Keynote Lecture: Geosynthetics for Africa

K.R. Legge. Department of Water Affairs and Forestry, Pretoria, South Africa. leggek@dwaf.gov.za
P. Baxter, Geotextiles Africa cc. Cape Town, South Africa. geotex@iafrica.com
P.J. Meyer, Aquatan Pty Ltd. Kempton Park, South Africa. pmeyer@aquatan.co.za
M.G. Sander, Kaytech Engineered Fabrics, Durban, South Africa. mike@kaytech.co.za
D.T.V. Viljoen, Engineered Linings Pty Ltd, Cape Town, South Africa. dtv@englining.co.za

ABSTRACT

The broad range of resources and diverse climatic conditions of the African continent provide exciting opportunities for the use of geosynthetic materials in civil, environmental and mining applications. The rapid evolution of geosynthetics manufacturing and technology around the world has been adapted and developed as appropriate for site-specific African applications. This paper explores the development and use of local and imported geosynthetic materials and products, and their applications in resource utilization and infrastructure development. The water resource development and associated infrastructure sectors, and the environmental protection and transportation fields in particular have been the primary focus in the application of geosynthetics on this continent. The historic use of these materials is reported, along with the development of current products and applications. Some speculative thoughts are presented on possible future applications and solutions to challenges in this growing industry, be they materials, products or systems, in a specific application.

1. INTRODUCTION

Africa is the world's second-largest and second most-populous continent after Asia. At about 30.2 million km² including adjacent islands, it covers 6 % of the Earth's total surface area and 20.4 % of the total land area.

With a billion people (as of 2009) in 61 territories, it accounts for about 14.8 % of the world's human population. The continent is surrounded by the Mediterranean Sea to the north, the Suez Canal and the Red Sea to the northeast, the Indian Ocean to the southeast, and the Atlantic Ocean to the west. Not counting the disputed territory of the Western Sahara, there are 53 countries, including Madagascar and various island groups, associated with the continent.

Africa, particularly central eastern Africa, is widely regarded within the scientific community to be the origin of humans and the Hominidae tree (great apes), as evidenced by the discovery of the earliest hominids and their ancestors. Later discoveries have also been dated to around seven million years ago, with the earliest Homo sapiens (human) found in Ethiopia being dated to ca. 200 000 years ago. Some 350 km to the east of the conference venue, evidence has been found of cave habitation along the coast dating back about 165 000 years.

Africa straddles the equator and encompasses numerous climate areas; it is the only continent to stretch from the northern temperate to the southern temperate zones.

2. HISTORY

2.1 Paleohistory

At the beginning of the Mesozoic Era Africa was joined with the earth's other continents in Pangaea. Africa shared the supercontinent's relatively uniform fauna, which was dominated by theropods, prosauropods and primitive ornithischians by the close of the Triassic period. Late Triassic fossils are found throughout Africa, but are more common in the south than north. The boundary separating the Triassic and Jurassic marks the advent of an extinction event with global impact, although African strata from this period have not been thoroughly studied**.**

Early Jurassic strata are distributed in a similar fashion to Late Triassic beds, with more common outcrops in the south and less common fossil beds, predominated by tracks to the north. As the Jurassic proceeded, larger and more iconic groups of dinosaurs like sauropods and ornithopods proliferated in Africa. Middle Jurassic strata are neither well represented nor well studied in Africa. Late Jurassic strata are also poorly represented apart from the spectacular Tendaguru fauna in Tanzania. The Late Jurassic life of Tendaguru is very similar to that found in western North America.

Midway through the Mesozoic, about 150–160 million years ago, Madagascar separated from Africa, although it remained connected to India and the rest of the Gondwanan landmasses.

By the beginning of the Late Cretaceous epoch South America had split off from Africa, completing the southern half of the Atlantic Ocean. This event had a profound effect on global climate by altering ocean currents.

Africa is considered by most paleoanthropologists to be the oldest inhabited territory on earth, with the human species originating from the continent. During the middle of the twentieth century anthropologists discovered many fossils and evidence of human occupation, perhaps as early as 7 million years ago. Fossil remains of several species of early apelike humans thought to have evolved into modern man, such as *Australopithecus afarensis* (radiometrically dated to approximately 3.9–3.0 million years BC), *Paranthropus boisei* (c. 2.3–1.4 million years BC) and *Homo ergaster* (c. 1.9 million–600,000 years BC) have been discovered.

Throughout humanity's prehistory Africa (like all other continents) had no nation states, and was instead inhabited by groups of hunter-gatherers, such as the Khoi and San.

At the end of the Ice Ages, estimated to have been around 10 500 BC, the Sahara had again become a green fertile valley and its African populations returned from the interior and coastal highlands in sub-Saharan Africa. However, the warming and drying climate meant that by 5000 BC the Sahara region was becoming increasingly dry and hostile. The population trekked out of the Sahara region towards the Nile Valley below the Second Cataract where they made permanent or semi-permanent settlements. A major climatic recession occurred, lessening the heavy and persistent rains in central and eastern Africa. Since this time dry conditions have prevailed in eastern Africa, and increasingly so during the last 200 years in Ethiopia.

The domestication of cattle in Africa preceded agriculture and seems to have existed alongside hunter-gathering cultures. It is speculated that by 6000 BC cattle were already domesticated in North Africa. In the Sahara-Nile complex, people domesticated many animals including the pack ass and a small screw-horned goat, which was common from Algeria to Nubia. In the year 4000 BC, the climate of the Sahara started to become drier at an exceedingly fast pace. This climate change caused lakes and rivers to shrink significantly and caused increasing desertification. This, in turn, decreased the amount of land conducive to settlements and helped to cause migrations of farming communities to the more tropical climate of West Africa.

By the first millennium BC ironworking had been introduced in northern Africa and quickly spread across the Sahara into the northern parts of sub-Saharan Africa, and by 500 BC metalworking began to become commonplace in West Africa. Ironworking was fully established by roughly 500 BC in many areas of east and West Africa, although other regions didn't begin ironworking until the early centuries AD.

2.2 Early Civilizations

At about 3300 BC, the historical record opens in northern Africa with the rise of literacy in the Pharaonic civilisation of Ancient Egypt. One of the world's earliest and longest-lasting civilizations, the Egyptian state continued, with varying levels of influence over other areas, until 343 BC.

European exploration of Africa began with ancient Greeks and Romans. In 332 BC, Alexander the Great was welcomed as a liberator in Persian-occupied Egypt. Following the conquest of North Africa's Mediterranean coastline by the Roman Empire, the area was integrated economically and culturally into the Roman system.

Pre-colonial Africa possessed perhaps as many as 10 000 different states and polities characterised by many different sorts of political organisation and rule. These included small family groups of hunter-gatherers such as the San people of southern Africa; larger, more structured groups such as the family clan groupings of the Bantu-speaking people of central and southern Africa; heavily-structured clan groups in the Horn of Africa; the large Sahelian Kingdoms and autonomous city-states and kingdoms such as those of the Yoruba and Igbo people in West Africa; and the Swahili coastal trading towns of east Africa.

Slavery has been practiced in Africa, as well as other places, throughout recorded history. Between the seventh and twentieth centuries, Arab slave trade (also known as slavery in the East) took 18 million slaves from Africa via trans-Saharan and Indian Ocean routes. Between the fifteenth and the nineteenth centuries, the Atlantic slave trade took 7–12 million slaves to the New World.

The gradual decline of slave-trading, prompted by a lack of demand for slaves in the New World, increasing anti-slavery legislation in Europe and America, and the British navy's increasing presence off the west African coast, obliged African states to adopt new economies. Between 1808 and 1860, the British West Africa Squadron seized approximately 1 600 slave ships and freed 150 000 Africans who were aboard. Anti-slavery treaties were signed with over 50 African rulers. The development of "legitimate commerce" in the form of palm oil, cocoa, timber and gold formed the backbone of West Africa's modern export trade. The Oyo Empire, unable to adapt, collapsed into civil wars.

In the late nineteenth century the European imperial powers engaged in a major territorial scramble and occupied most of the continent, creating many colonial nation states and leaving only two independent nations: Liberia, an independent state partly settled by African Americans; and Orthodox Christian Ethiopia (known to Europeans as "Abyssinia"). Colonial rule by Europeans would continue until after the conclusion of World War II. Independence movements in Africa gained momentum following World War II, and most of the continent became independent over the next decade.

Today, Africa contains 53 independent and sovereign countries, most of which still have the borders drawn during the era of European colonialism.

3. AFRICAN CONDITIONS

3.1 Geography

From the most northerly point, Ras ben Sakka in Tunisia (37°21' N), to the most southerly point, Cape Agulhas in South Africa (34°51'15" S), is a distance of approximately 8 000 km (5 000 miles); from Cape Verde (17°33'22" W), the westernmost point, to Ras Hafun in Somalia (51°27'52" E), the most easterly projection, is a distance of approximately 7 400 km (4 600 miles). The coastline is 26 000 km (16 100 miles) long, and the absence of deep indentations of the shore is illustrated by the fact that Europe, which covers only 10 400 000 km² (4 010 000 square miles) about a third of the surface of Africa has a coastline of 32 000 km (19 800 miles). Africa's largest country is Sudan, and its smallest country is the Seychelles, an archipelago off the east coast. The smallest nation on the continental mainland is The Gambia.

Geologically, Africa includes the Arabian Peninsula, the Zagros Mountains of Iran and the Anatolian Plateau of Turkey mark where the African Plate collided with Eurasia.

3.2 Climate, Fauna and Flora

The climate of Africa ranges from tropical to subarctic on its highest peaks. Its northern half is primarily desert or arid, while its central and southern areas contain both savannah plains and very dense jungle (rainforest) regions. In between, there is a convergence where vegetation patterns such as sahel and steppe dominate.

Africa boasts perhaps the world's largest combination of density and "range of freedom" of wild animal populations and diversity, with wild populations of large carnivores (such as lions, hyenas, and cheetahs) and herbivores (such as buffalo, deer, elephants, camels, and giraffes) ranging freely on primarily open non-private plains. It is also home to a variety of jungle creatures (including snakes and primates) and aquatic life (including crocodiles and amphibians).

3.3 Minerals

Africa produces more than 60 metal and mineral products, and is a major producer of several of the world's most important minerals and metals including gold, PGEs, diamonds, uranium, manganese, chromium, nickel, bauxite and cobalt. It is interesting to note that Africa's contribution to the world's major metals (copper, lead and zinc) is less than 7 %. As a result, silver production is low (less than 3 % of the world's production) due to the fact that most silver is produced as a by-product of lead, zinc and copper mining. Although under explored, Africa hosts about 30 % of the planet's mineral reserves, including 40 % of gold, 60 % cobalt and 90 % of the world's PGM reserves making it a truly strategic producer of these precious metals.

The increase in exploration and mine development in Africa has been primarily focused on gold and diamond exploration. Undoubtedly, there is still great scope for these commodities and, riding on the back of improving base metal prices, this sector could see an increase in activities. Mozambique, Nigeria and Madagascar are but a few countries that have tremendous potential exploitation of base metal and industrial mineral deposits.

South Africa, Ghana, Zimbabwe, Tanzania, Zambia and the DRC dominate the African mining industry, whilst countries such as Angola, Sierra Leone, Namibia, Zambia and Botswana rely heavily on the mining industry as a major foreign currency earner. Unfortunately, several African civil wars are funded (and often caused) by some of these commodities, in particular diamonds.

Major new mines opening in Africa or under development are distributed between South Africa, Namibia, Botswana, Tanzania and Gabon producing gold, diamonds, niobium products, PGEs, chrome and base metals. Major discoveries over the last year include the discovery of several potentially diamondiferous kimberlites in Mauritania and, still on the diamond scene, potential marine deposits in offshore southern Namibia.

3.4 Economy

Although it has abundant natural resources Africa remains the world's poorest and most underdeveloped continent, due to a variety of causes that may include the spread of deadly diseases and viruses (notably HIV/AIDS and malaria), corrupt governments that have often committed serious human rights violations, failed central planning, high levels of illiteracy, lack of access to foreign capital, and frequent tribal and military conflict (ranging from guerrilla warfare to genocide). According to the United Nations' Human Development Report in 2003, the bottom 25 ranked nations (151^{st} to 175^{th}) were all African.

Poverty, illiteracy, malnutrition and inadequate water supply and sanitation as well as poor health affect a large proportion of the people who reside in the African continent. In August 2008, the World Bank announced revised global poverty estimates based on a new international poverty line of $1.25 per day (versus the previous measure of $1.00). 80.5 % of the sub-Saharan Africa population was living on less than $2.50 (PPP) a day in 2005, compared with 85.7 % for India. The new figures confirm that sub-Saharan Africa has been the least successful region of the world in reducing poverty ($1.25 per day); some 50 % of the population lived in poverty in 1981 (200 million people), a figure that rose to 58 % in 1996 before dropping to 50 % in 2005 (380 million people). The average poor person in sub-Saharan Africa is estimated to live on only 70 cents per day, and was poorer in 2003 than he or she was in 1973, indicating increasing poverty in some areas.

Africa's rate of economic growth increased over the past decade, averaging 5% in 2005. Some countries experienced still higher growth rates, notably Angola, Sudan and Equatorial Guinea, all three of which had recently begun extracting their petroleum reserves or had expanded their oil extraction capacity. In recent years, the People's Republic of China has built increasingly stronger ties with African nations. In 2007, Chinese companies invested a total of US$1 billion in Africa.

3.5 Sport

Fifty-three African countries have football (soccer) teams in the Confederation of African Football. Cricket is popular in some African nations. South Africa and Zimbabwe have Test status, while Kenya is the leading non-Test team in One-Day International cricket and has attained permanent One-Day International status. The three countries jointly hosted the 2003 Cricket World Cup. Namibia is the other African country to have played in a World Cup. Morocco in northern Africa has also hosted the 2002 Morocco Cup, but the national team has never qualified for a major tournament.

4. APPLICATIONS

The forgoing reflects a continent with immense potential for development and a wide range in stages of development. The emergence of geosynthetics in the 1960s (Gundle, 2009) and 1970s (Lawson, 2009) introduced a new dimension to the civil, environmental and mining engineering industry. Advancements in technology, products and applications have passed back and forth between Africa and other continents while some developments have remained specific to the continent’s particular conditions in defined applications.

South Africa in particular has been an active participant in the advancing geosynthetics industry. Geomembranes have been represented by a wide range of materials from butyl rubber; ethyl vinyl acetate (EVA); linear low- and high-density polyethylene; flexible polypropylene; single- and co-extrusions; smooth or textured and colour variations. Similarly, geotextile products have been represented by non-woven, continuous filament and staple fibres, needle punched or thermally bonded; knitted; wovens being of tapes, multifilament or monofilament or combinations thereof. A range of geosynthetic drainage materials is available in the form of nets, cuspated sheets and pipes or conduits. Today the market is offered geotextiles; geogrids; GCLs and geomembranes, which are produced locally or imported for the infrastructure in progress.

The following limited examples are provided of geosynthetics applications in the civil, environmental and mining industry infrastructure focusing on water supply and protection, mining materials management and mitigation of environmental impacts.

4.1 Water Containment and Conveyance Infrastructure

Almost all developments, be they human settlement, agriculture or industrial, require water. Water containment and conveyance infrastructure typically comprises of dams, canals, pipelines, weirs, reservoirs and tunnels. In order to appreciate the range of applications in both the development of new infrastructure as well as the rehabilitation of existing infrastructure it is useful to consider the historical development of water resources.

4.1.1 A Review of the Historical Changes in South African Water Affairs Over the Past Century Using Extracts from Literature and Interviews

Taking ourselves back in time to the 1800s, we would have known of the history that had brought us to that time – a sparsely populated country that had seen several colonial powers and regional wars come and go. The Portuguese, the Dutch and the British amongst others had visited the country. In the late 1800s, the former provinces of Natal and the Cape were under British rule while the Transvaal and Orange Free State were Boer Republics.

The establishment of a hydraulics division in 1875 under the Commissioner of Public Works in the Cape Colony marked the birth of a very important Department of State. This Department's work varied widely and was of the highest technical order, which was indispensable to the development of all sectors of the economy at that time. The first hydraulic engineer was John G. Gamble who was an extremely competent engineer. The son of the famous Andrew Geddes Bain, known as Thomas Charles John Bain, followed him in 1885.

In 1903, following the changes brought about by the two Anglo Boer wars, arrangements were made to second two irrigation engineers (Messrs Kanthack and Hurley) from the Indian Irrigation Service, one to each of the colonies of the Cape and the Transvaal. These two engineers played a major role in moulding the early water policies and water resource development in South Africa.

During the period 1902 up to the Union in 1910, water matters were dealt with in the four colonies (Cape, Transvaal, Natal and the Orange Free State) as follows:

- In the Cape, the Irrigation Department was mainly a technical department attached to the Public Works Department with F.E. Kanthack as the Director, which had only scanty funds and a small staff component to undertake responsibilities. It was however due to the Cape Irrigation Act of 1906 that some extraordinary progress was made by a policy of assisting irrigation development through irrigation boards. These included irrigation farmers who were required to allocate and distribute water in their districts. However, the lack of staff and funds severally hampered the essential task of collecting hydrographic data and systematically surveying the colony;

- In the Transvaal, the Chief Engineer, F.A. Hurley, headed the Irrigation Department, which fell under the administration and control of the Secretary for Lands. The Transvaal concentrated on investigation of major projects, most of which proved to be too expensive to implement;

- In the Orange Free State irrigation matters were dealt with by the Director of Public Works; and

- In Natal, irrigation matters fell under the Surveyor General and for all practical purposes, no irrigation work was undertaken.

The Union Irrigation Department formally came into being by the establishment of a new act, Act No. 8 of 1912, known as the Irrigation and Conservation of Water Act. The objectives of this Act were to consolidate and amend the laws enforced in the Union relating to the use of water in public streams for domestic, irrigation and industrial use and to provide facilities/infrastructure for the irrigation of land and use of water. This Act was destined to encourage the construction of storage works where the river flow during the low-flow season was insufficient for direct irrigation by extracting water from run-off from river diversion works.

At Union, considerable reorganisation and rationalisation took place. The way forward then took the form of active involvement of groups of irrigators with a policy of systematic research and investigation taken from the Transvaal model. Thus, Kanthack became the first Director of Irrigation and F.A. Hurley the Assistant Director under the Union. The organization was established to administer and implement the provisions of the Act, focusing on decentralisation. This took the form of a Circle Engineer who was responsible for everything within his circle. Head Office essentially controlled and reviewed the activities that took place in the nine circles. The period 1912 to 1914 was largely taken up by reorganization, establishing circle boundaries, etc, and this period was immediately followed by the First World War, which brought about new challenges as many staff members enlisted for service and the prolonged drought was broken by unprecedented rain in 1916.

So it was in the following years that dams like Hartebeespoort, Lake Mentz, Tygerpoort; Kamanassie, Grassridge and Lake Arthur were built.

Co-operative governance was investigated as a Mr A.D. Lewis was called upon to investigate development of the lower Orange River where it formed the boundary between the South African Union and German South West Africa. Lewis left Cape Town on 20 November 1912 by horse and cart. Only two of the four horses drawing his cart made it to Pella on 27 November due to the tough going. Thereafter, he left the horses and cart behind, and made his way by foot carrying all necessities with him. Two weeks later, he had covered the 400 km downriver to the Orange River mouth, making notes of every physical feature and irrigation potential. By 30 December 1912, Lewis had completed a report on the irrigation potential of the lower Orange River.

The onset of the depression brought about actions to relieve unemployment in various districts and projects such as the Pongola Irrigation Scheme were started in 1932. Due to the increase in hardships for the unemployed and the consequences of the drought, the Department of Labour requested that the Department of Irrigation fast-track further schemes, and the Vaal-Harts and the Loskop irrigation schemes were started.

Further changes were brought about with the Vaal River Development Bill (Act 38 of 1934), which had the notable feature of a tendency towards State ownership of water.

At the end of the 1930s, the Department had a large staff component and many resources associated with a rapid growth in construction. Thus the outbreak of the Second World War brought about changes yet again with the Director of the Department of Irrigation being seconded to the Technical Committee of Defence on War Supplies, while a large number of officers took military rank in the Works Directorate and many other staff members became the core of four companies within the Mobile Field Force. Over 50 % of the Department's technical staff was released for military service.

The year 1945 brought a radical change in thinking on water management. During the past half century, the Department's emphasis had been on supplying water to irrigators who had used much of the water rather extravagantly. The ever-growing needs of expanding mines and industry as well as domestic use and the acceptance of the fact that the water resources were limited required a complete change in water legislation. Thus, the functions of the Department were expected to change. As a first step, pro rata tariffs for irrigators were introduced as far as possible, rather than the flat rate based on land schedules. The Minister was also empowered to grant subsidies to municipalities for the construction of municipal water supply schemes. The next step towards meeting the growing demands was to establish separate planning and research divisions in 1949.

On 7 April 1950, the Governor General appointed a water law inquiry commission to investigate and report on matters related to the existing laws and their required amendments in order to provide for the utilisation of water resources to the best advantage to the people as a whole. The result was that in 1956 Parliament passed an Act that repealed the 1912 Act and heralded a new era in water resources in South Africa. The new Water Act (Act 54 of 1956) specifically provided that there shall be no private ownership of public water, i.e. in a natural stream of water whether visible or not which flows over two or more original properties in a defined channel and which is capable of common use. This act also placed water use for agriculture, industry and urban demands more or less on an equal footing. Riparian rights were retained where the State did not control the water, that is to the extent that riparian owners were entitled to a fair share of the normal flow of a public stream. This act also gave the Minister absolute control over water in dolomitic areas and subterranean water controlled areas. The host of new responsibilities placed on the Department led to the establishment of additional divisions and sections such as the Division of Water Utilisation with its sub-divisions of agricultural water and industrial water; the separation of the design and planning functions; the creation of a hydrological division; and the formation of a section to deal with the administration of permits for the abstraction of water, etc.

In 1962, the Prime Minister announced in Parliament the development of the Orange Fish River project. This yielded another change from the norm of planning, designing and constructing in-house by the introduction of the use of consulting engineers and contractors for the design and construction of certain components of the work such as the main dam and tunnel. In 1966, the State President appointed a 15-member commission to investigate all matters pertaining to water, and this commission found a need for investment in scientific research. The hydrological research centre at Roodeplaat Dam was approved in 1969/1970 and opened in 1972. A number of regional committees were also established to advise the Minister of Water Affairs on matters including interactions with neighbouring states.

The 1970s were characterised by multi-purpose dam development projects. By the 1980s, the storage infrastructure development rate had slowed and the Department had been referred to by some members of Cabinet as a junior department. In 1992, an interim government came into being in preparation for the first fully democratic election of the country in which all South Africans of age participated. This brought about a process of development of principles for water resources management and a new legislation – the National Water Act (Act 36 of 1998). The primary objectives of this are sustainable water resources management and poverty alleviation.

The fundamental principles include the Reserve, being that quality and quantity of water required for basic human needs and biological functioning of any significant water body, as well as the requirement for a license for any one of 11 defined uses. These uses deviate significantly from the principle of abstraction for particular purposes.

Note: The foregoing section represents extracts from various unpublished reports and notes from colleagues.

4.1.2 South African Dams and Reservoirs: Interesting Facts

The South African Register of January 2009 contains information pertaining to 1 082 large dams. The record of large dams in RSA is available from the SANCOLD. To qualify for inclusion in the Register, a dam must meet the following criteria:

- The dam must have a height of not less than 15 m.
- Dams between 5 m and 15 m impounding more than 3 million m^3 are also included.

Some interesting information abstracted from the South African Register of Large Dams includes:

- The oldest dam is the Upper Mpate built near Dundee in 1880. It is an earthfill embankment with a height of 18 m and crest length of 293 m.
- The total storage capacity of the 1 086 dams is 31 619 million m^3, which is about 65 % of the mean annual runoff of South Africa of 49 000 million m^3.

The development of major dams over time can be determined from the Register. The initial development rate was low (there was a lull in dam development during the Second World War) but accelerated in the period from 1970 to 1980 with the construction of the Orange River Project and the Thukela-Vaal Project. There has been a progressive decline in dam development from 1980. While the rate of development has reduced, dams will still be required to provide water for various purposes to meet future rising demands.

The percentage distribution of dam types in South Africa is shown below. Most dams in South Africa are constructed from earthfill.

Table 1: SANCOLD registered dams by type

Dam Type	% of Total
Earthfill	74
Rockfill	2
Concrete gravity	12
Concrete arch/buttress	1%
Other	2

The distribution in heights of large dams in South Africa is tabulated below. Most large dams in South Africa are lower than 30 m in height.

Table 2: Height distribution of registered South African dams

Height range (m)	Number of Dams	% of Total
< 30	950	85
31 – 50	27	11
51 – 70	28	2
71 – 90	8	1
> 90	2	0.2

The highest dam in South Africa is the Vanderkloof Dam on the Orange River with a height of 108 m. The Big Five Dams in South Africa are given in the table below.

Table 3: South Africa's Big Five dams

Dam (alphabetic order)	Height (m)	Volume (million m^3)	Storage Capacity (million m^3)	Water Surface Area (km^2)
Gariep	88	1.4	5 343	352
Pongolapoort	89	0.6	2 267	132
Sterkfontein	93	19.8	2 617	67
Vaal	63	1.4	2 610	323
Vanderkloof	108	1.3	3 187	133

The storage capacity of the Sterkfontein Dam in the upper Vaal River catchment is virtually the same as that of the Vaal Dam, while its water surface area is only 20 % of that of Vaal Dam. The evaporation losses from Sterkfontein Dam are accordingly far lower than those from Vaal Dam. Water is therefore kept in reserve in the more efficient Sterkfontein Dam and only released once Vaal Dam is at its minimum operating level thus saving appreciable evaporative losses.

The dam with the largest storage capacity is the Gariep Dam on the Orange River, with a capacity of 5 343 million m^3.

The dam with the longest crest is Bloemhof on the Vaal River, with a length of 4 270 m.

The shortest dam is Hellsgate near Uitenhage built in 1910, with a crest length of only 4 m. This concrete dam with a height of 26 m is built in a narrow gorge.
The dam with the largest volume is Sterkfontein near Harrismith, with an earthfill volume of 19.8 million m^3. Sterkfontein Dam is the only South African dam in the ICOLD Register of the World's Largest Dams on account of this characteristic.

The largest floods are expected in the Vaal River and provision has been made in Vaal Dam for a spillway capacity of 25 000 m^3/s. The two major dams on the Orange River each have a spillway capacity of 20 400 m^3/s.

The dam with the largest water surface area is Gariep at 352 km^2 (352 million m^2).

The Woodhead Dam on Table Mountain constructed in 1897 (50 m in height) was recently awarded the American Society of Civil Engineers (ASCE) International Landmark status in 2008. See SAICE Journal October 2008.

The above record shows a change with time, and a predominance of earth over concrete structures. Thus filters and in particular geosynthetic filters have more importance in the future.

4.1.3 Geosynthetics in Dam and Reservoir Engineering

The use of geotextiles as filters and adjuncts to filters within earth embankment rockfill and tailings dams is an established practice (Legge and James, 1994). Geotextiles are used as the primary filter between base material and drainage material in toe drains blanket drains and chimney drains as well as under riprap on the upstream face and occasionally on the downstream face.

Mokolo Dam (formally Hans Strydom and before that Wildebeestfontein Dam), which is a 56 m high rockfill embankment that used a nonwoven continuous filament needle punched geotextile as an adjunct to the clay core protection filter (figures 1–4).

Figure 1: Embankment under construction

Figure 2: Geotextile adjunct between core and graded filters

Figure 3: Completed dam as at 2008

Figure 4: Seepage monitoring well

Kwena embankment dam (formerly Braam Raubenheimer Dam), which used a geotextile in the blanket and toe drain (figures 5–6).


Figure 5


Figure 6

Kilburn embankment dam (figures 7–8).


Figure 7: Geotextile under riprap on upstream face


Figure 8: Internal filter downstream interface of chimney drain

Zoeknog Dam, which failed on first filling in 1993 and revealed the sound performance of a geotextile under severe loading conditions, as well as the consequences of leaving a window in the internal filter system (figures 9–12).

Figure 9

Figure 10

Figure 11

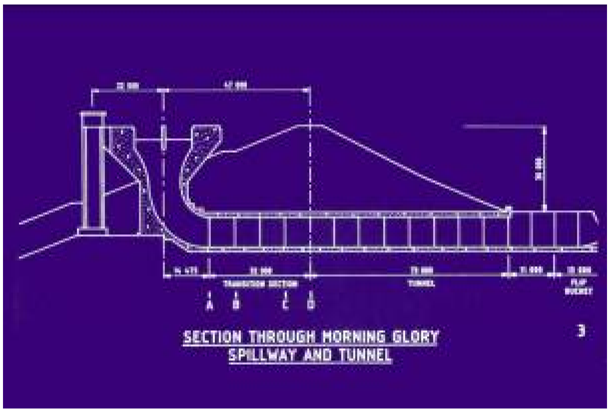

Figure 12

Canals regularly require under-drainage in which a geotextile is used, and are occasionally lined with geomembranes (figures 13–14).

Figure 13

Figure 14

Reservoirs for containment of raw or potable water may be open or covered (figures 15–18).

Figure 15: Onverwacht raw water reservoirs: HDPE lined earth embankment reservoir and refurbished concrete reservoir lined with HDPE

Figure 16: Reservoir Hills concrete potable water reservoir refurbished with a lining of EVA over a protective geotextile and drainage net

Figure 17: Floating cover and membrane lined potable reservoir in Africa

Figure 18: Floating cover and membrane lined potable reservoir in Africa

Tanzanian rain harvesting in which a thin membrane is used to capture rainfall, leading the water under gravity to a floating cover reservoir (figures 19–20).

Figure 19

Figure 20

Tunnel linings in which membranes are used to restrict ingress of groundwater (figures 21–22).

Figure 21

Figure 22

Geomembranes used as impermeable barriers (figures 23–24).

Figure 23: Rössing Dam, Namibia

Figure 24: Mafiteng Dam, Lesotho

4.2 Contaminant Containment

4.2.1 The Development of the Use of Geosynthetics in the Waste Management Industry of South Africa

This section briefly describes the research projects and findings undertaken in the 1970s and 1980s, which led to the development of the waste management philosophy contained in the three regulatory Minimum Requirements for Waste Disposal documents (1998). A review of the alternative liner designs proposed and used in waste disposal facilities and the mining industry in South Africa is presented along with an analysis of the various geosynthetic components. Results of tests conducted to evaluate geosynthetics and composite liner and drainage interaction are then described and analysed. This analysis identifies probable failure in the performance of a particular lining system. Recommendations are made for designers and the regulator for consideration in the evaluation of future alternative landfill base liner and capping designs.

4.2.1.1 Background

With limited surface and groundwater resources available and a growing use thereof, South Africa required an appropriate strategy for the protection of this precious resource. The climatic conditions vary considerably across the length and breadth of the country with average annual rainfall varying from 50 mm to 3 000 mm depending on location, and average annual evaporation as high as 1 800 mm. Development is however primarily situated in the central Highveld region and along the coast in the wetter portion of the country.

Disposal of waste did not receive priority attention for many years. Although the first legislation focussing on water quality came into being in 1919, it was research in the 1970s and 1980s that led to the principles and philosophy used for regulating waste management today.

Historical Review of Research

A most noteworthy piece of research was undertaken by a postgraduate student on the Johannesburg City Council's Waterval Landfill from 1976 to 1984 (Ball, 1984). The Waterval Landfill operated from 1928 to 1978. This investigation included both a study of the history of the landfill using aerial photographs dating as far back as 1933, as well as monitoring ground and surface water over a 7-year period to determine the impact of landfill leachate on the water regime. The mechanism which caused the generation of the leachate that was detected and monitored down-gradient of the landfill was done partly by sinking a 1.2 m diameter auger hole into the deepest part of the landfill and the researcher then descending into the reinforced hole while wearing breathing apparatus, so as to recover representative samples from the entire profile for moisture determination. By leaching the dry samples and analysing the product, it was also possible to measure solutes and develop a solute profile of the landfill.

This identification of solute transport and indication of moisture movement became the local reference for leachate fundamentals of landfilling, which led to further research.

In 1985, another project was launched at the University of the Witwatersrand, which focused on the philosophies of leachate management, particularly the "dilute and disperse" and "contain and concentrate" philosophies.

The Coastal Park landfill near Cape Town relies on leachate attenuation for leachate management and presented an ideal opportunity for researching attenuation. Groundwater monitoring on the original data base line at Coastal Park provided an excellent study of leachate generation in a water surplus climate, which could be compared with the leachate generation in a water deficit climate, i.e., the Waterval Landfill. This fieldwork was followed up with further "down the hole" sampling for consecutive wet and dry seasons, enabling comparisons to determine the seasonal flux of moisture in the landfill profile. This was done at both Coastal Park and Johannesburg's Linbro Park Landfill, the latter providing greater depths of waste than the original Waterval Landfill.

The groundwater monitoring at Coastal Park has continued throughout the 1980s and 1990s and is believed by some to show conclusive evidence of leachate attenuation in the saturated zone (Ball and Novella, 2002).

Research Results

In the 1970s and 1980s, landfill gas was hardly recognised as a problem. Furthermore it was accepted practice that the way to address landfill nuisances such as burning, odour, litter, aesthetics and pests was to apply the Sanitary Landfill principle of compaction and daily covering of waste. This however did not address the long-standing concern of water pollution from leachate.

While landfill leachate was not considered a threat when compared to other sources of water pollution such as industry, agriculture and wastewater in the mid 1970s, by the early 1980's this perception changed to considering pollution as one of the most serious threats facing the country's water resources.

The research programs thus resulted in an early definition of leachate (Ball, 1984). So too was the perspective adopted (Ball and Blight, 1986 and 1988) with regard to leachate that, where significant leachate is or may be generated, it must be managed.

The second significant research finding related to the causal mechanisms of leachate generation.

Since Waterval landfill's historical records showed that the Waterval landfill had not accepted significant liquids for disposal and that it had always been graded to promote run-off and avoid flooding by surface water, the two most probable causes of leachate were infiltration and percolation of direct rainfall precipitation and groundwater encroachment on the site.

The results however show that moisture was stored in the cover and waste, and that there was no evidence of downward movement of moisture in the profile. There was however strong evidence from the solute profile to indicate a seasonal upward movement of moisture, which was interpreted as evaporation. It was therefore concluded that, because of climate and liquid storage capacity, leachate generation by infiltration and percolation of precipitation would be localised and restricted to very wet weather (Ball, 1984).

While this was accepted to be true for water-deficient climates like Johannesburg where soil evaporation exceeds precipitation, it was questioned whether the assumption would hold true for water-surplus climates like Cape Town where precipitation exceeds evaporation for the wet part of the year. Following further research, the findings from Waterval were confirmed, and furthermore the results confirmed/indicated that leachate would indeed be generated seasonally by infiltration and percolation of direct precipitation in water surplus climates (Blight et al. 1989, 1991, 1992).

It was also shown that, even in a water-deficient climate, the generation of leachate would result from any super-imposed hydraulic loading on a landfill, such as due to poor surface drainage control allowing water to enter the landfill through ponding, secondly through poor design or perimeter drainage control which would allow surface water to enter the landfill or dam up below it, and thirdly co-disposal of liquids with waste.

The third significant conclusion of these two decades of research concerned the philosophy of "dilute and disperse" or "contain and concentrate".

While the "dilute and disperse" philosophy, which relies to a large extent on the natural attenuation capacity of the soil and other elements in the environment to purify leachate had been confirmed through the Waterval project and Coastal Park project, the problems with the dilute and disperse approach are considerable. If the volume of leachate generated exceeds the attenuation capacity for a given environment, then pollution results. Furthermore leachate attenuation is extremely difficult to predict or quantify, and therefore could not be used as a reliable defence perimeter.

The "contain and concentrate" philosophy, which involves preventing leachate from entering the surrounding environment by means of providing liners, leachate collection systems and leachate treatment works, although a sophisticated and expensive technology, is a cautious solution which was not always considered an appropriate, affordable or sustainable approach in South Africa.

National Diversity Standards for Waste Containment

It was recognised that no single approach would satisfy South African requirements, but that there was probably scope for both of the diverse philosophies. While it is desirable to use conservative containment technology, although expensive, for hazardous waste disposal and the management of significant volumes of leachate, it did not appear appropriate to use the technology in an arid environment or region where minimal leachate would be generated. This forms the basis for the range of sanitary landfill designs, ranging from low-risk situations of general waste and water-deficient areas to high-risk situations where hazardous waste and co-disposal takes place or in water-surplus areas, which are suited to containment design.

Landfill Classification

Based on the above range of conditions landfill designs were developed ranging from attenuation designs to lined containment sites based on the type of waste, the size of operation and the water balance. The table below depicts the classification, and examples are given in Figure 1.

Table 4: Minimum Requirements – The Typical Table Format

Legend B = No significant leachate produced B+ = Significant leachate produced R = Requirement N = Not a requirement F = Flag (special consideration to be given by expert and/or Departmental representative)	Classification System									
	G								H	
	General waste								Hazardous waste	
	C		S		M		L		H:h	H:H
	Commercial landfill		Small landfill		Medium landfill		Large landfill		Hazard rating	
Minimum requirements	B–	B+	B–	B+	B–	B+	B–	B+	3&4	1–4
Appoint responsible person	R	R	R	R	R	R	R	R	R	R
Minimum number of boreholes	N	N	1	1	3	3	5	5	F	F
Leachate management	N	N	N	F	N	R	N	R	R	R
Daily cover	F	F	F	F	R	R	R	R	R	R

4.2.1.2 Base Liner Designs

Design Philosophy

The design of a landfill follows the site selection, investigation and assessment processes, and is based on the outcome of this as well as the environmental impact assessment. The primary objective of the design is to provide a cost effective and environmentally acceptable waste disposal facility.

Typical liner layouts and cross sectional details of typical liner systems are presented in Appendix 8 of the Minimum Requirements and for significant leachate essentially consists of a double-liner system separated by a leak detection system. The guiding philosophy is that the overlying leachate collection system reduces the hydraulic gradient to a near-unity over the primary composite liner, whose performance is monitored through the leak detection system that is made functional by the secondary liner. Alternatives to the composite liner system of a geomembrane and compacted clay liner (CCL) usually comprise a geomembrane overlying a geosynthetic clay liner (GCL). This regulatory liner thickness is of the order of 600 mm thick.

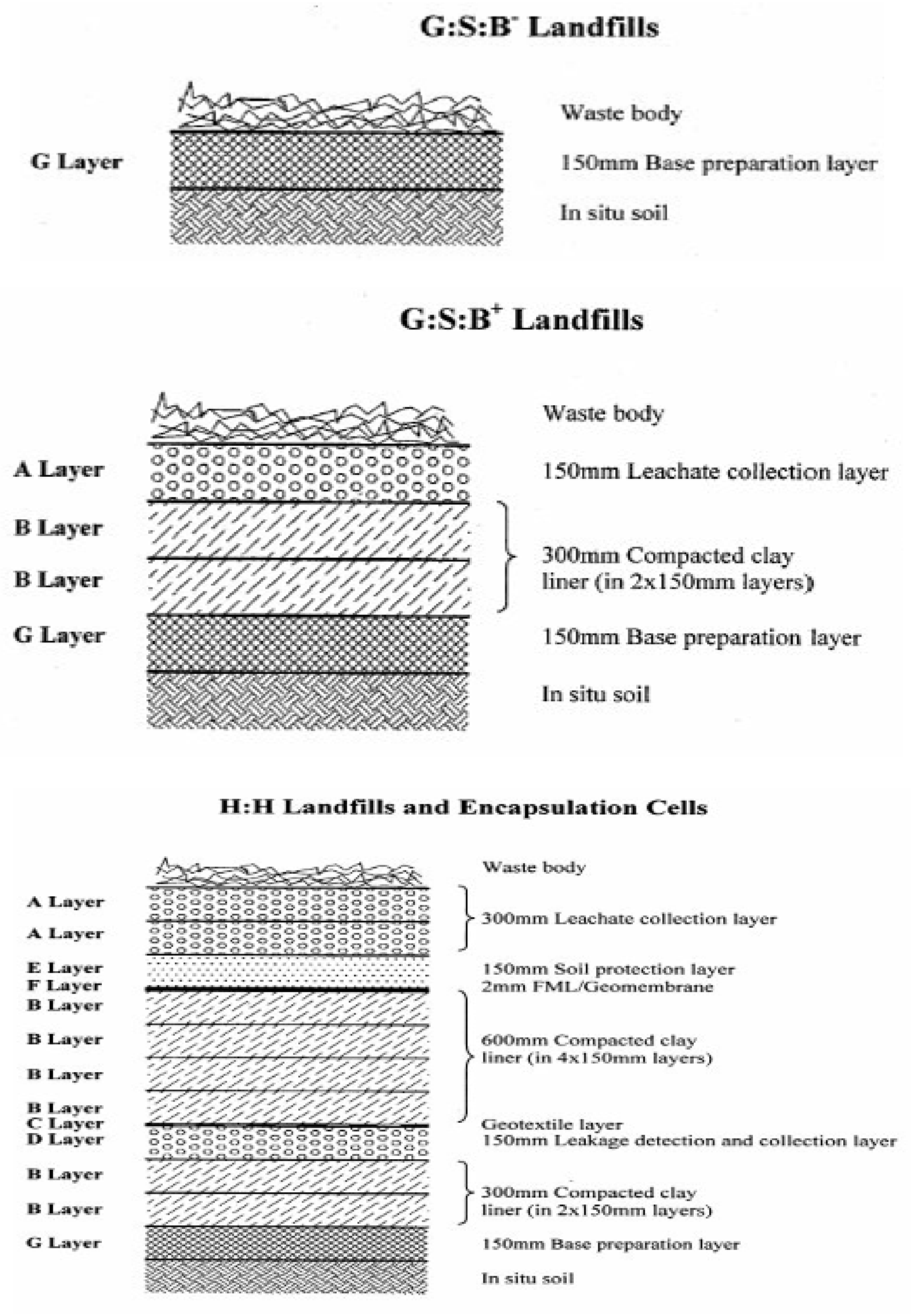

Figure 21: Landfill classification examples

This latter alternative is chosen for various factors or combinations thereof, and may include issues such as the lack of suitable clay soil on or near site for a compacted clay liner, a high rate of construction being required, the value of air space, or combinations of these.

In the Minimum Requirements, the leak detection system between the primary and secondary liner comprises a layer of geotextile on top of a drainage material that consists of single-sized gravel or crushed stone having a size of between 38 mm and 50 mm, and is 150 mm in thickness. The geotextile is to protect the drainage layer from contamination by overlying fine soil material intruding and reducing the effectiveness of the leak detection and collection layer. Alternatives to this layer can include drainage net (or geonet), a cuspated drainage layer, a thick geotextile, or some other form of pervious geosynthetic. For the purposes of this paper, only the first two alternatives are considered as, at present, no locally available geotextile has adequate transmissivity and capacity to be compared to the specified drainage layer performance. Conceptual sketches of typical current liner combinations are presented in figure 2.

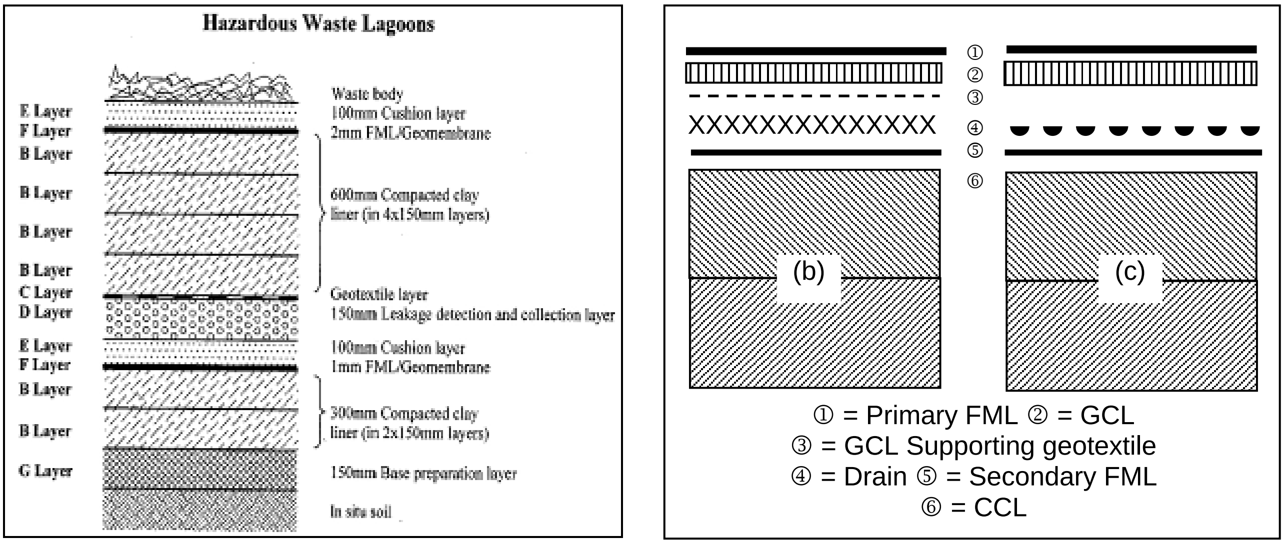

Figure 22:Typical profiles of hazardous waste liner systems

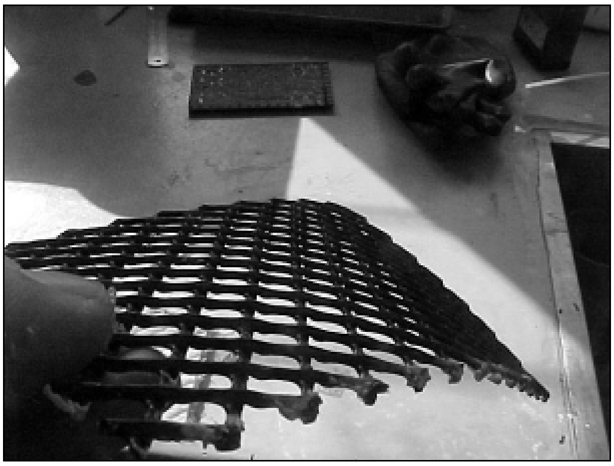

Figure 23: Geonet geosynthetic

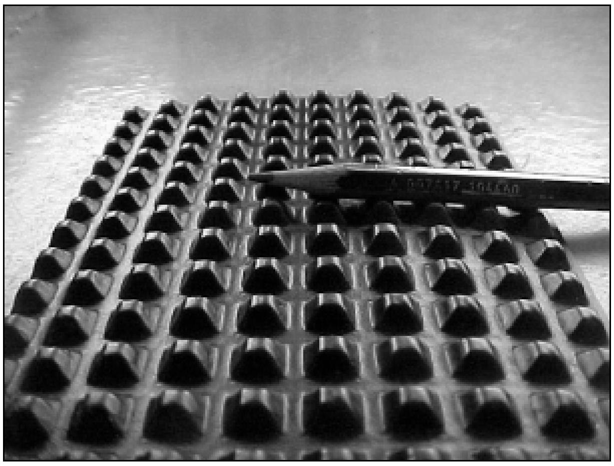

Figure 24: Cuspated sheet

4.2.1.3 Geosynthetic Materials Considerations

Geomembranes

Several decades ago, polyvinyl chloride (PVC) geomembranes were commonly used in landfill liners, partly due to the ease of joining seams with solvents for “chemical welding”. By far the majority of geomembrane landfill linings over the past two decades however have now been constructed of high-density polyethylene (HDPE) and, at time of writing, around 3 500 landfill liners have been constructed of this material worldwide. However, in South Africa in particular, limited use has been made of other materials such as flexible polypropylene (FPP) and low-density polyethylene (LDPE). To date the tests called for, for proof of compatibility between the flexible polypropylene used in the liners of some landfills and their leachates, have not been submitted. In one particular case, tests undertaken in accordance with a modified EPA 9090 test procedure were submitted claiming that the mass loss was so small that it confirmed the proposed use was suitable. A linear extrapolation of the results over the 28-day period however showed that within five years, if the mass loss shown continued at a constant rate, there would be no liner left at all. On rejection of these test results by the regulator, the consultant and material supplier investigated the test results and put forward that the test was undertaken incorrectly, thus giving the distorted results. However, to date no substantive compatibility test for this material has been submitted. The permit holder thus relies on commercial product data for guidance on compatibility and will carry the risk in case of premature liner failure.

The use of product data sheets for chemical compatibility considerations is not unusual. When considering shear strength, a particular manufacturer's product data shows the angle of friction for FPP/soil to be 28 degrees. A subsequent series of shear tests has shown that this is a rather ambitious claim and has found that the geomembrane/soil sheer strength varies between 8 and 18 degrees, depending on the soil, degree of saturation and the type of the liquid with which the FML is in contact. The danger of relying on published data is well documented (Day, 1999) and specifiers would be well advised to take notice of this.

The present South African geomembrane industry standard has been brought about because of the workshop on geomembrane liners in landfills held at WasteCon 2000. This was put to 350 persons involved in the waste industry, recommending the adoption of the USA Geosynthetics Research Institute's GRI-GM 13 and GRI-GM 17 standards for FMLs on landfill liners. No negative responses were received and designers are thus encouraged to use these comprehensive specifications as a minimum for geomembranes in landfill liners. The local standards authority has amended national standards accordingly.

4.2.1.4 Geosynthetic Clay Liners (GCLs)

At present there are four GCL products available on the South African market, all having different characteristics. Limited test results and even more limited experience are available on some of these products, and designers should be aware of the range of constraints that could impact upon performance. GCLs have proven to be an equivalent alternative to CCLs (Giroud, 1994) and can be used as stand-alone liners if properly designed (von Maubeuge, 2002). Minimum mass of bentonite for a GCL should theoretically be 2 700 g/m^2 for natural bentonite and at least 3 700 g/m^2 if sodium activated calcium bentonite is used. It should be noted that depending on the manufacturing process between 10 and 20 % extra bentonite needs to be added to achieve these levels. The pressure at which bentonite is extruded from a GCL will depend on the form of bentonite and particularly the type of geosynthetics and their construction used in the GCL, as well as the characteristic of the underlying soil or drainage layer. Internal erosion of bentonite can take place at heads as low as 17 m for a particular geosynthetic carrier. At failure, the hydraulic conductivity of the GCL can increase by between 1 and 2 orders of magnitude. Other GCLs show no internal erosion failure at pressure heads in excess of 60 m (Rowe and Orsini, 2002). The possibility of internal erosion is indeed a concern where a design requires the use of poor sub-grades (and geonets or other open-texture drainage layers immediately below the GCL) coupled with the risk of exposure to high hydraulic gradients.

Assessment in 2004 of materials performance on the three locally available products shows that the two produced with ISO 9000 certificates exceeded the minimum value claimed on peel strength by a significant margin. The other, however, had a peel strength less than half of the minimum claimed on its product data sheet, and a variation in mass distribution of the other of 40 %. This product is no longer on the market.

Accordingly, specifiers have a duty to make themselves acquainted with all the relevant issues.

4.2.1.5 Drainage Spacers

The most commonly used geosynthetic alternatives for the leakage detection and collection layers specified in the Minimum Requirements are geosynthetic composite drainage layers (GCDs). In South Africa these are usually either a geonet associated with a geotextile, or a cuspated sheet drainage layer, both of which have a profile height of the order of 4 mm as opposed to the 150 mm thick single-sized gravel layer specified in the Minimum Requirements. Specifiers should be aware that manufacturers' product data sheets employ index tests and do not always accurately reflect the material performance when deployed on site. The author's research has shown that, on thickness alone, products can be as much as 10 % thinner than the minimum claimed by the suppliers. This difference, along with the heat-of-manufacture induced deformations and compressive creep, will significantly affect the claimed transmissivity under site-specific conditions. Drainage performance can further be affected by the installed orientation of the geosynthetic drain. Designers need to recognise that the true flow path for a liquid flowing in a GCD layer is the resultant vector of two slopes (being the slope towards a central valley or pipe [for a landfill floor, typically 5 %] and the slope towards the sump). Research has made it clear that the installation orientation of the GCD can have a major impact on whether or not the collection system will function as intended, as there are inherent preferential flow directions in the various products. While it is common practice to apply reduction factors in calculations to take into account long-term creep, allowance for geotextile intrusion and biological clogging alone may have a cumulative factor of safety as high as 20. Proper allowance for these factors is not often seen in South Africa. When one considers that the reduction factor should also include a partial factor for GCD orientation, it is questionable as to whether many geosynthetic drainage systems do in fact meet performance requirements. In some types of GCD, orientation alone can reduce in-service transmissivity by as much as 80 % of the flow claimed in the manufacturer's specification sheet (Sieracke & Maxson, 2002).

4.2.1.6 Composite Base Liner Performance

Geomembrane and GCL or CCL Interfaces

It is common knowledge that the interface shear resistance of geosynthetic systems is dependant on a range of factors, including inter alia soil characteristics, the constituent polymer of the geomembrane as well as its surface texture and the moisture regime that will exist during the service life of the system. Valuable research has been conducted in this area, demonstrating the range of shear interface angles that are characteristic for the materials used in landfills (Day 1999).

The perceived problem of leachate leaking through the FML and its subsequent flow within a geomembrane/GCL interface has been addressed by a number of researchers. It is noted that intimate contact can be assumed under heads exceeding 5 m (Walton et al, 1997). So too has the transmissivity of this interface been shown to be significantly lower for geomembrane/GCL interfaces than for geomembrane/CCL interfaces (Harper et al, 1993).

4.2.1.7 Containment of Solutes

Geomembranes are practically impervious to diffusion of inorganic solutes compared to many other organic solutes (Haxo and Lahey, 1988; Rowe et al, 1995). Thus, the most probable path of inorganic solutes passing through a composite liner is through defects in the geomembrane such as holes and defective seams etc, and then passing through the soil liner via advection, diffusion or a combination thereof. While organic solutes also pass through such defects, they can also diffuse through intact geomembranes at appreciable rates (Park and Nibras, 1993; Mueller et al, 1998). The two pathways for transport through composite liners are shown in figure 3.

A comparison of solute transport through three different composite liners, being:

- A 6.5 mm thick GCL overlain with a 1.5 mm HDPE geomembrane;
- A United States Environmental Protection Agency (USEPA) Subtitle D composite liner consisting of 610 mm of compacted clay overlain with a 1.5 mm thick geomembrane; and

- A Wisconsin NR500 liner consisting of 1 220 mm of compacted clay overlain with a 1.5 mm thick HDPE geomembrane

has been done using one-dimensional and 3-dimensional mathematical modelling to simulate solute transport through defects and the entire liner respectively. It should be noted that results are based on relatively low heads, being of the order of 300 mm. If however the driving head is of the order of 10 m (as can be the situation in lagoon systems or where the underlying drainage system fails), then the advection component becomes significant – especially in composite liners incorporating a GCL. In considering leakage rate only, the GCL composite liner leaks 200 to 300 times less than the composite geomembrane/CCL liners respectively (Foose et al, 2002).

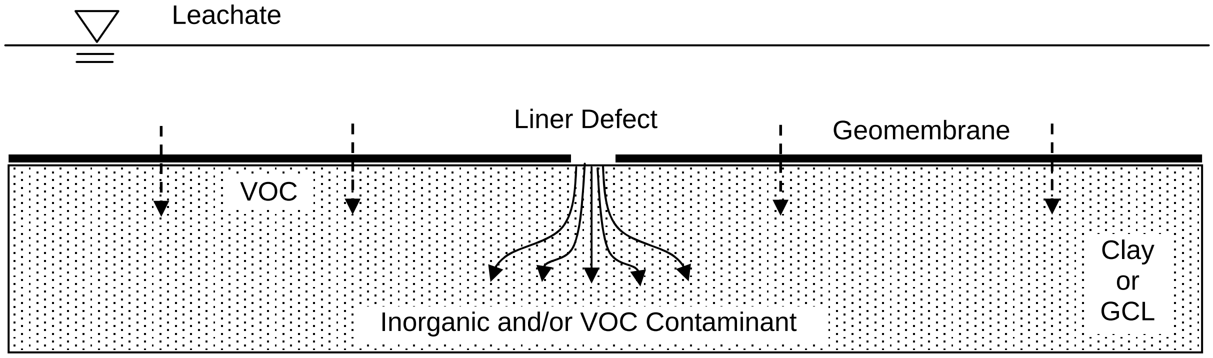

Figure 25: Solute paths through composite liners (after Foose et al, 2002)

Other investigators have confirmed this finding (Koerner and Daniel, 1993; Rowe, 1998) and thus it is generally accepted that the leakage rate through GCL composite liners should be less than that for thicker composite CCLs. Field data has further confirmed this conclusion (Bonaparte et al, 1996). Foose et al conclude that equivalency of alternative liner designs should be based on solute transport rather than leakage rate alone. This is because for similar concentrations of inorganic and volatile organic compounds (VOCs) the mass flux of VOCs may be as much as six orders of magnitude greater than that for inorganic contaminants. Failure to include an assessment of diffusion of VOCs through intact liners can lead to the incorrect conclusions regarding equivalency.

4.2.1.8 Double Composite Liners

Noting that the South African system generally employs double composite liners in which the primary liner is a geomembrane and GCL liner overlying a drainage system, and the secondary liner is a geomembrane overlying a CCL, the aspects of diffusion are not as serious because the leak detection layer (if functional) acts as a boundary condition beneath the primary liner. Nevertheless, diffusion will still take place through the secondary liner but to a significantly lower rate.

4.2.1.9 Overall Performance of Multiple Composite Liner Systems

Noting the foregoing, the performance of the primary liner and drainage system together are critical to the effectiveness of a hazardous waste landfill or lagoon lining system. As this aspect had not been investigated through laboratory testing in support of any permit applications received to date, the Department of Water Affairs and Forestry was concerned about the overall performance of such systems and the authors embarked on a testing programme.

4.2.1.10 Testing of GCD Drainage Systems

The composite liners shown as alternatives in figure 22, (b) and (c), were evaluated through compressive testing of the individual components and combinations thereof, with the purpose to ascertain the intrusion of a GCL into the two types of GCD drainage materials commonly used. In addition, the throughflow or drainage capacity of the systems was evaluated under increasing load.

The purpose-made transmissivity test apparatus used is shown in figures 26 and 27, and is equipped with a lever arm capable of loading the sample up to 400 kPa in any range of increments. It is suitable for both static and falling head testing.

Figure 26: Transmissivity test apparatus

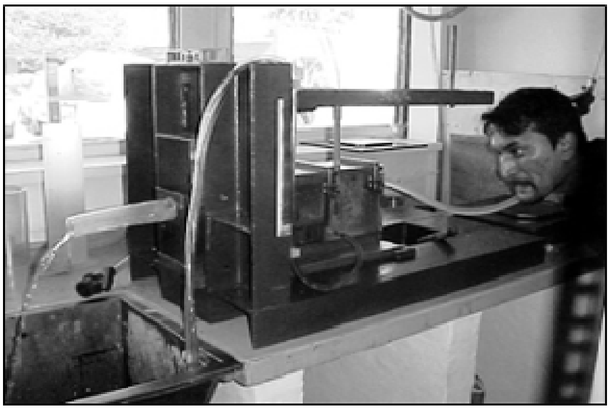

Figure 27: Transmissivity test apparatus

Test Results: Effects of compression on GCDs

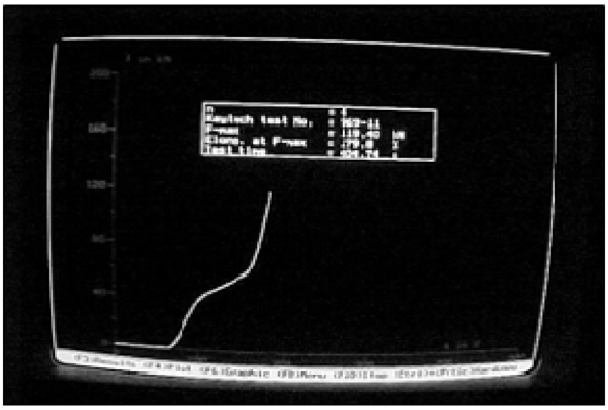

Figure 28: Cuspated GCD at 300 kPa

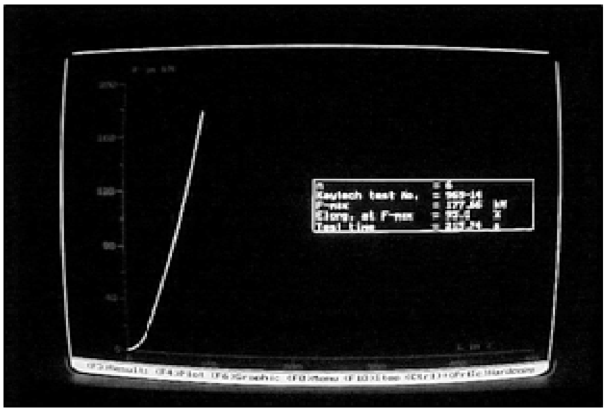

Figure 29: Cuspated GCD filled with sand, at 2 000 kPa

While the geonet tested resisted compression normally up to 1 000 kPa, the cuspated drainage system tested underwent an initial collapse through buckling of the cuspations at approximately 300 kPa (see figure 28). By filling the cusps with silica sand before loading, only marginal deformation occurred up to a pressure of 2 000 kPa (see figure 29). This demonstrates that collapse of the cuspation wall under load is an issue that needs consideration in this type of GCD. Although the nominal sheet thickness of this type of product is given as 0.5 mm, pressing cuspations into the flat sheet under elevated temperature forms the product. This leads to a thinning of the sheet in the cuspation wall area, with a commensurate reduction in the wall's capacity to support the crown area under load, causing collapse as can be seen in figure 31. Further research is needed into how this cuspation wall geometry is affected by long-term loading under various compressive forces. It is noted that the compressive testing done is a short-term loading condition and thus no creep effects are taken into consideration.

It should be noted that only the worst-case scenarios were pursued. The GCL used had a composite carrier of woven and nonwoven fabric, and the GCDs tested are the lighter products commonly used prior to 2005 (being of the order of 500 g/m^2 and having a 4 mm profile height). However, the loads were applied at right angle to the plane of the samples.

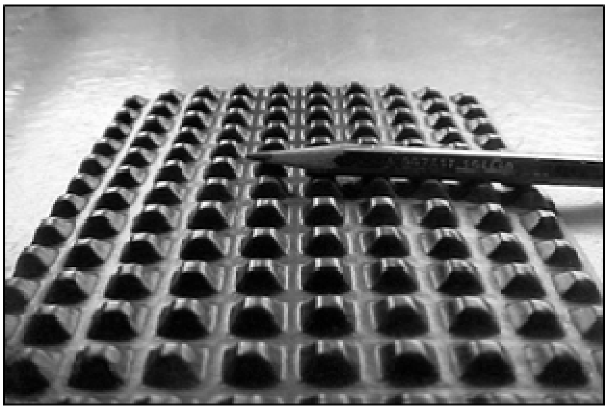
Figure 30: Cuspated GCD geometry before loading


Figure 31: Cuspated GCD geometry after loading to 300 kPa

Transmissivity Testing Results

The results for both GCD products show a significant reduction in transmissivity as the load increases from 30 kPa to 400 kPa.

The drainage capacity reduces by more than 50 % under these conditions for both materials in isolation. Reduction in transmissive flow rate is shown in figure 32 for the drainage net alone; figure 33 shows the reduction in the cuspated system alone.

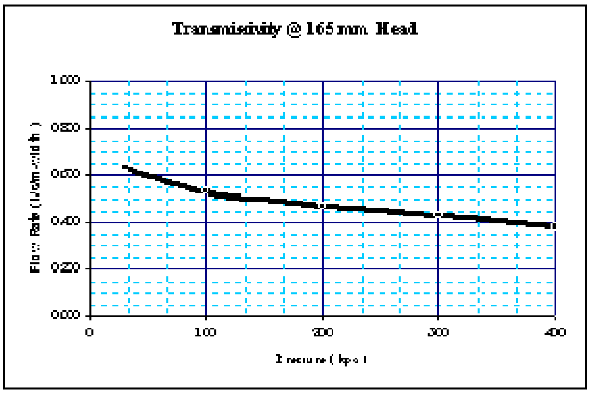

Figure 32: Geonet transmissivity under increasing compressive load

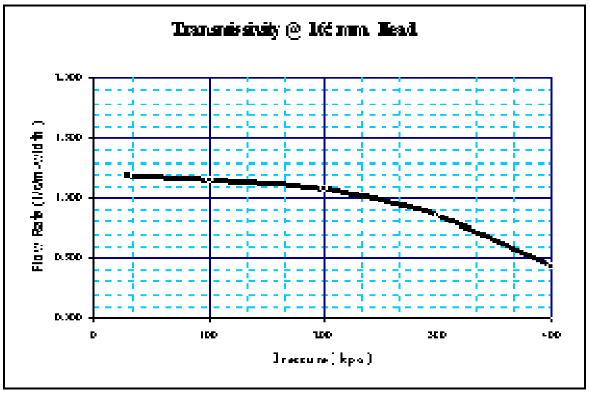

Figure 33: Cuspated sheet transmissivity under compressive load

In each case shown (figures 32 and 33) the GCD was tested laid in its Machine Direction in the test apparatus. That is to say, the sample was cut so that when placed in the test apparatus, water flow was parallel to the long axis of the roll the product is normally supplied in.

4.2.1.11 The Issue of GCL Support Over Drainage Layers

As has been shown in figure 22, it is common practice in South Africa to use a GCD to act as a leakage detection layer below a GCL in a double composite lining system. In the case of a geonet, a high-modulus supporting structure (typically a geomesh or a suitable geotextile) is required between the drainage layer and the GCL, in order to limit hydrated GCL intrusion into the drainage voids in the GCD (Shaner & Menoff, 1992, Hwu et al, 1990). In the case of a low-profile cuspated sheet GCD, this intermediate layer is not used, as the GCD is laid “upside down” so that the base of the sheet supports the GCL while the crowns of the cuspations form the drainage path. Figures 34 and 35 demonstrate the transmissive flow through both systems.

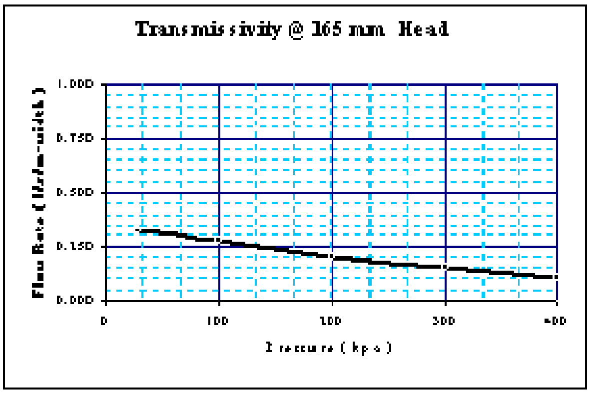

Figure 34: Transmissive flow through geonet system overlaid with geomesh and GCL

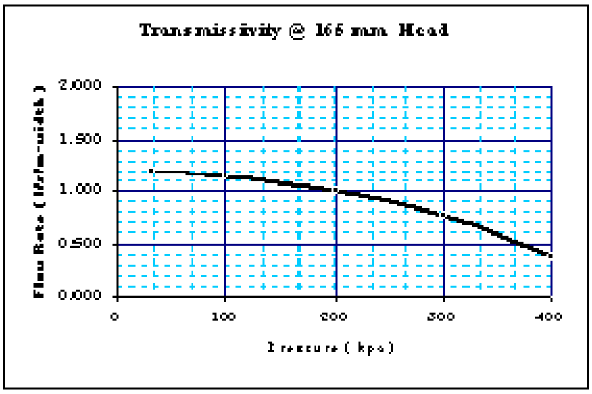

Figure 35: Transmissive flow through cuspated sheet system overlaid with GCL

Testing was also done on a GCL unsupported over the geonet. When a load of 400 kPa on the GCL/geonet combination was maintained for 14 hours, the flow rate through the drainage medium reduced to zero under a gradient of one (i.e., representing a head of 165 mm over a flow path length of 165 mm). This gradient is far in excess of typical landfill floor slopes and sidewall slopes, which are of the order of 1:20 and 1:3 for floors and walls respectively.

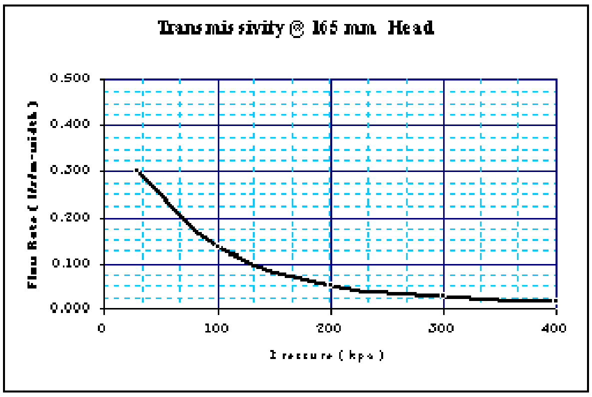

Figure 36: Transmissive flow through a geonet directly overlaid by a hydrated GCL

It would thus seem that a geonet should not be used to serve as a drainage media when there is no supporting geosynthetic between it and an overlying GCL under significant high-load, as the "soft" GCL can deform into the drainage voids in the net to the point that residual flow is unacceptably low.

Preliminary investigations into the effect of heat on GCD behaviour using the same apparatus as above and with the permeant at a temperature of 70 degrees Celsius has shown a further reduction in drainage capacity. The temperature of 70 degrees Celsius was chosen based on investigations into what temperature can be expected at the base area of landfills and, while literature reports temperatures of the order of 60 degrees Celsius, measurement of leachate outflow as high as 53 degrees Celsius have been measured.

4.2.1.12 Capping Liner Designs

Capping Design Philosophy

The assessment and mitigation of environmental impacts associated with waste disposal by landfill is undertaken with the objectives of:

- To identify the various ways in which an existing, proposed or closed landfill will affect its receiving environment; and
- To ensure that the identified impacts can be eliminated or mitigated / minimised by means of proper design and operation combined with ongoing monitoring.

While both direct impacts and cumulative impacts need to be considered in designing the mitigatory capping system, the environmental consequences of the failure of any of the environmental defence measures need also to be taken into consideration. This could be the failure of a liner or as a collection system.

The three major ways recognised as the probable escape cause for contaminants from a landfill site are:

- Airflow or wind
- Surface water flow
- Groundwater flow

At present, it is recognised that the final capping or cover system's purpose is to separate the waste body from the atmospheric environment and to isolate the waste from the long-term effects of wind, etc. So too, the cap's purpose is to limit and control the quantities of precipitation that enter the waste. It is recognised that the cap works in conjunction with the base liner by limiting the long-term generation of leachate.

Typical Cap Layouts

The series of elements used are required to maximise the runoff of precipitation and to minimise infiltration and prevent ponding of water on the landfill. The elements consist of a layer of topsoil that can be replaced by gravel (particularly in arid regions), and soil cap layers having a plasticity index of between 5 and 15 with a maximum particle size of 25 mm and "compacted to the maximum density reasonably attainable under the circumstances to ensure the required impermeability", which is specified as an infiltration rate not exceeding 0.5 m/y (and equates to a permeability of 1.6 x 10^{-7} cm/s).

Theory and Practice

Since the implementation of the performance requirements some fifteen years ago, only limited information has been obtained on capping. Noting however that during the first five years after closure of a site the maximum settlement and in particular differential settlement takes place within the waste body, it is not surprising that soil-only covers crack extensively and their performance thus cannot be expected to reflect what is currently prescribed. The use of compacted clay liners is shown to result in significantly higher water ingress rates than caps having geosynthetics components (Koerner and Heerten, 2009). This is not true for tailings type deposits. However, at this stage the mining industry is exempt from the legislation for a limited period, although some mining houses voluntarily comply.

Alternative earth soil covers are considered as having some potential for use in arid and semi-arid regions. These covers rely on the design of the soil vegetative layer being thick enough to absorb the precipitation during the wet season and store it for an adequate period for evapo-transpiration by the covering vegetation.

Results of a significant research project in the United States covering a range of designs and climatic conditions and undertaken by co-operation between the regulator, academics and industry show that alternative earth (evapo-transpiration) capping systems can be effective in keeping infiltration into the waste to low levels, provided there is adequate storage capping within the capping system. Much higher infiltration rates can result if the storage capacity is inadequate or if the vegetation is or becomes ineffective. The study concludes that in general performance of alterative earth caps "is more complicated than is currently believed and that more study is needed to understand the likely factors that can affect their hydrology" (Albright, W et al, 2003).

Notwithstanding this, the data from this study confirms that conventional covers with composite barriers are effective in limiting percolation in all climates in contrast to conventional covers relying only on clay barriers, which indicate that they can quickly become ineffective. The study identified that, even in humid climates, the clay only barriers cracked within months of placement adversely affecting the performance of the cover.

4.2.1.13 Conclusions as at 2009

The literature has confirmed the suitability and desirability of geosynthetics for use in landfill liners. In many applications, the use of geosynthetics, such as geomembranes and GCLs, show superior performance to natural materials, both as individual components and especially as composite liners.

The tests on the GCDs were done using loading forces perpendicular to the plane of the sample. There is good cause to believe that, if tangential loading forces had been employed (as would frequently be the case on site), the transmissivity values could be even lower than those shown, at corresponding pressures, as this type of load would exacerbate the "roll-over" effect on the cusps of the unfilled cuspated sheet or of the strands of the geonet. In both types of product, this effect can lead to a reduction in profile height and in consequence transmissivity.

Equivalency based on leakage rate alone can lead to significant errors in adjudication of performance; however, the use of different double composite liner systems reduces environmental risk.

Although limited in scope, the authors believe that the tests done have raised cause for concern. The omission of construction materials' testing to support the design assumptions used in certain liner designs may have placed several existing installations at risk of non-compliance with the Minimum Requirements and, worse, placed the environment at risk.

4.2.2 Current Use of Geosynthetics in Waste Containment

The above section reflects the thinking that led to the South African regulatory standards as at 1998 (Minimum Requirements for Waste Disposal, 2nd edition, 1998). These standards were amended and adopted by neighbouring Botswana. The RSA standards are however referred to in many sub-Saharan countries and have been used as the performance criteria by Namibia and Mozambique.

The range of performance standards being applied from small communal sites to large regional and hazardous waste sites is evolving towards the latter as more and more old sites close. It is also noted that these requirements are already applied to industrial waste and that the current mine waste stream exemption is not indefinite. Furthermore, environmental protection legislation is developing to provide protection from the increasing utilisation of our resources.

We thus see the employment of geosynthetics functions as protective layers; single-, double-, or composite barriers; drainage and leak detection layers; filters and drains for groundwater; reinforcing layers; and permanent or temporary covers.

TSB Sugar Mill Landfill, in which a GCL serves as the primary base liner

Figure 37

Figure 38

Composite liners in the Movoco hazardous waste landfill, Mozambique

Figure 39

Figure 40

Liquid waste containment facility for Emalahleni mine waste water treatment and recovery system

Figure 41

Figure 42

Emalahleni triple liner leakage monitoring system

Figure 43

Figure 44

4.3 Mining Applications

The mineral wealth of Africa is exploited by open cast and underground mining depending on the location and economics. Irrespective of the depth of the mineral or ore, the concentration of desired element (usually metal) influences the treatment process. This may be metal recovery through capturing an enriched solution which has permeated through a heap of usually low-grade ore and then recovered as a pregnant solution for further treatment and metal extraction. Deep level mines usually extract high-grade ore, which is crushed and treated at a refinery for extraction, resulting in a waste stream of tailings, which is disposed of either above-ground in tailings dams, or below ground in backfill systems, or combinations thereof.

Heap leaching is the biggest consumer of geosynthetics (Smith, 2008) in which geomembranes and GCLs are used for containment, while geotextiles are used for protection, in various components of the heap leach process, i.e., pads, solution trenches, pregnant solution ponds and storm water ponds. The processing or extraction process also makes use of membranes in thickener tanks. The disposal of tailings in dams makes extensive use of geotextiles as filters, both in ground water under-drainage and in perimeter wall seepage drains. Backfill makes extensive use of geotextiles as containment and filters under harsh loading conditions.

4.3.1 Heap Leach Pads

To date South African based contractors have lined only gold heap leach pads (all over West Africa, as well as in Kazakhstan and Tajikistan), as well as in all of the associated ponds and solution corridors. We believe the design for copper ore heap leach pads is very similar. On most of these leach pads the in-situ soil is reworked to the required slopes and compacted (typically to 95 % Std. Proctor) density and then a 450 mm thick clay liner is imported and compacted in 150 mm layers to 98 % Std. Proctor density. A 1.5 mm smooth GRI-GM13 compacted HDPE lining is then installed on top of this compacted clay layer, which is then typically (but not always) protected by a (typical) 300 g/m² geotextile. The perforated pipe drainage/collection system is then installed, prior to the pioneering layer of crushed rock being placed directly on top of the geotextile by end-tipping and spreading. A conveyor belt system with stacker is then installed, to place the crushed ore (typically 10 mm nominal diameter size) in 10 m lifts, up to a total heap height of typically 40 m. The heap stability is obtained by inter alia filling up against the perimeter berms.

There is always a solution corridor, which runs alongside the pads, leading to an entire series of dams/ponds: typically for pregnant-solution, excess solution-, intermediate-, solution, silt trap, storm water and barren ponds.

The solution corridor base design is similar to that of the pad, whilst most of the ponds are usually double-lined with a base geotextile as protection, 1.5 HDPE secondary lining, geonet (or cuspated sheet) for leak detection, and a 2 mm HDPE primary lining.

One of the biggest construction challenges is to work on top of the clay liner, as it rains very regularly in tropical West Africa (there is a very short window of "drier" weather – approximately 4 months annually), and once the wet season starts, it rains every day in the afternoon for an hour or two. The clay thus seldom gets time to dry out properly to allow it's reworking, leading to substantial bad production delays for all involved. Installation is labour intensive, local plant and equipment can be quite primitive, and it is not uncommon to have up to 70 labourers involved with the lining installation alone.

Due to the vast areas involved (up to a million square meters), wind is also a very important factor to allow for in design and construction.

Typical design for a Uranium leach pad is in-situ compaction to 95 % Std. Proctor, then overlain with a GCL, with a 2 mm thick smooth HDPE lining directly on top of it, after which a geotextile protection layer and the piping system is installed. The cover stone, typically 90 cm thick, is then placed. We have also seen a design where the GCL was replaced by a soil/bentonite layer (allegedly selected for heap stability reasons). Local climatic conditions may severely affect the performance of such.

The outer edge of the heap stops short of the perimeter berm, and a 30 m wide section of double-textured HDPE lining is installed at this (future) toe location to ensure the overall stability of the heap.

There is also a single-lined (1.5 mm HDPE) solution corridor to convey the pregnant solution to the series of double-lined (1.5 HDPE; geonet/cuspated detection layer; 2 mm HDPE) ponds, which may consist of a pregnant-, 3 intermediate-, excess storm water, 2 rinsing- and a barren pond.

Figures 45–54: Heap leach pads for low-grade gold ore treatment in West Africa.

Figure 45

Figure 46

Figure 47

Figure 48


Figure 49


Figure 50

Figure 51


Figure 52


Figure 53


Figure 54

4.3.2 Thickener Tanks

Many processing plants which make use of thickener tanks use an internal geomembrane lining which is advantageous in that realigning can be undertaken with a minimum of shut down time when required.

4.3.3 Mine Backfilling

Placed backfill support in worked out sections of deep mines brings many benefits. These include increased safety, the opportunity to remove ore bearing pillar supports, and reduced costs of ventilating disused mine space. Containers formed from proper woven and knitted geotextiles are proving to be valuable products for impoundment of backfill materials (usually liquefied tailings), whilst these drain and solidify. This section specifically reports on the use of geotextile containers in very deep gold mine back-filling, but it would seem probable that they could also be used to retain liquefied fill when available, in other types of mines.

4.3.3.1 Advantages

Innumerable developments in technology, achieved in over a century of deep level mining in South Africa, have generated a modern, safe and highly efficient industry. One innovation – the refilling of worked out areas deep underground with barren waste rock material, often held in containers which are formed from geotextiles – is redefining mining practice. Backfilling is really not a new concept. As long ago as 1888 mine sands were used in an attempt to support the roof of vacated mine workings at the Wemmer section of the Village Main Reef mine. However, this attempt to improve safety was fraught with practical engineering constraints and limited by technology. Miners were reported to have been at a far greater danger of drowning from sudden outbursts of the water, used to transport the waste material to the backfill, than protected from the hazards of rockbursts and rock falls. Further, the backfill was generally placed too far from the working face to be effective.

The economic rationale behind the increasingly attractive safety practice of stope backfilling lies primarily in providing hanging wall (roof) support, to permit the removal of gold bearing support pillars and to facilitate mining in difficult ground conditions.

Evidence suggests that backfill could radically reduce deaths caused by rock-burst and serious ground fall occurrences, which account for about 50 % of gold mining fatalities. In addition, the very presence of backfill forms a safety barrier, as it reduces the area of exposed roof under which persons can move.

Provided the backfill programme keeps support sufficiently near to the stope to be effective (in order of 5 m and in some cases within 2 m) rockbursts and rockfall are reduced which, in turn, reduce stope closure time.

The presence of backfill material masks off large areas of heat emitting hanging and footwalls in worked out areas. Thus, backfill ensures both better ventilation along the working faces and lower costs.

Trained backfill labour teams and efficient material management make backfilling economically attractive, compared to the conventional support methods which lock in ore in pillars and on footwalls.

Suitably filled geotextile containers, or barriers, minimise the need for wood supports. This significantly diminishes the fire risk associated with conventional stacked timber supports. Successive backfill applications also mask previously used timber bracing from air.

4.3.3.2 Backfilling Mechanism

Backfill material influences the backfilling mechanism employed in underground mining. There are generally three types of backfill material available for use underground:

Dewatered tailings:
This product contains the full range of particle sizes usually associated with milled ore, after the gold extraction, and forms a stiff paste. The advantages of such material lies in its low water content – no spillage and drainage problems occur underground. However, the need for high-pressure positive displacement pumps, within 300 m of the deposition point, and a slow drainage characteristic count negatively for this material.

Waste rock:
Research and development work has been undertaken to retain underground development waste rock. This is crushed to a suitable size and used as fill material. Whilst this saves the cost of raising the material to the surface, crushing and placement are expensive.

Deslimed tailings:
The third and most commonly used backfill material is deslimed tailings (processed discharge material with the fine fraction removed). This forms a relatively free draining material nearly ideal for support. Separation is done by single, double or three-stage cycloning, with the remaining more suitable material going to a slimes dam.

Cyclone feed material must be of high moisture content, typically a ratio of water to dry solids by mass of 3.5 to 4.0 parts to 1 has worked well. The underflow containing the coarser portion of the split has a ratio of 0.6 water to 1 solids by mass, and has a specific gravity of around 1.6. This material is pumped to the backfilling zone. The very wet overflow is retained above-ground and formed into tailings dams.

Almost every type of geotextile has been available on the local market and tried in the early stages of the development of backfill containers. Problems encountered with various geotextile types have been deformation induced clogging, excessive loss of fines, and a sometimes lower than required fabric and/or seam strengths.

Now specific woven tape and knitted geotextiles are used with defined mine tailings. Filtration properties are of particular importance, due to the large volumes of water in the underflow from the cyclone, which is pumped to the backfill zone.

The method of backfill chosen for a particular mine depends on factors such as mining techniques, rock conditions, stope height and dip and available backfill, amongst others. Typically, the backfill is pumped into a paddock system or a bag, in close proximity to the stope. A geotextile forms the main backfill container, while some timber is often used to lend early support to the geotextile.

The correct geotextile will retain the tailings fines until the backfill has fully drained and become self-supporting. A geotextile must be able to remain undamaged by rugged handling and excessive forces from blasting at the stope, some two metres away. It is also important that the geotextile container is supplied in a form, which can be quickly an easily installed.

4.3.3.3 Closure

While the tailings themselves vary from mine to mine, so does the material at a specific mine vary with time. The geotextile container is required to allow the efficient dewatering of the variable backfill to provide earliest possible support and, at the same time, pass the minimum amount of fines (which would then find their way back to the ore-pass and mills with resulting wasteful reprocessing). Escaped fines also pose a health and safety risk to underground workers.

Through the very close co-operation between some mines and geotextile manufacturers, near optimum and specific methods, including specially designed geotextiles, have now been developed. Other mines still need to research cyclone underflow quality and, if necessary, flocculent dosage. Further, they need to co-operate with appropriate geotextile manufacturers in the development of a range of products and installation aids, fitting to their type of mining operation and hence their backfilling methods.

Figure 55: Backfill bag support in deep level gold mining

Figure 56: Backfill bag support in deep level gold mining

Under-drainage for mine waste containment facilities

Figure 57

Figure 58

Geotextile wrapped groundwater drains beneath compacted clay liner of tailings dam

Figure 59: Tailings dam perimeter drain

Figure 60: Tailings dam perimeter drain

4.4 Transport Systems

4.4.1 Rail Systems

Railway network expansion is not common; however, when such civil works come about there is a significant opportunity for geosynthetics use in separation, filtration and reinforced applications.

Gautrain

Figure 61: Geogrid reinforced foundation for Gautrain rapid rail route over dolomitic area

Figure 61: Geogrid reinforced foundation for Gautrain rapid rail route over dolomitic area

Figure 63: Geogrid reinforced soil abutment for construction vehicle overpass on Gautrain route

Figure 64: Geogrid reinforced soil abutment for construction vehicle overpass on Gautrain route

4.4.2 Road Systems

4.4.2.1 The First Mountain Pass Built in South Africa (SAICE, 2005)

Jan van Riebeeck, the fellow who was dumped on the shores of Table Bay in April 1652 and told to supply passing ships with fresh vegetables and other provisions, had to get timber from up Kirstenbosch way. So on 26 May 1653 he built a two-wheeled carpenter's cart on which he balanced the trees and things, and on 30 May "in order that the cart may run over the road more easily, others were sent with picks, mattocks, shovels and spades to level the road somewhat, being rather uneven". To supplement their praiseworthy construction efforts, it is recorded this "wagen pad na t'Bosch" had to be kept maintained by occasional flurries of men with picks and shovels.

A noteworthy event: Road transport and the essential supporting road building and road maintenance activities had arrived in South Africa!

Now, when they had chopped down all the nice trees in Kirstenbosch (talk about sustainable development) they had to look for another source of timber. So they moved on to Hout Bay where as, the name implies, at that time there were lots of trees.

Commander Wagenaer, in charge at the time, said, "Let there be a road over Bosheuwel so that we may cut timber in the Hout Bay Valley." Thus, on 18 August 1666 Lieutenant Schut and 24 soldiers went out towards the evening with some crowbars, picks and shovels in order to make a road. If they only had the rest of the day to build the road, it really cannot have been much of a highway!

However, apparently the road was used successfully. With time, the traffic grew, and we find that the road was lengthened and improved by order of Commander Simon van der Stel in 1679 and that further road works were done in early 1693. In fact, this pass and the road to Hout Bay never looked back. It was improved at regular intervals, until it reached the state you see today.

Now, some people will tell you that the road up to the Silvermine plateau (what we today call the Ou Kaapse Weg) was the first mountain pass built in our country, but in my opinion Cloof Pass, the timber road over Constantia Nek, deserves that title.

4.4.2.2 Geosynthetic applications in road works today

Geosynthetics are used primarily in a drainage function in road works, both as side drains and at bridge abutments. Geotextiles are however also used in erosion control applications as part of and adjacent to transport routes. This could take the form of geotextiles beneath riprap or gabion baskets; multi cell soil containers or silt fences. A significant consumer of geotextile is the repair of pavement cracks in road maintenance programmes.

Figure 65: Findrain on route N3

Figure 66: Paving fabric in road rehabilitation, Namibia

Figure 67: Silt fence after vegetation destruction by fire

Figure 68: Geocell drift construction on Amadiba Road poverty alleviation project

Figure 69: Geoanimal exclusion – Cape Mole Rat

Figure 70: Mole Rat barrier installation

5. DEVELOPMENTS IN RESPONSE TO CHALLENGES

Although the use of geosynthetics is common practice and in some cases a regulatory requirement in civil, mining and environmental applications, there are occasions where geosynthetics come to the fore because of their significant advantages over natural and other manmade materials. Examples of these are often associated with extreme events such as floods, droughts, time constraints or accessibility. Some examples are noted below:

- Usutu River Emergency works: When the Usutu River, which forms the international border between South Africa and Mozambique, came down in flood in 2005 it broke its banks and eroded a new channel. This channel cut a line from a position on the Usutu River approximately 12 km upstream of the confluence with the Pongola River, through the near flat area adjacent to and into the Banzi Pan, and onto the Pongola River. The Banzi Pan is of enormous conservation value and is a Ramsar site. When the flood receded the riverbed between the breech and confluence in the Usutu was left dry and consequently some rural subsistence farmers without access to run of river water. Geotextile containment bags filled with sand were used to develop a partial weir across the breech to redirect water along its original route. The weir was so designed to allow for self-collapse under future elevated flows.

- Natal Beach revetment: The recent storm surges, which denuded beaches of sand to the north and south of Durban, threatened shoreline infrastructure. The rapid deployment of large geotextile containment bags was embraced to prevent further damage and initiate beach rehabilitation.

- River diversion for dam construction: The first and in particular second stage river diversion during dam construction is timed to take place during the dry season. It is thus critical to avoid generating suspended solids during low flows to minimise impacts on in-stream biota. A geotextile bed protection and geosynthetic bags were used to generate a backwater in the stage 1 diversion channel to allow for continuous and unpolluted flow through the stage 2 diversion works at the De Hoop Dam, Limpopo Province in 2009.

The affects of elevated temperature on service life are known and quantification thereof has been presented at this conference (Rowe, 2009). In applications where elevated temperature becomes a concern there are mitigatory solutions such as the use of thermal barriers including geofoam; the use of polymer modifiers; or cooling systems such as pipe networks or the multi-purpose Enhanced Barrier System, the latter being an option for removal of heat or volatile organic compounds or for hydrating clay components in barrier systems.

Similarly, the advancement of products and technology will increase the range of applications such as the potential use of unclassified tailings in mine backfill support, military and rescue operations.

6. CONCLUSIONS

The use of geosynthetics in numerous and varied applications over decades brings us to the situation where these materials and their use are no longer a mere economic alternative to be considered. Geosynthetics applications are today the accepted norm for modern professionals. This is confirmed by the fact that legislation prescribes geosynthetics use as a minimum standard in, amongst others, waste containment applications and road drainage.

It is time for developers to advance geosynthetics considerations to the planning phase, rather than the later design phase.

ACKNOWLEDGEMENTS

The permission of the Director-General of the Department of Water Affairs to publish and present this paper is gratefully acknowledged.

The significant assistance of Geosynthetic Laboratory and especially of Mr P.L. Davies of Kaytech Engineered Fabrics of Pinetown, Kwa-Zulu Natal, RSA, who provided testing facilities and support is gratefully acknowledged. Similarly, contributions have been appreciated from Anton Bain, Garth James, Megan Nortjé, Peter Legge, Michelle Parker and Ronnie Scheurenberg.

REFERENCES

Africa. UNESCO, 2005. http://portal.unesco.org/ci/en/ev.php-URL

Atlas-Xpeditions@nationalgeographic.com *National Geographic Society. 2003*. http://www.nationalgeographic.com/xpeditions/atlas/index.html?Parent=Africa&Rootmap==Mode=d

Ball, J. M. New Landfill Legislation. (Based on the presentation The implication of disposal site licensing presented at an IWM Seminar, Johannesburg, 4 October 1985). *Municipal Engineer*, Vol. 16, No. 8, November 1985).

Ball, J. M. and Blight, G. E. Ground Water Pollution Downstream of a Long-established Sanitary Landfill. *Proceedings of the International Symposium on Environmental Technology*, Allentown, Penn., USA, 1986. Also in Municipal Engineer, Vol. 17, No. 9, September 1986.

Ball, J. M. and Blight, G. E. The Philosophy and Framework for a Sanitary Landfill Design Manual for South Africa. *Proceedings of the South African Institution of Civil Engineers, International Conference on Mining and Industrial Waste Management*, Johannesburg, 1987.

Ball, J. M. and Blight, G. E. The Fate of Leachate from a Landfill Site. *Proceedings of IWM (SA) Biennial Congress*, Durban, August 1988.

Ball, J. M. and Novella, P. Coastal Park Landfill: Leachate Plume Migration and Attenuation, *Proceedings WasteCon 2002*, Institute of Waste Management, Durban, SA, September 2002.

Blight, G. E. and Ball, J. M. Studies of the Water Balance for Landfill Sited in Water Deficient Area. *Proceedings of the Third International Landfill Symposium*, Cagliari, Sardinia, 1991.

Bonaparte, R., Othman, M.A., Rad, N.S., Swan, R.H., and Vander Linde, D.L. (1996). Evaluation of Various Aspects of GCL Performance. Appendix F, Rep. *Of 1995 Workshop on Geosynthetic Clay Liners*, D.E. Daniel and H.B. Scranton, eds, Rep. No. EPA/600/R-96-149, F1-F34.

China and Africa: Stronger Economic Ties mean more migration, by Malia Politzer, *Migration source*, August 2008

Day, P. (1999). *Interface testing of Geomembranes and Its Application to Landfills*. SAICE Geotechnical Division evening lecture, 24 February 1999

DWAF (South African Department of Water Affairs & Forestry) (1998). *Minimum Requirements for Waste Disposal by Landfill*. Second edition, September 1998. ISBN 0620-22993-4

Decret & Fantar, 1981 Names of countries

Diamond, Jared. (1999) *Guns, Germs and Steel: The Fates of Human Societies*. New York: Oxford University Press, 2005. pp22-23
Economic report on Africa 2004: unlocking Africa's potential in the global economy, (Substantive session 28 June- 23 July 2004) United Nations
Eyma, A.K. & C.J. Bennett. (2003) Delts-Man in Yebu: Occasional Volume of the Egyptologists Electronic Forum No1, Universal Publishers. P210. ISBN 1-58112-564-X
Focus on the slave trade, BBC
Foose Gary J.; Benson Craig H.; Tuncer B. (2002). Comparison of Solute Transport in Three Composite Liners. *Journal of Geotechnical and Geoenvironmental Engineering*, May 2002, pp 391-403
Genetic study roots humans in Africa, BBC News/SCI/TECH
Giroud J.P., Badu-Tweneboah K., & Soderman K.L. (1994) Evaluation of Landfill Liners, *Proc. Fifth International Conference on Geotextiles, Geomembranes and Related Products*, Vol. 3, Pages 981-986, 1994. SEAC-IGS. ISBN 981-00-5823-3
Harper, W.A., Wilson-Fahmy, R.F., & Koerner, R.M. (1993) Evaluation of the Contact Between Geosynthetic Clay Liners and Geomembranes In Terms Of Transmissivity. *Proceedings of the 7th GRI Seminar*, Geosynthetic Liner Systems: Innovations, Concerns and Designs. December 14-15, 1993, Philadelphia, PA, USA.
Hassan Fekri A. (2002) *Droughts, Food and Culture*, Springer. P17. ISBN 0-306-46755-0
Haxo, H.E. and Lahey, T.P. (1988). Transport of Dissolved Organics from Dilute Aqueous Solutions Through Flexible Membrane Liners. *Hazard. Waste. Hazard. Mater*. 5(4), 275-294.
History survey, Slave societies, Encyclopaedia Britannica
Homo sapiens: University of Utah News Release: Feb 16, 2005
Hoare, Ben. (2002) *The Kingfisher A-Z Encyclopedia*, Kingfisher Publications. P. 11. ISBN 0-7534-5569-2
Hwu, B-L., Koerner, R.M., & Sprague, C.J. (1990). Geotextile Intrusion Into Geonets. *Proc. Fourth International Conference on Geotextiles, Geomembranes and Related Products*, Vol. 1, Pages 351-356, 1990. Balkelma, Rotterdam ISBN 90 6191 120 6
Jacobs, Louis L (1997). African Dinosaurs. *Encyclopedia of Dinosaurs*. Edited by Phillip J. Currie and Kevin Padian. Academic Press. P.2-4
Kimble, William H. & Yoel Rak & Donald C. Johnson. (2004) *The Skull of Australopithecus Afarrensis*, Oxford University Press US. ISBN 0-19-515706-0
Koerner, R.M., and Daniel, D.E. (1993). Technical Equivalency Assessment of GCLs to CCLs. *Proc. 7th GRI Seminar*, Geosynthetics Research Institute, Drexel Univ., Philadelphia, 255-275
Loveday P.E. *Transformations in slavery: A History of Slavery in Africa* p25
Martin and O'Meara. Africa, 3rd Ed. Indiana: Indiana University Press, 1995.
McGrail, Sean. (2004) *Boats of the World*, Oxford University Press. P48 ISBN 0-19-927186-0
Merriam-Webster's Geographical Dictionary (index), (1998) pp10-11. ISBN 0-87779-546-0
Migration of early Humans from Africa Aided by wet weather, sciencedaily.com
Mokhtar, G. (1990) UNESCO *General History of Africa, Vol 11, Abridged Edition: Ancient Africa,* University of California Press. ISBN 0-85255-092-8
Mueller, W., Jakob R., Tatzky-Gerth, R., and August, H. Solubilities, Diffusion, and Partition Coefficients of Organic Pollutants in HDPE Geomembranes: Experimental results and Calculations. *Proc. 6th Int. Conf. On Geosynthetics*, Atlanta, Industrial Fabrics Association International, St. Paul, Minn., 239-248.
O'Brien, Patrick K. (General Editor). *Oxford Atlas of World History*. New York: Oxford University Press, 2005. pp22-23
Park, J.K., and Nibras, M. (1993). *Mass Flux of Organic Chemicals Through Polyethylene Geomembranes*. Water Environ. Res., 65(3), 227-237.
Syre, April Pulley. (1999) Africa, Twenty-First Century Books. ISBN 0-7613-1367-2
Ptolemaic and Roman Egypt: 332 BC-395 AD
Rowe, R.K., Hrapovic, L., and Kosaric, N. (1995). Diffusion of Chloride and Dichloromethane Through a HDPE Geomembrane. *Geosynthetics International*, 2(3), 507-536.
Rowe, R. K. (1998), Geosynthetics and the Minimization of Contaminant Migration Through Barrier Systems Beneath Solid Waste. *Sixth International Conference on Geosynthetics*, Atlanta, Georgia, USA. International Geosynthetics Society. ISBN0-93583-07-6

Rowe, R.K., & Orsini, C. (2002). Internal Erosion of GCLs Placed Directly Over Gravel. *Proceedings of the International Symposium IS Nuremberg 2002*, Nuremberg, Germany 1-17 April 2002. AA Balkema Publishers.
Sandbrook Richard. (1985), *The Politics of Africa's Economic Stagnation*, Cambridge University Press, Cambridge
Shaner, K.R. & Menoff, S.D. (1992). Impacts of Bentonite Geocomposites on Geonet Drainage. *Geotextiles and Geomembranes*, 11 (4-6), (503-512) ISSN 0266-1144
Simon, Julian L. (1995) *State of Humanity*, Blackwell Publishing. P.175. ISBN 1-55786-585-X
Swahili Coast, *National Geographic*
The Developing world is poorer than we thought, but no less successful in the fight against poverty. *World Bank*. http://econ.worldbank.org/external/default/main
The Fate of Africa – Survey of Fifty Years of Independence (html). *Washingtonpost.com* http://www.washingtonpost.com/wp-dyn/content/discussion/2006/01/11/D12006011101372
The West African Squadron and slave trade
Tudge, Colin. (2002) *The Variety of Life*, Oxford University Press. ISBN 0-19-860426-2
United Nations
Van Sertima, Ivan. (1995) *Egypt: Child of Africa/S V12 (Ppr),* Transaction Publishers. Pp.324-325
Visual Geography. Africa. General info. http://www.visualgeography.com/continents/africa.html
Von Maubeuge, K.P. (2002) Investigation of Bentonite Requirements for Geosynthetic Clay Barriers. *Proceedings of the International Symposium IS Nuremberg 2002*, Nuremberg, Germany 1-17 April 2002. AA Balkema Publishers
Welcome to Encyclopaedia Britannica's Guide to Black History, Encyclopaedia Britannica
Were Egyptians the first scribes?, BBC News/Sci/Tech
Walton, J., Rahman, M., Casey, D., Picornell, M., and Johnson, F. (1997). Leakage Through Flaws in Geomembrane Liners. *Journal of Geotechnical and Geoenvironmental Engineering*. 123 (6), (534-539)