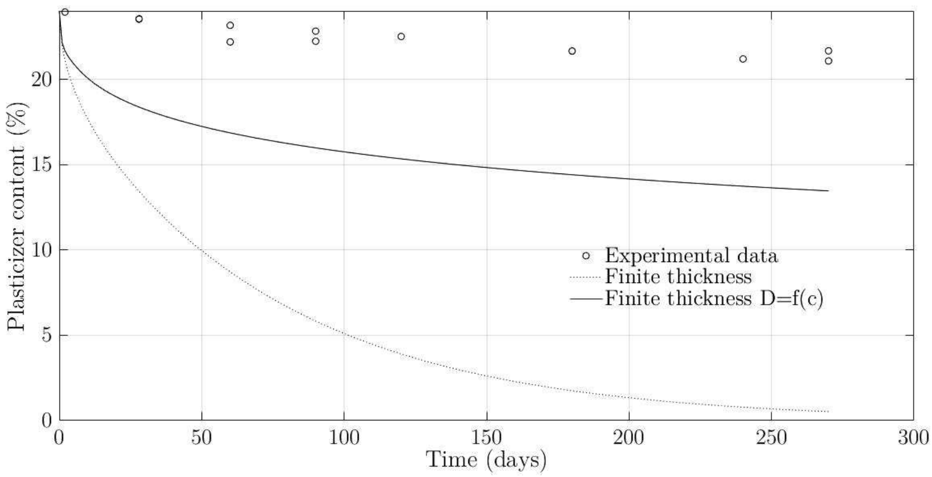


Figure 10.10: Comparison between experimental data at 60°C and the model according to Fick with the diffusion coefficient obtained function of the concentration for material A

carbonate.

The values of diffusion coefficients that better describe the experimental data have been obtained fitting Equation 10.4 on the data and are reported in Table 10.3. A good correlation with the data has been obtained (Figure 10.13, 10.14, 10.15, 10.16 and 10.17). These diffusion coefficients are about two order of magnitude lower than the ones obtained from the plasticizer absorption tests. Material B has diffusion coefficients lower than material A.

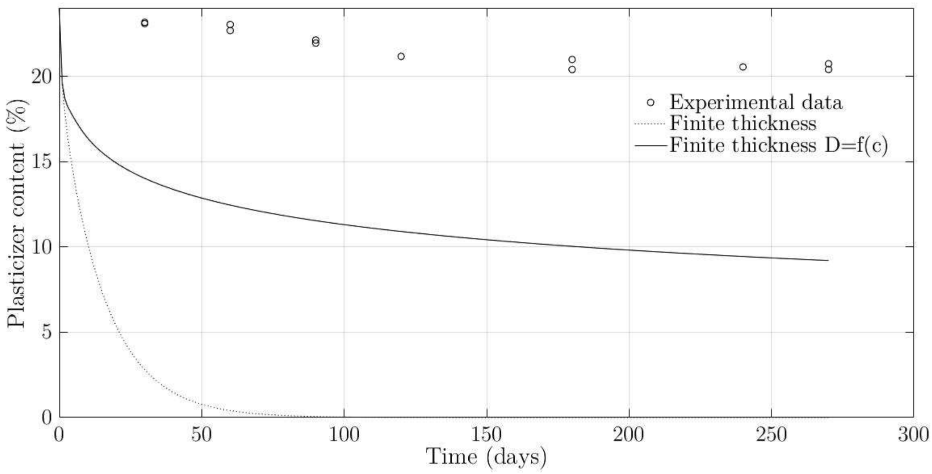


Figure 10.11: Comparison between experimental data at 75°C and the model according to Fick with the diffusion coefficient obtained function of the concentration for material A

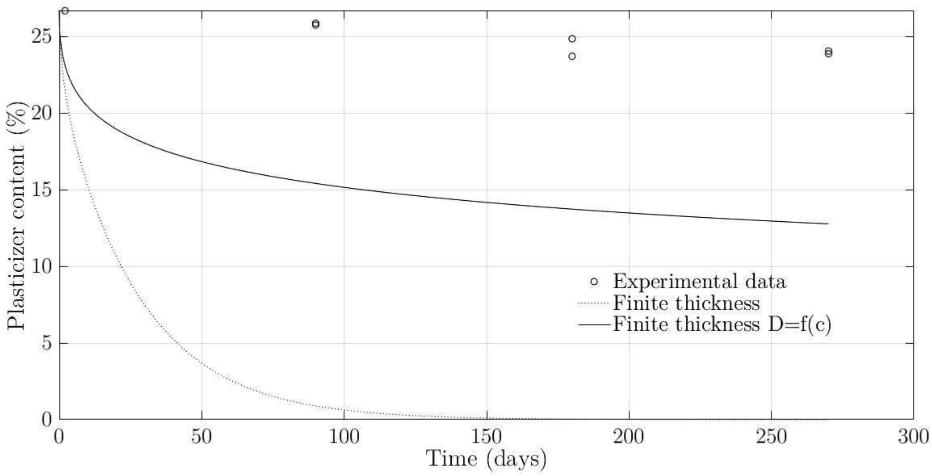


Figure 10.12: Comparison between experimental data at 75°C and the model according to Fick with the diffusion coefficient obtained function of the concentration for material B

If the dependence of D on the plasticizer content is considered the curve fits the experimental data for slightly different D values (Table 10.4).

Figures 10.13, 10.14, 10.15, 10.16 and 10.17 compare the results of the described models with different input parameters and the experimental data.

The dependence of diffusion coefficient on the concentration reduces the loss of plasticizer on the long term. This is more evident when using the parameters coming from the plasticizer absorption tests, while is less evident for the experimental data

Table 10.3: Diffusion coefficients D obtained for materials A and B in mm^2/s from experimental data

	Temperature (°C)		
	45	60	75
Material A	$4.0\ 10^{-10}$	$1.6\ 10^{-9}$	$2.8\ 10^{-9}$
Material B	$7.0\ 10^{-11}$	-	$1.2\ 10^{-9}$

Table 10.4: Diffusion coefficients D obtained for materials A and B in mm^2/s from experimental data considering $D=f(C)$

	Temperature (°C)		
	45	60	75
Material A	$4.5\ 10^{-10}$	$2.1\ 10^{-9}$	$4.2\ 10^{-9}$
Material B	$7.4\ 10^{-11}$	-	$1.6\ 10^{-9}$

Table 10.5: Values of D_0 and E_A for materials A and B from experimental data

	D_0 (mm^2/s)	E_A kJ/mol
Material A	3.25	60.02
Material B	14470	87.15

because the loss of plasticizer is lower and, consequently, the difference between the constant D value and the value dependent on the concentration is lower.

10.2.1 Long-term extrapolation of the loss of plasticizer

Using Fick's law and the described results, it is possible to analyse the long-term behaviour of the geomembrane with the diffusion coefficients obtained both from plasticizer absorption tests and from the experimental data.

The extrapolation is evaluated at a site temperature of 15°C, that can be a typical temperature value for swallow tunnels and urban tunnels. For the diffusion coefficients obtained from plasticizer absorption the dependence from temperature has been analysed in Paragraph 8.5.1. For the once obtained from the experimental data, the same procedure has been used to obtain a relationship with temperature according to Arrhenius' equation. In Table 10.5 the parameters of this correlation are reported.

Therefore, at 15°C the diffusion coefficient from the experimental data are 4.23 10^{-11} for material A and of 2.26 10^{-12} for material B, while those obtained from the plasticizer absorption tests are 6.48 10^{-10} and 3.58 10^{-11}, respectively.

In order to take into account the dependence of the diffusion coefficient on the

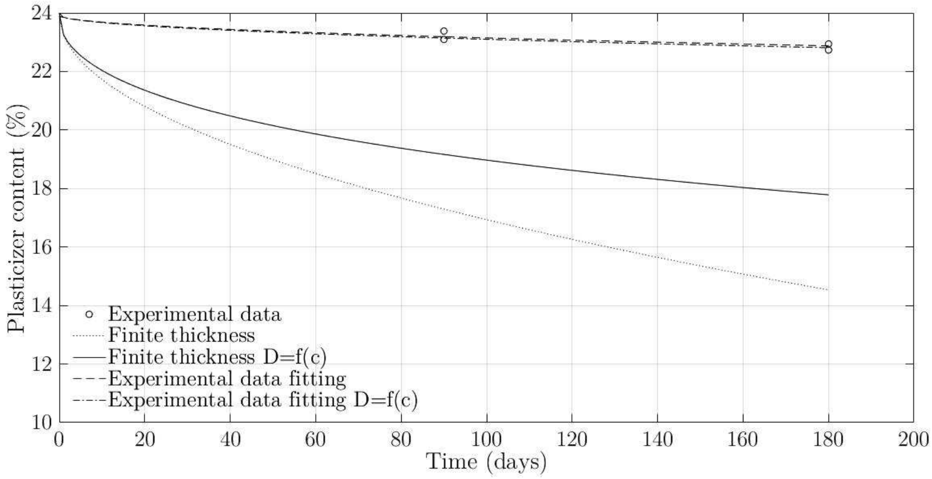


Figure 10.13: Comparison of the models and the experimental data for the tests at 45°C for material A

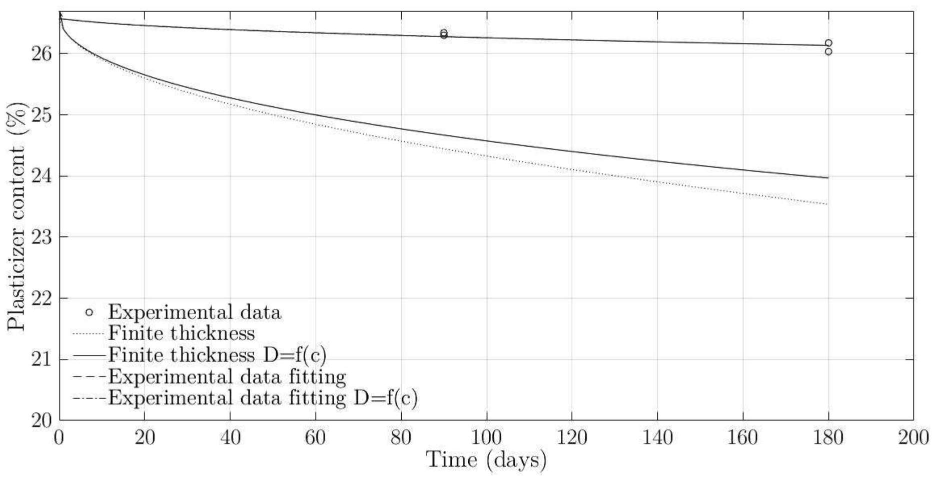


Figure 10.14: Comparison of the models and the experimental data for the tests at 45°C for material B

plasticizer content the identified potential law has been applied. In the absence of a clear relationship of b with temperature, for the 15°C computation the value measured at 20°C has been used. D_1 has been computed from Equation 9.1 as

$$D_1 = \frac{D}{{C_P}^b} \tag{10.5}$$

Figures 10.18 and 10.19 plot the 200 years extrapolation of plasticizer content and the values of plasticizer loss ratio after 50, 100, 150 and 200 years are reported in Table 10.6.

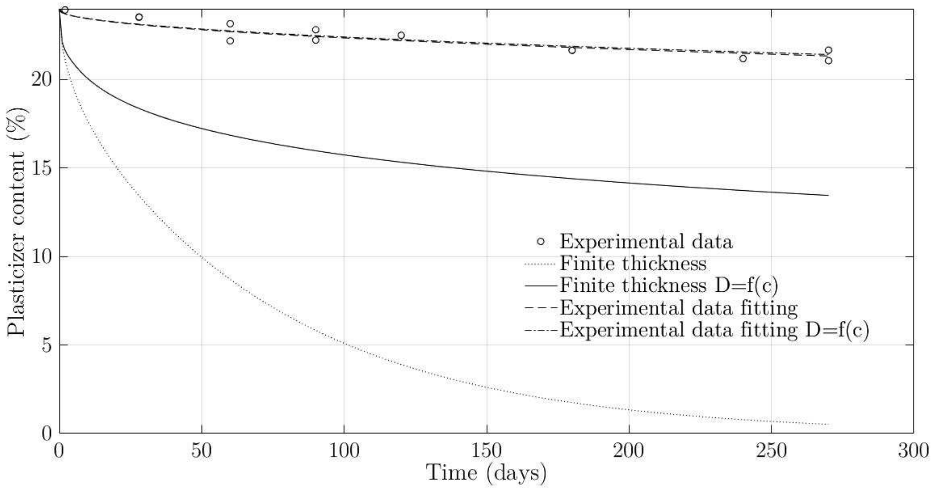


Figure 10.15: Comparison of the models and the experimental data for the tests at 60°C

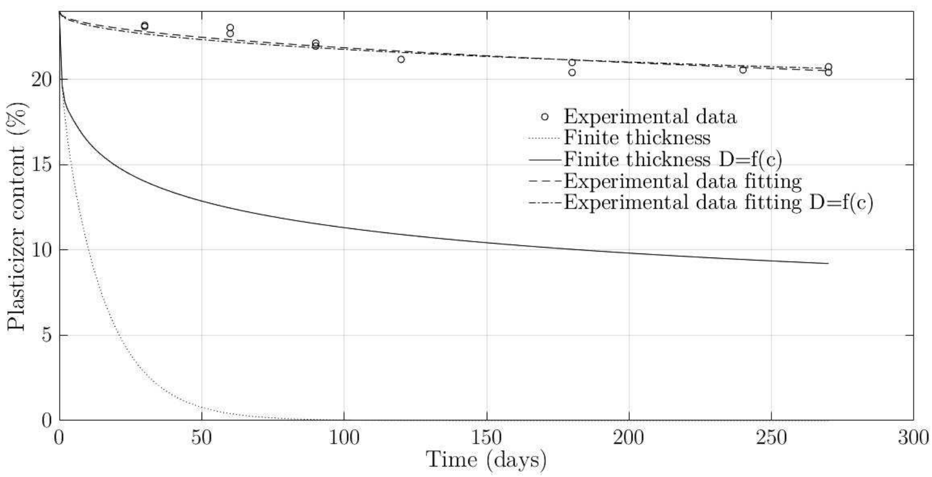


Figure 10.16: Comparison of the models and the experimental data for the tests at 75°C for material A

Material A has, using the equation based on plasticizer absorption tests, an high loss of plasticizer. The loss obtained fitting the experimental data is lower. Material B behaves better, with lower loss of plasticizer in all the possible extrapolations and with negligible loss values for both the cases of the curve fitting experimental data.

Directly using the coefficient derived from the tests at 45°C, it is also possible to perform the same extrapolations at a site temperature of 45°C, that is a very demanding condition for PVC-P membranes, but is the highest temperature measured in some deep tunnels (Parisi et al., 2017).

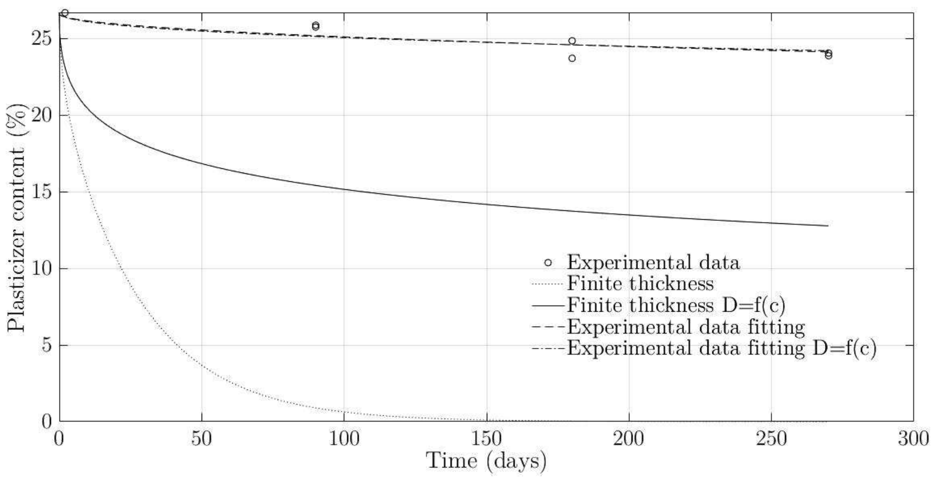


Figure 10.17: Comparison of the models and the experimental data for the tests at 75°C for material B

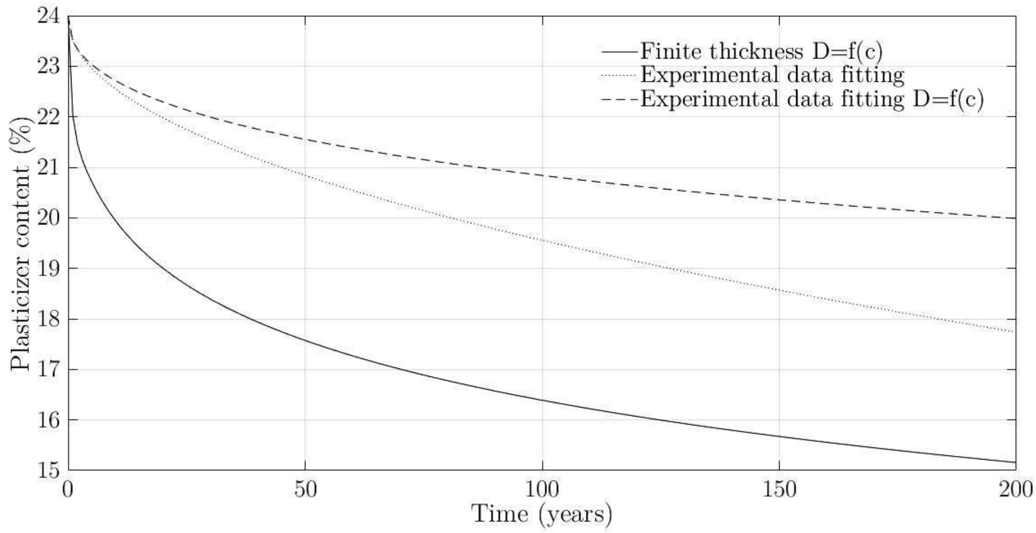


Figure 10.18: 200 years extrapolation of plasticizer content at 15°C for material A

Figures 10.20 and 10.21 report the extrapolations at 200 years in this condition and Table 10.7 summarizes the plasticizer loss ratios obtained for different ageing times.

The PVC-P membranes obviously behave in a worse way than in the previous extrapolation. Material A has extremely high loss of plasticizer with the loss of the 75% of plasticizer for the worst case after 50 years but with values of plasticizer loss ratio of about 0.5 at 200 years for the extrapolation fitting the experimental data and considering the dependence on the plasticizer content. Material B behaves

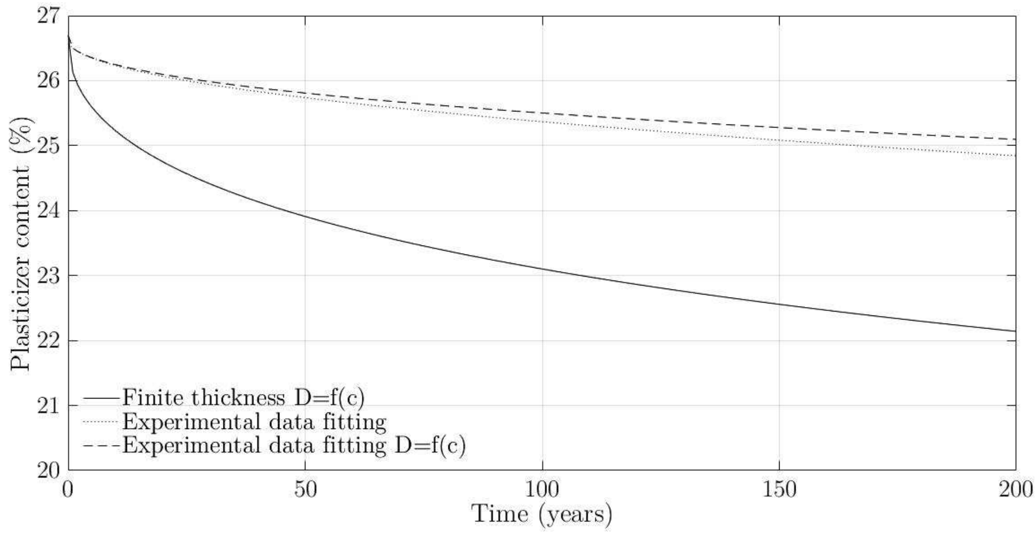


Figure 10.19: 200 years extrapolation of plasticizer content at 15°C for material B

Table 10.6: Plasticizer loss ratio at different times from the extrapolations at 15°C

		Plasticizer loss ratio (-)			
		50 years	100 years	150 years	200 years
Material A	Finite thickness with $D = f(C)$	0.32	0.38	0.41	0.43
	Experimental data	0.17	0.23	0.28	0.31
	Experimental data with $D = f(C)$	0.13	0.17	0.19	0.21
Material B	Finite thickness with $D = f(C)$	0.14	0.18	0.20	0.22
	Experimental data	0.05	0.07	0.08	0.09
	Experimental data with $D = f(C)$	0.05	0.06	0.07	0.08

better, even if, using data coming from the plasticizer absorption, the plasticizer loss ratio is always higher than 0.5. At the contrary, using the parameters coming from the experimental data of accelerated ageing test, the loss of plasticizer is lower.

10.3 Discussion on the long-term extrapolations

Long-term extrapolations have to be handle with care because they are based on several simplifying hypotheses. The longer the extrapolation period, the higher

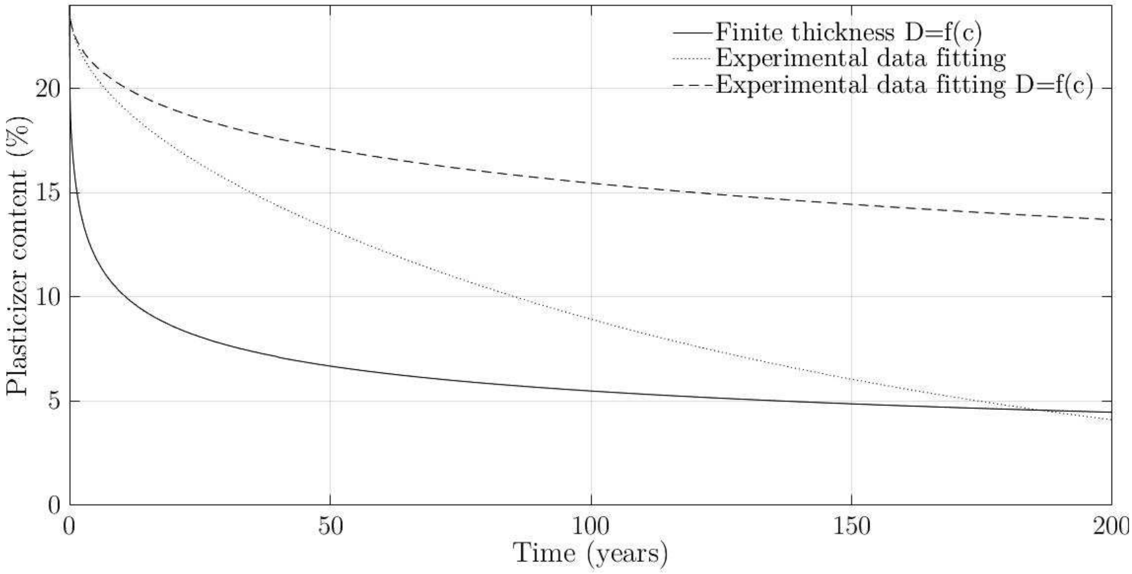


Figure 10.20: 200 years extrapolation of plasticizer content at 45°C for material A

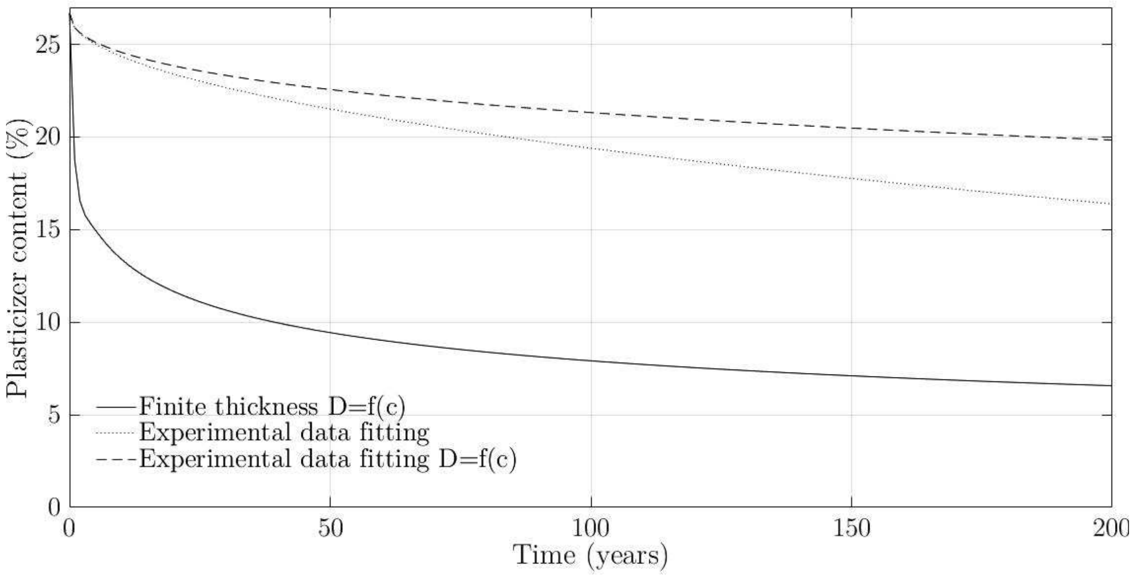


Figure 10.21: 200 years extrapolation of plasticizer content at 45°C for material B

the possible error in the estimation.

Nevertheless, the model used is based on the theoretical equation describing the diffusion phenomenon and this model fits well with the experimental data. The hypothesis at the basis of the extrapolations are:

Table 10.7: Plasticizer loss ratio at different times from the extrapolations at 45°C

		Plasticizer loss ratio (-)			
		50 years	100 years	150 years	200 years
Material A	Finite thickness with $D = f(C)$	0.77	0.82	0.84	0.85
	Experimental data	0.52	0.67	0.80	0.86
	Experimental data with $D = f(C)$	0.35	0.42	0.47	0.50
Material B	Finite thickness with $D = f(C)$	0.54	0.60	0.64	0.66
	Experimental data	0.24	0.33	0.40	0.45
	Experimental data with $D = f(C)$	0.20	0.26	0.29	0.32

- the diffusion of plasticizer is the only degradation phenomenon occurring in the geomembrane in the conditions of application for waterproofing systems (i.e. temperature lower than 50°C, absence of UV rays and microbiological attack);
- the diffusion occurs only in the direction of the geotextile because, the absence of water or air circulation on the side of cast concrete inhibits the removal of plasticizer from the surface and, consequently, stops the diffusion through that surface;
- the surface in contact with the geotextile is always washed by the water flow at a concentration of plasticizer equal to zero. If the water flux is low or absent or if the geotextile clogs and salt and particles deposit on the surface of the geomembrane the removal of plasticizer from the surface will be inhibited and the loss of plasticizer reduced.

From the analysis of these hypotheses, it is evident that the obtained extrapolations are the upper limit of the possible plasticizer loss. Particularly, the extrapolation coming from the data of the plasticizer absorption tests are the theoretical upper limit of the plasticizer loss.

The accelerated ageing tests results are fitted quite well with Fick's law and give a diffusion coefficient lower than that obtained from the plasticizer absorption tests. This difference can be due to the fact that the accelerated ageing tests do not represents the same ideal condition of the plasticizer absorption tests. Indeed, in these tests the membrane is wet and in contact with water containing dissolved salts and the surface of the membrane is not perfectly clean because it has not been cleaned before the test, in order to simulate the real installation conditions. Moreover, the presence of calcium carbonate in the water can reduce the ability of the plasticizer to migrate from the surface to the water. Furthermore, if the calcium carbonate permeates in the PVC matrix it can reduce the D value. Usman and Galler (2014) reports evidences of the occurrence of penetration of calcium carbonate in geomembranes in underground applications.

The extrapolations taking into account the dependence of the diffusion coefficient on the plasticizer content are the more realistic ones. However, since they are based on more experimental data, they can be subjected to higher errors on the very long term than that of the ones not considering this dependence.

The results of the extrapolations can be compared to the results of the tests on natural ageing of PVC-P geomembranes in underground structures reported by Usman and Galler (2014) and Maehner et al. (2018) and analysed in Chapter 7. Those case histories refer to geomembranes with filler aged in underground structures from 30 and 43 years. The information about the soil and water temperature are not reported but for urban environment and for shallow tunnels it can be reasonable to assume a temperature close to 15°C. Both the studies report that no relevant changes in the behaviour of the membrane occurs. Unfortunately, not any information is reported on the original and residual plasticizer content and on the type of plasticizer used. Nevertheless, if a qualitative comparison is performed with the results of the extrapolation at 15°C of material A after 50 years (Figure 10.18 and Table 10.6) the estimation of the plasticizer loss ratio obtained from the experimental data fitting are in the range 0.13–0.17, that corresponds to a residual plasticizer content of 20.7%–21.6% on the 24% original. This variation is small and, as obtained from the tests on the extruded membranes, results in small changes in the mechanical behaviour. If the extrapolations coming from the plasticizer absorption tests are used, the range of plasticizer loss ratio is of 0.32 corresponding to a residual plasticizer content of 17.68% that should result in more significant variations of the mechanical properties.

Although the reported cases histories are only two and many relevant informations are missing (e.g. temperature, water composition and flux, membrane composition and plasticizer content and type), these cases seem to confirm that the extrapolations based on the experimental data obtained from accelerated ageing tests can represent the loss of plasticizer in the real underground conditions.

10.4 Long-term effectiveness of waterproofing geomembranes

Benneton (1994) suggests that the end of effectiveness of a waterproofing PVC-P geomembrane can be defined at the moment when the plasticizer loss ratio is equal to 0.5. However, the author does not give any explication about the origin of this assumption.

In order to asses the durability of the waterproofing geomembranes the variation of the properties of the material during the service life of the structure has to be analysed. In Chapter 5 continuity has been identified as the required property for waterproofing geomembranes.

The time dependent degradation of PVC-P geomembrane in the conditions of application of waterproofing systems (low temperature, absence of UV and microbiological attack) is correlated only with the loss of plasticizer.

From the tests performed in Chapter 9, the effect of plasticizer loss is of increase the tensile strength and elastic modulus and decrease the elongation at break. Since during operation, the waterproofing membrane can not deform because it is constrained by the cast concrete and the shotcrete, the reduction of elongation at break is not relevant. Moreover, the residual value of elongation at break for a membrane with 15% of plasticizer content is still higher than 150%, that is a very big value compared to the possible deformations of concrete. Nevertheless, the loss of plasticizer causes the change in the tensile behaviour of the material from a soft-rubber like to an elasto-plastic one with a clear yielding point. For the studied extruded materials, this is evident for membranes without filler for plasticizer content below 20% and for the membranes with filler for plasticizer content of 15%. Only the portions of waterproofing membrane in the construction joints will be subjected during their service life to significant deformation that can cause the yielding of the PVC-P. The use of waterstops in the construction joints can avoid this issue. The commercial membranes analysed in this study have lower starting elastic modulus than the extruded material with the same content of plasticizer, and therefore it is possible to hypothesizing that the commercial materials will require lower plasticizer content than the extruded ones to have an elasto-plastic behaviour.

Furthermore, the loss of plasticizer causes increase of surface hardness of the membrane. As showed in Chapter 9, higher surface hardness implies higher resistance to penetration of the irregularities of the substrate or of the cast concrete. Therefore, if the initial properties of the geomembrane are well defined in order to avoid the formation of holes due to compression of irregular substrate, the loss of plasticizer can only increase the performance of the material.

Finally, the only effect of the loss of plasticizer that can affect the effectiveness of the waterproofing membrane is shrinkage. Indeed, as the plasticizer is lost, the membrane shrinks and this causes tensile stresses that can create holes. Particularly, this can be a problem if some irregularities have penetrated in the membrane reducing its thickness and creating a localized concentration of the stresses.

The shrinkage observed on the aged membranes studied in Chapter 8 resulted lower than the theoretical one proposed by Giroud (1995). However, the experimental data are not enough to define a different relationship. Therefore, this theoretical equation is used to compute the shrinkage considering it as an upper limit. Figure

10.22 reports the theoretical value of the axial deformation due to the shrinkage computed from Equation 7.11 for materials A and B.

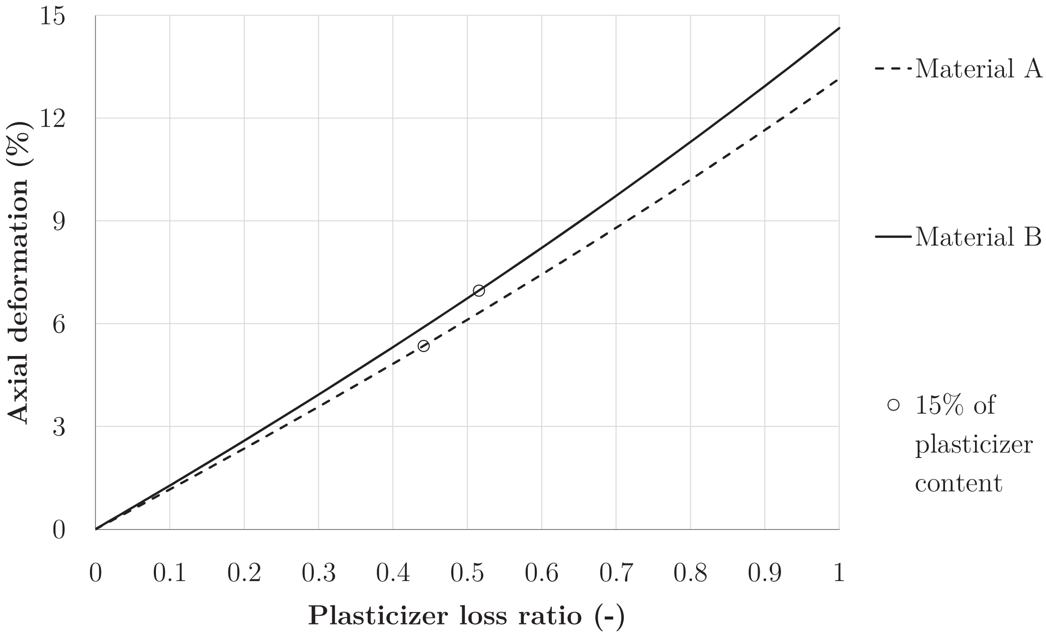


Figure 10.22: Axial deformation due to shrinkage with loss of plasticizer

The shrinkage can be considered as an elongation on the membrane and therefore compared to the mechanical behaviour of the membrane. The values of elongation are very low compared to the elongation at break of the geomembranes. However, with loss of plasticizer, the mechanical behaviour of the membrane changes: the extruded membranes with lower content of plasticizer (15%) begin to deform plastically after 5–6% of elongation. Therefore, in order to avoid plastic deformation of the membrane the limit is fixed to the minimum between 6% of elongation and the plasticizer loss ratio corresponding to 15% of plasticizer content. Material A reaches the limit on the plasticizer loss ratio while material B reaches the one on the elongation (Figure 10.22). For both materials the limit of plasticizer loss ratio is of 0.45.

This evaluation does not take into account that the long-term relaxation of PVC-P geomembranes will reduce the effective elongation and stress due to the shrinkage. Moreover, as already stated above, the behaviour of the extruded materials studied in Chapter 9 is stiffer than that of the commercial membranes that means that the trigger of plastic deformation for the commercial membranes will occur for higher plasticizer loss ratios.

Although the plasticization of the membrane is not directly connected to the failure of the material or to the formation of holes in the membrane, it can cause a reduction of the thickness of the membrane and a variation of its response to further actions. These are not necessarily limit conditions for the effectiveness of the membrane, but, in order to be on the safe side, these are considered not acceptable.

10.5 Final remarks

On the basis of the previous observations it is finally possible to define the end-of-life of the two commercial geomembranes as the time they have a plasticizer loss ratio of 0.45. From the extrapolations reported above, this means that in an environment at 15°C for 200 years materials A and B are still effective in all the simulations even if material A has lower safety factors and, in the more pessimistic extrapolation, is close to the limit after 100 years. Therefore, at 15°C both materials behave well and can be considered effective, even if a big difference in the ageing exists and the degradation of material B is almost negligible after 200 years when considering the data coming from the accelerated ageing tests.

In a demanding environment at 45°C, the commercial membrane A fulfils the required plasticizer loss only for 100 years in the more optimistic extrapolation, while it is not in the threshold in all the other simulations. Material B has plasticizer loss ratio lower than 0.45 up to 200 years in both the simulations based on experimental data, while exceed the limit for all the ageing times for the extrapolation based on the plasticizer absorption tests.

Therefore, in this very demanding environment, that can be considered as a technological limit for PVC-P membranes, material A can not be a design option while material B can be used on the basis of the simulations considering the accelerated ageing tests, even if great care has to be paid since the upper limit condition is not fulfilled. Higher thickness of the membrane can reduce the loss of plasticizer and therefore permit a safer use in this environment.

Chapter 11

Conclusions

This work studies the design and durability of waterproofing of underground structures using geomembranes both with the development of design procedure based on risk analysis and with laboratory tests on the mechanical properties and degradation of commercial and specifically defined PVC-P geomembranes.

A procedure based on the risk analysis approach has been developed as a tool for the choice of the most suitable waterproofing solution to be applied in a project. The procedure is based on the analysis of all the possible factors connected to the interaction between underground structures and water. The Monte Carlo method has been applied to obtain the statistical evaluation of the results. This procedure permits the cost-benefit comparison of different technologies taking into account the whole lifespan of the structure. Moreover, from the outcomes of this procedure, the effectiveness of each solution can be computed and the probability of failure or the probability of the residual risk, expressed as a cost, evaluated.

From the analysis of the potential actions on the waterproofing geomembrane during its life, it is clear that the damage on the waterproofing membrane is mostly due to the installation phase: in this phase the most important actions are the static and dynamic loads due to punching that can create holes in the geomembrane. Unfortunately, these actions are very complex to be defined and foreseen because they depend on several causes: the quality of the substrate (smoothness, absence of metallic elements on the surface), the type, properties and protection effectiveness of the regularization layer, the presence of a protection layer, the skills and the care of the manpower during installation of the membrane, during the operations before casting and during the rebar positioning. The properties of the waterproofing geomembrane can only partially change the impact of these actions. In order to reduce this impact, the substrate should be made according to the state of the art in terms of smoothness and great care has to be paid by the manpower.

From the performed compression tests, a substrate with a maximum diameter of the aggregates of 10 mm does not damage the membrane for pressures up to 5 MPa. Furthermore, the presence of a regularization layer of only 500 g/m^2 reduces the penetration of about 50% for high pressures and higher specific weight of the geotextile will result in higher protection.

The geotextile layer has to be designed considering two aspects: the effect of the protection of the geomembrane and the drainage flow rate, taking into account also the long-term reduction of drainage. Similarly, drainage pipes have to be designed based on the water flow and the possibility of regular cleaning has to be foreseen to avoid clogging.

The thickness of the waterproofing geomembrane influences the behaviour of the system because a bigger thickness reduces the possibility of punching of the membrane from the irregularities of the substrate or of the cast concrete. Moreover, increasing the thickness, the loss of plasticizer is slowed with a non-linear dependence: thickness lower than 2 mm will result in very fast loss of plasticizer. Furthermore, the tensile stresses are lower if the thickness is greater and, consequently, the section of the membrane bigger.

A test method for the accelerated ageing of geomembranes in conditions similar to those of the jobsite installation has been designed and the ageing of two geomembranes studied. The accelerated ageing tests simulating the real conditions of the geomembrane in the tunnel allowed to better study the degradation phenomenon of PVC-P geomembranes in tunnel conditions. These tests permit the extrapolation of the long-term behaviour of plasticizer loss in two commercial geomembranes.

Arrhenius' correlation, usually applied for this aim, has resulted to be not suitable for this phenomenon because the rate of plasticizer loss is not constant but changes with plasticizer content and the concentration gradient between inside and outside the membrane. Therefore, Fick's law has been used to analyse the results of the accelerated aged tests since it has a good correlation with the experimental data. The dependence of the diffusion coefficient on the plasticizer content and on the temperature has been defined from plasticizer absorption tests.

The diffusion coefficients obtained from plasticizer absorption tests are higher than those obtained fitting the experimental data. This can be due to the different conditions of the two tests: the plasticizer absorption test is performed on clean and dry samples of PVC-P immersed in pure plasticizer, while the accelerated ageing tests are performed on geomembranes saturated with water and not perfectly clean due to the effect of water flow on the surface, that is a condition more similar to the real one in tunnels. Moreover, the presence of dissolved salts in the water (e.g. calcium carbonate) can affect the diffusion coefficient. In effect, a thin calcium carbonate layer has formed on the PVC-P geomembranes after the test. This condition can be realistic in many underground cases where the groundwater is usually rich in dissolved salts.

A model to extrapolate at the jobsite temperature the loss of plasticizer has been developed for the studied geomembranes. The extrapolation has been done both using the values coming from plasticizer diffusion tests and using the values obtained fitting the results of the accelerated ageing tests. The former represents the maximum theoretical plasticizer loss value, while the latter is a condition that can be considered more realistic in many practical underground applications. Moreover, it is to be noted that the accelerated ageing tests have been carried out under constant water flow. If in the tunnel there is no water flow on the geomembrane, the removal of plasticizer from the surface will be lower and consequently the plasticizer loss will be inhibited.

In order to define the end-of-life of the geomembrane, the mechanical properties of PVC-P membrane with different plasticizer contents have been studied on eight specifically designed PVC-P formulations. As plasticizer is lost, the geomembrane increases its tensile strength and surface hardness, thus having a better resistance and lower risk of penetration of external grains. The increase of elastic modulus can be an issue only for expansion joints.

The only consequence of plasticizer loss that can affect the effectiveness of the waterproofing membrane is shrinkage, that, in association with the more rigid behaviour of the material with lower plasticizer content, can induce the plasticization of PVC-P. Plasticization is not necessarily a limit condition for the effectiveness of the membrane, but represents a change of behaviour of the geomembrane and causes the reduction of the thickness and possible opening of small holes. For the analysed membranes, the limit of plasticization has been defined at a value of plasticizer loss ratio of 0.45.

The studied geomembranes are a coloured one with filler and a transparent one without filler. The first one behaves better in the compression tests because the filler increases the resistance to penetration of external grains and is less susceptible to be burnt during welding. However, the material without filler has better mechanical properties (higher tensile strength and elongation at break) and diffusion coefficients one order of magnitude lower than the ones of the coloured membrane. Therefore, the durability of the material without filler is higher and this type of membrane can be considered suitable to be used for 200 years in environment at 15°C and border line for 100 years in a very demanding environment at 45°C.

Since the diffusion behaviour is strictly depending on the material properties and structure, the extrapolations reported in this study are valid only for the studied geomembranes and the studied plasticizer. The carried out tests could be repeated on different materials in order to extend the results to more applications. This can be done using the proposed test methodology that has proved to be feasible.

The creep behaviour of the geomembranes with different plasticizer content should be analysed to investigate if the stresses due to shrinkage are partially reduced by the relaxation of PVC-P. Furthermore, the distance between the diffusion coefficients obtained from plasticizer absorption tests and from the accelerated ageing tests should be better analysed and the influence of calcium carbonate further studied in order to define a relationship between the quality of the water and the loss of plasticizer. Nevertheless, even if those issues are still to be investigated, the results of this study allow to perform an extrapolation of the degradation of the geomembranes and to evaluate the end-of-life time in different installation environments that is a key issue to be known by the owners of an underground infrastructure. This assessment permits to better define the range of application of PVC-P geomembranes and to base the choice of the waterproofing system material for long-term applications on more scientific considerations.

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