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Chapter 1: Introduction

1.1 Background

According to the National Environment Agency meteorological services, Singapore's climate is characterized by uniform temperature, pressure, high humidity and abundant rainfall throughout the year. Such tropical climate would inevitably cause harsh weathering attack to the roof, in particular the waterproofing membrane which would be subjected to wear and tear. Being constantly exposed to rain or sun, the roof surface experiences high fluctuations in temperatures. The problem is exacerbated when ponding occurs for roofs of improper gradient or in the absence of internal drainage (for cases of large spanning roofs), resulting in roof surface temperatures to hit as high as 80°C. Being literally submerged in hot water, the waterproofing membrane fails as it was never designed to withstand extreme heat. Such defects pose issues to do with maintainability, thereby affecting the efficiency of the roof in carrying out its performance duty to protect the building's interior.

Also, due to the inaccessibility to many of the major components of roof including the waterproofing and structural deck, it will be difficult to conduct regular maintenance and repair, thus, durability becomes crucial. Providing the right system in the right place is of paramount importance to provide for durability as well as to the structural integrity of the building. However, such importance to provide for a sound structural waterproofing system is one that is often overlooked.

This paper attempts to overcome and reduce the maintainability issues related to roof waterproofing by customizing an appropriate system to be employed in different situations possible. Through the derivation of a user-friendly toolkit modelled after an expert in this field, it aids professionals and amateurs alike, to help propose a waterproofing system which is more practical and functional, increasing maintainability in turn and providing significant cost benefits in the long run.

1.2 Objectives of Study

The main objective of this research is:

1. Develop a user-friendly toolkit modeled after an expert that serves as a reliable selection guideline for users to adopt the best-suited waterproofing system compatible for their designed roofs.

To achieve the above-mentioned main objective, the following sub-objectives will have to be dealt with:

1. A comprehensive literature study to determine the common waterproofing-related defects of roofing systems.
2. An in-depth review on the characteristics of waterproofing systems commonly used: Liquid, Pre-formed and Integral.
3. Interviews with experts to seek professional advice on the selection guideline toolkit.

1.3 Scope and Limitations

Due to time constraints and insufficient resources, this research to derive the toolkit would only be limited to flat roofs (less than 10 degrees slope) in Singapore, which is widely chosen to be used for storage and maintenance. Hence, the findings would tend to be more relevant and applicable to the local context, although there could be some other generalized areas.

A roof serves to enclose space, prevent penetration of inclement weather and control heat gain, or heat loss. Providing the right system in the right place is of paramount importance, as it would reduce the chances of defects that threaten or fail the waterproofing system, or in worse cases, affect the building's integrity. These problems result in high maintenance costs. As building structures get increasingly complex with the roof area being largely exploited for different purposes such as mechanical and engineering storage, recreational use and landscaping, it is no longer possible to generally rely on traditional systems of waterproofing for overall applications. Instead, sound structural waterproofing systems should be tailored accordingly to the needs required by the building structure and layout, with regards to the roof's usage and the client's requirements. As such, by deriving a toolkit customized to aid users with the bothersome decision process, a better-suited waterproofing system could instead be considered to provide for significant cost and time savings.

However, this toolkit will serve to act merely as a rudimentary guideline for the choice of a most appropriate waterproofing system, since there is no hard and fast rule with regards to the selection process from the many options available.

1.4 Organization of Study

This paper consists of 6 chapters in total. Following the introduction, Chapter 2 deals with the extensive literature study on the different types of defects related to roof waterproofing, as well as a tabulated comparison of the characteristics of three widely-adopted waterproofing systems: Liquid, Preformed and Integral. Chapter 3 will address the methodology adopted for this research. Following, Chapter 4 concentrates on the interview findings from the experts approached and addresses other pertinent findings. Chapter 5 is with regards to the formulation of the selection guide toolkit, explaining the different factors governing the selection of waterproofing systems and also including the decision flowchart that decomposes the problem statement. A sample of the checklist toolkit will also be presented. Lastly, the conclusion, significance of study and recommendations will be provided in the final Chapter 6.

Chapter 2: Literature Review

2.1 Defects Related to Roof Waterproofing

There are many different types of defects related to roof waterproofing. Poor choice of waterproofing systems as well as insufficient provision to meet external weather conditions will lead to such defects. However, in this section, only a few common and significant defects related to roof waterproofing will be discussed.

2.1.1 Blistering

Blistering is a means of failure because it represents a weakening and breakdown of the waterproofing membrane, leading to the intrusion of water (National University of Singapore, 2005). It occurs when there is entrapped air and/or moisture over the voids in a roof system (Paroli & Booth, 1997). When exposed to weathering, the trapped air and moisture expand under sun and displaces the waterproofing membrane to form blisters. The expansion is due to the increase of temperature on roof surface hence resulting in a pressure built up within the blisters. Pressure will then cause displacement and stretching of membrane when air pocket increases in size (Chew Y. L., 2010).

They are typically 2 types of blistering:

1. Blisters between the roof membrane and the substrate;
2. Blisters between the membrane plies

The principles behind the cause of these blistering are the same. However, they differ in the layers in which the blisters are formed. Blisters range from small spongy spots to large pronounced areas (Paroli & Booth, 1997). When blisters occur, it may worsen due to the weight of foot traffic or snow and ice as they cause further tension on the surface and thus bursting the blisters. In local conditions, only the former applies.

2.1.2 Alligatoring of Membrane

Resembling the characteristics of an alligator's skin pattern, the surface cracks that can be found on the waterproofing membranes are termed as alligatoring. It is the outcome of the sun causing the top surface of asphalt to be fragile (Dunlop, 2003). The membrane will dry out from exposure to sunlight (Simmons, 1989), thus cracking will occur. Alligatoring is always most severe where asphalt coating is thickest. Over time, the cracks deepen and this will eventually allow water through the upper layer of asphalt into the felts leading to rapid deterioration of the roof surface (Dunlop, 2003).

Figure 1 illustrates an example of alligatoring:

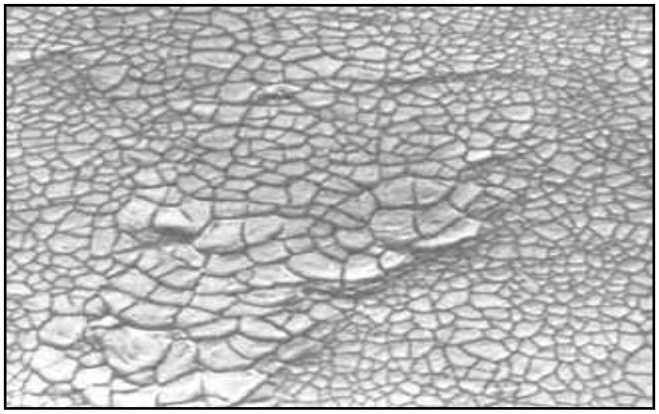


Figure 1 Alligatoring (Integrated Publishing, n.d)

2.1.3 Delamination of Membrane

Delamination is the disjointing of the plies in a roof membrane system or laminated layers of insulation. Unlike other defects directly related to roof waterproofing, delamination usually indicates a manufacturing defect (Griffin & Fricklas, 2006). Such statement is in accordance with the few common reasons for delamination which Chew (2010) listed. This includes the use of substandard quality materials, poor workmanship, inappropriate surface preparation or incompatibility of components.

Figure 2 Delamination of Waterproofing Membrane in Thailand Airport Carpark (Fosroc)

2.1.3 Ridges of Membrane

Ridging also can be termed as wrinkling, which may be caused by installation problems like inadequate stretching of membrane during application, uneven application of base coat and components underneath. The differential thermal expansion of the roof and expansion due to moisture (Chew Y. L., 2010) (Dunlop, 2003) resulting from the various problems create ridges. Moisture is formed due to the condensation of the water vapour which comes through the roof deck from building interior. These ridges may influence the rainwater runoff and result in water ponding.

Ridges may emerge as parallel lines of long ripple felts, above the insulation boards, along the roof surface. If another set of parallel lines appear in the other direction, it would form a pattern called picture framing (Figure 3). In a less orderly pattern, ridges may resemble long blisters however the causes of both differ (Griffin & Fricklas, 2006).

Figure 3 The staggered grid pattern is called picture framing (Griffin & Fricklas, 2006)

2.1.4 Water Ponding

Water ponding is a defect that is generally seen on flat roofs. The accumulation and retention of water forms the water ponding on roof. The existence of such defect implies that the roof might have these following symptoms (Ratay, 2000):

- Inadequate roof sloping to drain off
- Drainage obstructions
- Insufficient drainage
- Deflection of the roof's underlying structural component

When ponding happens, instant repair is needed as it may subsequently be associated as the cause of other problems. Firstly, ponded water can damage roofing materials by chemically altering their composition (Piper, 2004). If ponding attacks the insulation, moisture will increase the heating and cooling cost as water absorption will triple the heat loss through the roof system (Burgess, 2003). Secondly, when the water-proofing membrane fails, the accumulated water may find its way out of the roof, resulting in leakage in the uppermost storey. Lastly, the most critical problem is that it may cause the failure of the structural component as the weight of the accumulated water may deflect the roof. However, as mentioned above it could also be the deflection of the structural component that leads to water ponding. The relationship of water ponding and roof deflection is considered as a chicken-and-egg type of relationship (Ratay, 2000).

2.1.5 Service Penetration through Membrane

Service penetration breaks the continuity of a waterproofing system creating opportunities for water seepage into the building interior (Chew Y. L., 2010). Thus careful consideration should be given in the design stage to limit the number of penetrations through a roof. The occurrence of this defect can be controlled with proper planning and design of the roof waterproofing membrane.

2.1.6 Adhesion Failure of Membrane

There are 2 types of adhesion failures which will lead to defects on the roof waterproofing membrane – interfacial or interphasal adhesion failure (Nicastro, 1997). Typically, adhesion failures are interfacial which occur at the interface between two materials. It can be caused due to poor workmanship when the waterproofing membrane is adhered onto surface with wet or dirty substrate or any surface with chemical incapability with substrate. Interphasal adhesion failure on the other hand, occurs immediately next to the bond line within one of the material and is usually associated with water saturation.

2.2 Types of Waterproofing Systems

2.2.1 Liquid Applied Waterproofing Membrane

Liquid applied waterproofing membrane is an elastomeric barrier material that can be applied by squeegee, roller, brush, trowel, or spray. It is formulated as "single- or multiple-component products such as neoprene (polychloroprene), neoprene-bituminous blends, polyurethane, polyurethane-bituminous blends, and epoxy-bituminous blends" (ACI Committee 551, 1988).

They are often preferred due to their seamless application and ability to cover unusual shaped surfaces with ease. Construction detailing for protrusions and transition points is done easier as compared to other systems. While most can be purchased premixed and ready for use, the popular sprayed polyurethane foam system must be carefully mixed and moderately heated on site. As it is a cold applied membrane, as opposed to traditional hot applied alternatives, it does not require an open flame or high temperatures on site. To an extent, this ensures the safety of workers when working with such systems.

Due to it being a cold applied system, many manufacturers are prompted to claim that it is easy to apply, but it should not be considered a '*do-it-yourself*' project. An expert must be hired because liquid applied systems are sensitive to misuse and need careful handling during application. Any change or inconsistency in the method of application will be noticeable and could affect the effectiveness of the product. Since there are no standardized methods of application, experts are able to bank on their expertise to make slight application variations to help direct the flow of water to prevent ponding. It is recommended to apply multiple layers of liquid applied waterproofing to avoid the effects of pin hole formulation, which is an application defect typical of this system. Subsequent layers must be applied within 24 hours of the first application to ensure proper cohesion.

The membrane requires a relatively short period of curing time to be ready, and the majority can withstand light foot traffic. Although liquid applied systems can be ready for use relatively quickly, the weather conditions during application must be taken into account. If the temperature is too low, the material may become too viscous and not adhere well or be able to form a continuous thickness.

Currently, liquid applied waterproofing membranes are experiencing an increase in popularity as they are being used in remedial works to upgrade current roofs that may be showing signs of aging such as leaks or cracks. Many manufacturers actively promote liquid waterproofing as an option. However, it is not suggested to use liquid systems over concrete decks that already have a membrane underneath, as trapped moisture formed between the layers of membrane could cause future problems. Venting is also not an option for such membranes.

Sometimes it is required to use a glass cloth or mesh to reinforce. Many of the systems require a dry thickness of 50 mil (1 ¼ mm).

Table 1 General Information on Liquid-Applied Waterproofing Membrane

	Descriptions
Application methods	▪ By squeegee, roller, brush, trowel, or spray ▪ Cold adhesive
Advantages	▪ Seamless ▪ Can cover undulating surfaces with ease ▪ Details around transitions are usually simpler than sheet systems ▪ Excellent elongation characteristics at moderate temperatures ▪ Easy to patch up
Disadvantages	▪ As a bonded barrier, it is not possible to relieve pressure by venting ▪ Will not cover, hide, or level surface irregularities ▪ Varying thickness will affect performance ▪ Needs multiple coats to minimize pin hole formation
Important considerations	▪ Do not use over light-weight aggregate concrete fills

a. Polyurethane Foam

A popular liquid applied waterproofing membrane in the United States is sprayed polyurethane foam (PUF). This type of system has been in use for over 40 years. Its seamless finish usually reserves it for roofs with unusual shaped like hyperbolic parabaloids or domes as transition detailing is simple. The system is composed of a high-density urethane foam coated with an elastomeric roof coating. The foam is made on site by heating then carefully mixing a proportioned amount of a polyol and a catalyst, and spraying it from a gun. While silicone coatings generally have a higher performance level, its high cost acts as a deterrence which impedes users from using it as an option. Cheaper options are asphalt or acryclic coatings, but these materials tend to have a shorter life span. This coating is necessary because PUF needs protection from ultra violet radiation. Small penetrations and general wear and tear can be repaired with elastomeric caulk.

One of the characteristics that set apart PUF from other systems is that it contributes insulation to the roof, providing an R-value of 7.14 per 1 inch thickness. Usually they are installed ½ - 6 inches thick. It also enhances the wind-uplift resistance of the substrate. The main disadvantage to this system is that weather conditions must be ideal during the time of application. Any moisture, humidity, or condensation will cause the foam to blister. Apart from having to be very careful in regards to moisture levels, the person applying the PUF must be consistent because any variance in application will stand out. This means an expert must be hired. Conversely, the expert can slope the PUF to aid in drainage.

Due to the little preparation work necessary, the use of PUF is popular for patching up old roofs. However, it is not recommended to use PUF for completely reroofing failed or leaking roofs as it is likely there is trapped moisture beneath the original roof. If the water moisture is not allowed to escape into the environment, blistering and delamination might occur, proving it to be ineffective in the long run.

Table 2 General Information on Sprayed Polyurethane Foam Roofing

	Descriptions
Application methods	▪ Spray applied ▪ Cold adhesive
Advantages	▪ Seamless ▪ Can cover undulating surfaces with ease ▪ Details around transitions are usually simpler than sheet systems ▪ Provides insulation (R-value of 7.14 per 1 inch thickness) ▪ Lightweight roofing
Disadvantages	▪ As a bonded barrier, it is not possible to relieve pressure by venting ▪ Requires careful on-site mixing, heating, and ideal weather for application as any moisture will cause foam to blister ▪ Susceptible to ultraviolet weathering
Important considerations	▪ Do not use over concrete decks that have a membrane beneath to prevent blistering and delamination from trapped moisture

b. Polyurethane

As a waterproofing membrane that has great resistance to ultraviolet weathering, polyurethane is preferred as a roof coating in Singapore, though it can also be used on horizontal surfaces. Its wide range of colors available makes it preferred as an aesthetically pleasing membrane that will be exposed to sight. It is a non-biuminous liquid-applied membrane that can be applied by brush, squeegee, roller, or airless spray. Polyurethane may also be mixed with higher polymers to improve its properties. A common combination includes polyurethane and epoxy or polyurethane and urethane (BCA, 2003).

Table 3 Prescriptive and Performance Criteria for Modified Liquid Polyurethane (Fosroc, 2007)

Properties	Typical values
Color	Black
Application temperature range	5 to 50 °C
Service temperature range	-40 to +70 °C
Tack free time at 25 °C	15 to 24 hours
Specific gravity	1.15
Viscosity	200 p
Solids content	92 %
Elongation	500 – 700 %
Tensile strength	1.60 N/mm^2
Recovery from 200% elongation	95 %
Tear resistance (N)	10
Water vapor transmission	9.5
Initial hardness	26

Table 4 General Information on Modified Liquid Polyurethane

	Descriptions
Application methods	▪ Applied by brush, squeegee, roller, airless spray ▪ Cold adhesive
Advantages	▪ Seamless ▪ Can cover undulating surfaces with ease ▪ Details around transitions are usually simpler than sheet systems ▪ Does not biodegrade
Disadvantages	▪ May experience inter-layer delamination
Important considerations	▪ Unaffected by mild acids, alkalis and water borne salts.

c. Acrylic

Another waterproofing membrane commonly used in Singapore is acrylic waterproofing. Acyrlic formulas usually consist of emulsified acrylic resin, fillers like calcium carbonate, wetting agents, bacteria killers and plasicisers (BCA, 2003). In addition to concrete, acrylic will adhere to asbestos, cement, corrugate iron, and timber. It can be applied by brush, roller, or airless spray on either horizontal or vertical surfaces. It offers great elasticity for roof movement, and is resistant to many chemicals, pollutants, and mold growth. Its micro-porous skin allows the substrate to dry out. In addition, many acrylic waterproofing membranes contain low or no Volatile Organic Compounds (VOCs) and are also Green Labelled, making them a preferred choice for developers interested in sustainability and achieving the Green Mark status. It is also desired for its aesthetic appeal and is often left exposed.

The following Table 5 presents a suggested prescriptive and performance criteria for liquid applied acrylic waterproofing, while Table 6 provides some other relevant general information.

Table 5 Prescriptive and Performance Criteria for Liquid Applied Acrylic Waterproofing (Fosroc, 2007)

Properties	Typical values
Color	Black, Neutral, Red, Gray
Application temperature range	10 to 60 °C
Wet film thickness per coat	0.4 – 1.0 mm
Tack free time at 25 °C	< 1 hour, subsequent cats 2 -4 hours
Density	1.29 ±0.04
Solids content	62 ±3 %
Elongation	300 – 400 %
Tensile strength	> 2.0 N/mm^2
Crack bridging	5 mm maximum
Crack filling	0.1 to 3 mm
Shore hardness	65 - 80°

Table 6 General Information on Liquid Applied Acrylic Waterproofing

	Descriptions
Application methods	▪ Applied by brush, roller, airless spray ▪ Cold adhesive
Advantages	▪ Seamless ▪ Can cover undulating surfaces with ease ▪ Details around transitions are usually simpler than sheet systems ▪ Micro-porous skin allows substrate to dry out naturally
Disadvantages	▪ May experience inter-layer delamination ▪ Susceptible to ultraviolet weathering
Important considerations	▪ Not recommended for us in below-grade applications

2.2.2 Preformed Waterproofing Membrane

Preformed waterproofing membrane is a flexible or semi-flexible roof covering sheet which is manufactured off-site (with or without reinforcement or backing) (SISIR, 1994). It is also known as waterproofing sheet membrane. This type of waterproofing membrane can be fully bonded or loosely laid on the substrate serving as a barrier between the water and the building structure so as to prevent water ingress (Kubal, 2008).

Being manufactured in factories, these membranes usually come in rolls with widths from 3 to 10ft and their thickness range from 20 to 120mil (Kubal, 2008). Due to their huge width size, these membranes are highly suitable for application on large areas such as rooftops and basements (Chew, 2010). Such installation would effectively maximize productivity in application and hence reduce the time taken for completion. Conversely, preformed membranes are not commonly use in small internal areas like bathrooms and kitchens as these areas require high degree of detailing and high workmanship. It is therefore critical to determine the most suitable type of waterproofing membrane otherwise the waterproofing system may fail or may not perform efficiency (Arup Singapore Pte Ltd, 2003).

The application methods for preformed waterproofing membranes come in various ways which include self adhesive, adhesive bonding, chemical welding, hot air welding, and mechanical fixing. However, under certain circumstance, it is essential to combine different application methods in one installation so as to produce efficient and quality outcomes (Chew, 2010 and Singapore Concrete Institute, 1995).

a. Examples of Preformed Waterproofing Membrane

There are two general types of preformed waterproofing membrane, namely bituminous and non bituminous membranes. Table 7 shows various types of membranes classified under preformed waterproofing members and the characteristics of each membrane.

Table 7 Characteristic of Preformed Waterproofing Membranes (BCA, 2003)

Examples	Characteristics
Bituminous	
Asphalt	▪ Obtain from raw minerals mined from the ground ▪ Offers excellent waterproofing and adhesive properties ▪ Usually used as fully adhered system
Bitumen	▪ Residue (or by-product) derived from the process of refining crude petroleum ▪ Quality of bitumen obtained vary from different locations

	Usually used as fully adhered system
Modified Bitumen	▪ Also known as “Straight-run” bitumen ▪ Addition of organic polymers make straight-run bitumen soft and flexible ▪ Not resistant against prolonged exposure to sunlight (Ultraviolet radiation) and often get oxidized and cracks ▪ Oxidized bitumen are produced through an oxidation process by passing forced air through the straight-run bitumen ▪ Usually used as fully adhered system
Non- Bituminous	
Ethylene-Cpolymer Bitumen (ECB)	▪ Extrusion of chemical combination of bitumen and coal tar (residue of coat after distillation) produce ECB sheet ▪ Considerable resistance to ageing and weather exposure Application: Loosely laid, mechanically fastened, fully adhered
Polyvinyl Chloride (PVC)	▪ Material nature: Hard and brittle ▪ Addition of plasticisers and stabilizers with proper formulation make PVC membranes resistant to ageing and weather exposure ▪ Addition of synthetic or fabric mesh aid in improving its tear resistance ▪ Application: Loosely laid, mechanically fastened, fully adhered
Polyethylene (PE)	▪ Protection of membrane from UV radiation exposure enable long life span and stability ▪ A non-breathing membrane which is used as low cost vapor barrier ▪ By itself, it is not used as a waterproofing membrane
Chlorinated Polyethylene (CPE)	▪ A non-breathing membrane ▪ Application: Loosely laid or fully adhered with a water-based synthetic resin adhesive
Butyl Rubber	▪ A solvent based adhesive which is non-breathing ▪ Use to seal lap joints ▪ Difficult to adhere to concrete substrate ▪ Application: Loosely laid
Ethylene Proplyene Diene (EPDM)	▪ Similar to Butyl rubber, but more resistance to weather exposure ▪ Good resistance to corrosive chemicals, ozone, weathering ▪ Extremely low water permeability ▪ Application: Loosely laid

Neoprene	▪ A synthetic rubber which is relative resistance to chemical attack ▪ Produced from acetylene and hydrochloric acid ▪ Good flexibility with ability to bend and molds to surfaces ▪ Easier slice sheets ▪ Not commonly used for underground as waterproofing membrane
Polyisobutylene (PIB)	▪ Usually reinforced with a non-woven synthetic felt ▪ Good ozone, UV resistance ▪ Extremely low vapour permeability ▪ Application: Loosely laid, partially adhered, mechanically fastened
Bentonite clays	▪ Usually made up of silica, alumina, ferric oxide, magnesia, lime and soda ▪ Excellent expansion from 10 to 20 times from its original volume when allowed to free swell in standing water. However, when it is exposed to external pressure, it will decrease its swell ▪ Placed against the structures (in board form). Joints between boards are usually coated with liquid bentonite to assure a tight seal ▪ Swells occur in the presence of pressure during backfilling soil and water, restriction of swell will prevent further water penetration

b. Common Preformed Membranes

In Henshell's book (2002), he identified some commonly used membranes, namely: modified bitumen membranes, Ethylene Propylene Diene monomer sheet (EPDM), Butyl rubber sheet and polyvinyl chloride (PVC) sheet.

The following sections will then go in depth to discuss on these frequent used membranes. General information such as the properties, application methods, uses, advantages, disadvantages and the important considerations will be evaluated.

i. <u>Modified Bitumen Membranes</u>

Modified bitumen membranes were developed in Europe in the mid-1960s and had been widely used since 1975. These bituminous sheets are modified with synthetic rubbers or plastics so as to achieve greater flexibility, elasticity and cohesive strength of the bitumen (Singapore Concrete Institute, 1995).

The following Table 8 presents a suggested prescriptive and performance criteria for modified-bitumen waterproofing membranes, while Table 9 provides some relevant general information.

Table 8 Prescriptive and Performance Criteria for Modified Bitumen Waterproofing Membrane (Henshell, 2000)

Properties	Typical values
Thickness	60 Mils
Tensile strength	250 – 320 psi
Elongation, Ultimate failure of rubberized asphalt	300%
Cracking cycling at -32oC (-25°F), 100 cycles	Unaffected
Lap adhesion at minimum application temperature	4 to 7 lb/in
Peel strength	7.5 to 9
Puncture resistance membrane	40 lbs
Resistance to hydrostatic head	150 to 230 ft
Exposure to Fungi in Soil, 16 weeks	Unaffected
Permeance	0.05 perms
Water absorption	0.1 to 0.25 wt

(Values are obtained through American Society for Testing and Materials, ASTM)

Table 9 General Information on Modified-Bitumen Waterproofing Membrane

	Descriptions
Application methods	▪ Torch applied ▪ Mopped in with hot asphalt ▪ Cold adhesive ▪ Self adhesive
Advantages	▪ Good adhesion on concrete substrate ▪ Improve resilience and bonding adhesion ▪ Improve resistance to vapor flow
Disadvantages	▪ Not suitable for blindside application ▪ Does not adhere to substrate when applied to mud slab ▪ Poor ultraviolet-radiation resistance ▪ Application is limited to temperature of 25^{0}F and higher only
Important considerations	▪ Ensure appropriate water absorption rates and vulnerability to wicking of moisture through edges. ▪ Require inspection on pressure rolling of membrane and field splicing seams to make ensure tight bonding adhesion. ▪ Require sealing of top edges

ii. <u>Vulcanized rubbers</u>

Vulcanized rubbers are commonly found in EPDM and Butyl rubber sheet. These materials obtain better elasticity and durability through the addition of sulfur which therefore allows them to be highly resistant to diverse weather conditions. Moreover, such materials are also good in elongation and are puncture-resistant. (Ruggiero, 1990)

- Ethylene Propylene Diene monomer sheets (EPDM)

Since early 1960s, EPDM sheets were widely used as waterproofing coverings for roofs in the United States as the materials do not pollute the runoff rainwater. EPDM sheet is an elastomeric compound synthesized from ethylene, propylene and a small amount of diene monomer. (Singapore Concrete Institute, 1995)

- Butyl rubber sheet

Butyl rubber is a synthetic rubber, a copolymer of isobutylene. It is considered as a non-breathing material. Due to its poor adhesion on concrete substrate, it is often loosely laid with solvent applying on the lapping to seal the laps. (Addison, 1986)

A comparison of EPDM and Butyl is established as shown in Table 10 and Table 11 provides the general information on the two membranes as stated.

Table 10 Prescriptive and Performance Criteria for EPDM and Butyl Waterproofing Membrane (Henshell, 2000)

Properties	Typical values	
	EPDM	Butyl rubber
Colour	Black or white	Black
Thickness	30 – 60 mils	60 mils
Tensile strength	1300 psi	1200 psi
Hardness	60 -/+10	60 -/+10
Elongation, Ultimate failure of rubberized asphalt	300%	300%
Tear resistance min	150 Ibf/in	150 Ibf/in
Brittleness temperature	-49°F	-40 °F
Heat aging at 240 °F		
Tensile strength	1200 psi	900 psi
Elongation ultimate	210%	210%
Water absorption	4	2
Water vapor permeance max	0.060 perms	0.0025 perms

Table 11 General Information on Modified-Bitumen Waterproofing Membrane

	Descriptions	
	EPDM	Butyl
Application methods	▪ Loosely laid	▪ Loosely laid
Use in	▪ Suitable for green roofs	▪ Suitable for industrial roof
Advantages	▪ Very low permeability ▪ High resistance to ultraviolet radiation, weathering, and abrasion ▪ Good low-temperature flexibility ▪ Long life span – Last for approximately 30 to 50 years ▪ Reflect heat thus reduce heat temperature on roof ▪ Repairs are done simply and inexpensively	▪ Minimise frequency of laps due to large width size of the rolls ▪ Low water permeability ▪ Offers vastly superior vapor permeance ▪ High temperature and heat resistance ▪ Good resistance to corrosive chemicals ▪ Gas tightness ▪ High elongation
Disadvantages	▪ Installation could be costly due to high workmanship required	▪ Poor adhesion on concrete substrate ▪ Difficulties in applying on vertical surfaces as the Butyl sheet stretches under its own weight, especially in warm weather.
Important considerations	▪ Ensure that bonding adhesive is kept off seams ▪ EPDM is highly resistant to ultraviolet, hence it is more suitable for above-grade waterproofing sheets.	

iii. Polyvinyl Chloride PVC membranes

PVC is made up of PVC resin, plasticizer, filler, and heat and ultraviolet stabilizers. It is produced by coating, extrusion, or calendaring processes in both reinforced and non-reinforced form (Laaly, 1982).

Table 12 represents the prescriptive and performance criteria of PVC and the general information is evaluated in Table 13.

Table 12 Prescriptive and Performance Criteria for PVC Waterproofing Membrane (Henshell, 2000)

Properties	Typical values
Colour	Grey / Orange
Thickness	40 – 48 Mils

Tensile strength	1600 psi
Elongation at break, min. %	300 MD 280 CMD
Tear resistance min	35 Ibf
Weight change after immersion in water, maximum %	2.0
Puncture resistance	66.74

Table 13 General Information on PVC membranes

	Descriptions
Application methods	▪ Loosely laid ▪ Mechanically fastened ▪ Fully adhered
Uses in	▪ Roofing membranes
Advantages	▪ Easy to apply ▪ Flexible in a way that it can be tailor-made to suit any roof shape and even covering vent pipes ▪ Resistance to bacterial growth, roof penetration, industrial chemical atmospheres and harsh weather conditions ▪ Durability against rooftop soiling and contamination ▪ Good in fire resistance and seaming capability ▪ Low water absorption ▪ Good low temperature & high temperature tolerance ▪ Good elongation ▪ Puncture resistance
Disadvantages	▪ Not suitable for blindside application ▪ Does not adhere to substrate when applied to mud slab ▪ Poor ultraviolet-radiation resistance ▪ Application is limited to temperature of 25^0F and higher only ▪ Chemically incompatible with bituminous materials
Important considerations	▪ Ensure proper and adequate formulation of plasticisers and stabiliser so as to achieve its intended property to resistant ageing and weather exposure

2.2.3 Integral Waterproofing

Integral waterproofing is an unconventional form of waterproofing system. Unlike traditional waterproofing, it provides against water penetration based on the use of different admixtures with waterproofing properties in the concrete mix. These admixtures forms concrete with surfaces that are either able to repel water or fill the capillary pores, hence reducing water permeability of the concrete (Chew Y. L., 2009).

The integral waterproofing system is thus, able to block the passage of water from both the positive and negative sides of walls, basements and roofs by working within the concrete, extending to all aspects of watertightness of the concrete shell (American Concrete Institute , 1998).

a. Integral Waterproofing Admixtures

The addition of integral waterproofing admixtures into the cement mixture enhances and improves the in-place cementitious performance, imparting the concrete with desirable qualities that was not present initially. Added benefits to the concrete as mentioned by (Perkins, 1977):

- Colour
- Workability
- Shrinkage reduction
- Improved hydration
- Reduced porosity
- Improved (shorter) setting times
- Faster curing
- Improved waterproofing properties

Besides improving on the performance of the concrete, these admixtures also ensures complete hydration when it is added into the cement mixture promoting internal curing. As the mixture is cured internally, it will allow for reduction in shrinkage, providing a denser, stronger and a more water resistant product as the water absorption rates of the mixture is reduced (Perkins, 1977).

Admixtures added into the cement mix can come in 3 different forms namely: pastes, powders and fluids.

These admixtures can be either added into cement mixture as an admixture for the formation of concrete, added into surface applied slurry for existing concrete or added into dry shake application for concrete flatwork.

Comparison between the different forms of integral waterproofing admixtures is shown in Table 14. It should be noted that this is just a general comparison between the properties, advantages and disadvantages of all 3 forms. Specific properties vary with the different specifications as given by the manufacturers.

Table 14 Basic Comparison Between the Different Forms of Integral Waterproofing Admixtures (Hunter, 1947)

	Pastes	**Powders**	**Fluids**
Nature	▪ Dense ▪ Glutinous in nature	▪ Fine ▪ Dry form	▪ Liquid
Disadvantages	▪ Requires most effort during mixing Must be mixed extremely well to remove lumps Lumps will lead to problems during rendering, initiating cracks and crazing	▪ Usually mixed onsite Mixing operations should be protected to prevent other particles from going into the mixture. The addition of unnecessary particles will affect the performance of the mixture. ▪ Mixing operation requires supervision to ensure that correct proportion of powder in added into the mixture. Waste of human resources. ▪ Possibility of having voids within the mixture is high if not properly mixed.	▪ Usually more expensive as compared to the other 2 forms
Advantages		▪ Added when together during formation of concrete. Able to ensure that correct proportions of powder are added according to specific ratios to best fit waterproofing purpose of the structure. ▪ Usually cheapest in price.	▪ Fluid is added into cement mixture and brought to site. Waterproofed concrete has better ability to withstand corrosive action of acid, alkalis or any harmful salts present in industrial waters. Thus the properties of the waterproofed concrete will not be adversely affected. ▪ No effort required during mixing

			▪ Able to mix evenly with cement mixture. Less room for voids within the mixture as chemical reaction takes place when fluid waterproofers are added into the cement which fills up all possible voids, adding to the binding properties of the cement.

Examples of waterproofing admixtures include calcium chloride solutions, soaps, hydrated lim, butyl stearate and oils as well as bituminous and waxy substances (American Concrete Institute , 1998).

b. Hydrophobic Integral System V.S Hydrophilic Integral System

There are 2 forms of integral waterproofing systems namely the hydrophobic and the hydrophilic system. The basic principles of both systems are similar. They make use of the chemical reaction between the admixture and the cement mix to ensure that the cementitious admixture becomes an integral part of the concrete substrate.

i. <u>Differences</u>

The difference of both systems lies in the way in which water will be repelled or blocked from that surface of the structure.

In a hydrophobic integral system, the addition of admixtures will reduce the absorptivity and the rate of capillary transfer of moisture by either making the surface of the structure hydrophobic or water repellant (American Concrete Institute , 1998). Hydrophobic admixtures contain compounds with fatty acids. Hydrophobic tails of these fatty acids forms a barrier on either the positive or negative side of the concrete surface, blocking the pores within the concrete and repelling surface water, preventing water ingress.

Hydrophilic system on the other hand, uses a crystallization technology which replaces the water in the concrete with insoluble crystals when water ingresses into the concrete. Unlike the hydrophobic system which repels water at the surface, hydrophilic integral system allows surface water to first permeate into the concrete pores. As water enters into the concrete and comes into contact with the cemetitious admixtures, crystals will grow within the concrete effectively closing off any possible water pathways by filling up natural pores, capillaries and any hairline cracks found within the concrete. The crystal formation makes the concrete structure itself a barrier to water penetration, preventing surface water from entering and damaging the concrete.

The Integral system is analyzed in general using the following table:

Table 15 General information on Integral waterproofing system (Hydrophilic and Hydrophobic)

	Descriptions
Application methods	▪ Injected into concrete structure ▪ Sprayed, brushed or troweled on surface ▪ Added into cement mixture during formation of concrete
Curing Period	▪ 24-48 hours depending on the properties of the admixtures
Advantages	▪ Permanent waterproofing solution ○ Integrates with the concrete becoming a permanent part of the concrete structure ○ Reactivates in the presence of moisture even after long period of application ○ Self-seals small space within concrete (e.g. Hairline cracks) ○ No visible seams or joints when crystals are reactivated or self-sealed (seamless application) ○ No waterproofing membrane at the surface thus, it will not tear or puncture ○ Remains impervious to physical damage and deterioration over the lifetime of the concrete structure ▪ Added longevity to life cycle of concrete elements when exposed to weathering or wear and tear as compared to other waterproofing methods ○ Protects reinforcing steel by preventing the penetration of waterborne contaminants and chloride-laden liquids that cause the corrosion of reinforcing steel. ▪ Increase the pace of construction when time scheduling is critical ○ For admixtures that are brushed or troweled, they do not require a completely dried or cured concrete before it can be applied, eliminating well pointing and the need for water control during construction (Kubal M. T., 2008) ○ It allows for application on vertical and horizontal structures to be done at the same time, eliminating staging operations (Kubal M. T., 2008) ▪ Easy application ○ Not subjected to stringent workmanship.

	○ No need for professional labour or sophisticated equipments ○ Little chance for human error during application ▪ Can be applied on any side of existing concrete or structure ○ Advantageous when positive side is difficult to reach ▪ Not reliant on surface barrier ○ Crystal will grow, despite the type of material used for the surface which the waterproof concrete it is applied on as long as it is in contact with water ▪ Eliminates need for extra external surface membrane ○ Remains effective even if surface application is damaged
Disadvantages	▪ Intolerable to substandard materials or construction practices ○ Concrete acts as a water barrier thus improperly cured concrete or substandard construction practices will lead to poor consolidation or unplanned joints ○ Requires thorough, minute preparation of the substrate and proper supervision for admixtures to work most effectively. ○ The cement mixture and surface which it is applied on has to be free of dirt, laitance, form release agents and foreign materials (Kubal M. T., 2008) ▪ Unsuitable for applications under constant movement ○ Rigid when cured ○ Crystals formed during crystallization process will break when subjected to constant movement. ○ Rate of self-seal is lower at certain expansion joints, suspended slabs or roof decks with excessive cracking. ○ Inappropriate for flexible applications such as expansion joints or for repairing shifting cracks ▪ Lower compressive strength ○ The process of “Hydrophobizing” of aggregates will lower its compress strength by 3-10% as compared to controlled mixes that are applied as waterproofs. ▪ Requires mixing onsite ○ Proportion of admixtures and purity of cement mix might be affected by existing site conditions.
Cost	▪ Lower overall project cost ○ Material cost is up to 40% lower installed cost than a traditional membrane approach ○ Use of hycrete in Bovis Lend-Lease project help save $187,000 in material costs—a 32% improvement over traditional waterproofing approaches.

	▪ Lower labour cost ○ No need for professional labor for application thus will be able to cut down on labor cost
Effect on Environment	▪ Reduces material demand ○ Admixtures are integrated into the concrete ○ No need for additional materials to be used for the waterproofing membrane ▪ Concrete can be recycled (EG hycrete) thus it is a sustainable building material ▪ Chemicals used in the admixtures are non toxic, non-flammable, odourless ○ No gasous by-products are given out during the concrete's life cycle ○ Not a health or environmental hazard ▪ Has water-based properties making it a greener alternative as compared to traditional ammonia-based waterproofing systems
Effect of Time	▪ Shorten construction timeline ○ Can be applied to green or existing concrete or added directly to the new concrete ○ For new waterproofing construction, there is no need for membrane application thus there's no need to spend time to wait for membrane application and backfilling ○ For remedial works, membrane installation is a time-consuming process, as it requires near-perfect conditions to apply. Integral waterproofing admixtures can be sprayed or brushed on the surface as long as the surface clean and free of unnecessary particles ○ Integral waterproofing is done during the mixing stage simplifying the overall waterproofing process. ○ No vulnerabilities to weather, damage by other trades, and extra excavation
Uses	▪ Effective for waterproofing new concrete. ▪ Efficient for repairing cracks and holes, and waterproofing concrete construction joints, tieholes, and pipe penetrations which are difficult to reach. But not suitable for flexible joints.

Unlike the liquid and perform waterproofing membrane, as the American Society for Testing and Materials (ASTM) , does not provide for the prescriptive and performance criteria for integral waterproofing, no data were available for reference.

2.2.4 Types of Waterproofing Systems

There are two prime types of waterproofing systems, namely the concealed waterproofing system and the expose waterproofing system. Such systems are only applicable for liquid-applied and preformed waterproofing membranes (Kubal, 2008).

a. Concealed Waterproofing System

Concealed waterproofing membrane system has its membrane embedded within the roof structure and is not exposed to harsh environment which include ultraviolet weathering, wind-driven rain and acid rain (Kubal, 2008). One of the advantages is that the membranes are protected from adverse climates as the top layer, such as tiles or exposed concrete, acts as a protection against the adverse environment. Moreover no maintenance is required in this case. However, one of the drawbacks of such system is that the evaluation of concealed waterproofing membranes on concrete structures is not an easy task. Sufficient information about the waterproofing system, the underlying structure, and the owner's long-term intentions for the property must be obtained and evaluated to provide effective and economical rehabilitation options (Harrison, 2003).

According to Harrison (2003), there are many types of waterproofing membranes that may be used on concealed concrete structures. Table 16 presents a list of such alternatives.

Table 16 Types of Membranes and Application Used on Concealed Concrete Structures

Examples	Types of Applications
Urethane, Modified asphalts	Fully adhered, cold-applied, liquid membranes
Rubberized asphalt	Fully adhered, hot-applied, liquid membranes
Asphalt, rubberized, coal tar	Fully adhered, hot-applied, built-up or reinforced membranes
Modified asphalt/reinforcing sheet	Torch grade, modified asphalt composite roll membranes
Rubberized asphalt/polyethylene sheet	Cold-applied, composite sheet membranes
EPDM, PVC, butyl	Loose-laid, sheet membranes

Additionally, Figure 4 demonstrates the application of a concealed membrane system using preformed waterproofing membrane on a flat roof of a building in Singapore.

Figure 4 Application of a conceal waterproofing membrane system (Patent roofing)

1. Removing existing membrane

2. Primer has been applied on roof

3. Laying of waterproofing membrane

4. Laying of insulation foam over new waterproofing membrane

5. Laying of separating geotextile over the insulation foam

6. Laying cast-in-situ cement sand panel over

7. Completion of concealed waterproofing system

b. Exposed Waterproofing System

Another waterproofing system is the exposed waterproofing system. In this system, the waterproofing membrane is used as the top layer, designed to withstand wear from weather conditions, including rain, UV radiation, wind load and thermal contraction and expansion. Considerations of membranes used in this system includes its breathability, resistance to ultraviolet light, its aesthetics and adaptability to a wide range of temperatures. (Protan, N.A)

The disadvantages of exposed membranes include the membrane's vulnerability to detrimental weather conditions which could, as a result, cause wear and tear faster as compared to concealed system. However, membranes applied on the top surface can be repaired easily should any problems or defects occur. (Kubal, 2008, Pratt, 1990)

Figure 5 presents the application of an exposed waterproofing system using preformed membrane on a flat roof of a building.

Figure 5 Application of an Exposed Waterproofing Membrane System (Patent roofing)

1. RC roof primed

2. Exposed membrane work

3. Completion of exposed waterproofing system

Appendix A illustrates the details of the concealed and exposed waterproofing systems in construction drawings. Although only liquid membrane is shown in the drawings, the concept for the preformed membrane is similar.

2.2.5 Comparisons of the 3 Types of Waterproofing Membranes

	Liquid-applied waterproofing membrane	Preformed waterproofing membrane	Integral waterproofing membrane
Performance Specifications			
Thickness	Average	Thickness: 20-120mil	60mil
Elongation	Excellent	Good	Nil
Chemical & weathering resistance	Average	Good	Good
Examples	Bituminous Bituminous modified Non- Bituminous Acrylic, Epoxy, Polyurethane (PU), Polyisorene/Rubber, Cementitious, Silicon, Hypalon, Neoprene	Bituminous Asphalt, Bitumen, Modified Bitumen Non- Bituminous Ethylene-Cpolymer Bitumen (ECB), Polyvinyl Chloride (PVC), Polyethylene (PE), Chlorinated Polyethylene (CPE), Butyl Rubber, Ethylene Proplyene Diene (EPDM), Neoprene, Polyisobutylene (PIB), Bentonite clays	▪ Crystalline waterproofing ▪ Chemical admixture ▪ Waterproofing screed
Application methods	Cold applied ▪ Squeegee ▪ Roller ▪ Brush ▪ Trowel ▪ Spray	Self adhesive Adhesive bonding Chemical welding Hot air welding Mechanical fixing	Injected into concrete structure Sprayed, brushed or troweled on surface Added into cement mixture during formation of concrete
Other Considerations			

Installations	<u>Concealed system</u> Easy to moderate <u>Exposed system</u> Easy	<u>Concealed system</u> Moderate to difficult <u>Exposed system</u> Moderate to difficult	-
Repairs	<u>Concealed system</u> Moderate to difficult <u>Exposed system</u> Easy	<u>Concealed system</u> Moderate to difficult <u>Exposed system</u> Easy	
Advantages	▪ Seamless ▪ Can cover undulating surfaces with ease ▪ Details around transitions are usually simpler than sheet systems ▪ Easy to patch up	▪ Thickness of membrane can be controlled ▪ Ensure uniform application thickness throughout an installation ▪ Rapid and easy to install ▪ Safe to install ▪ Overlapping of membranes provide additional overlap security ▪ Good chemical and weathering resistance	▪ Permanent waterproofing solution ▪ Added longevity to life cycle of concrete elements when exposed to weathering or wear and tear as compared to other waterproofing methods ▪ Increase the pace of construction when time scheduling is critical ▪ Easy application ▪ Can be applied on any side of existing concrete or structure ▪ Not reliant on surface barrier ▪ Eliminates need for extra external surface membrane
Disadvantages	▪ Difficulty in ensuring uniform application thickness ▪ As a bonded barrier, it is not possible to relieve pressure by	▪ High cost due to numerous laps required ▪ Have limiting success, application difficulties and deteriorate with time	▪ Intolerable to substandard materials or construction practices ▪ Unsuitable for applications under constant movement

	venting ▪ Will not cover, hide, or level surface irregularities ▪ Varying thickness will affect performance ▪ Needs multiple coats to minimize pin hole formation	in limited life span of application ▪ Not self-flashing at protrusions and changes in plan ▪ Applications are challenging due to difficulty of handling and seaming materials ▪ Have difficulties when detailing around protrusions ▪ Seams will results in disbonding	▪ Lower compressive strength ▪ Requires mixing onsite

Chapter 3: Research Methodology

3.1 Research Design

To better understand the standard procedures or guidelines in choosing the right waterproofing systems for various types of roofs in Singapore, interviews were conducted with experienced practitioners to gain in-depth information and make the outcome of this study purposeful.

The interviews not only aimed to obtain the experts' opinions on the types of waterproofing systems commonly used for roofs in Singapore, but also to seek professional advice on a viable presentation of a standard guideline for other practitioners in the market to make use of in the selection of the best alternative among the mentioned waterproofing systems for their clients. Crucial deciding factors or considerations in the selection of waterproofing systems used for roofs, namely i) liquid-applied; ii) preformed sheet membrane; and iii) integral system; were explored in which their views and feedback received were subsequently used to formulate the deliverable of this study, in this case, the selection guide.

3.2 Structure of interviews

Two interview sessions were carried out with two respective waterproofing supplier companies.

Quantifications of the determinations of the roof sizes in terms of small, medium and large were derived. On top of that, issues to do with common problems in relation to roofs that could result in the deterioration of waterproofing systems; specific data such as cost, performance specifications as well as speed of supply and installation of each waterproofing systems, were also highlighted.

3.3 Data collection

A non-random purposive sampling technique was used in pre-selecting the leading waterproofing suppliers in the industry. This was to ensure that a certain degree of reliability and validity could be achieved for the establishment of the proposed selection guide.

Interview invitations were sent to the suppliers based via e-mail in early March 2010. With two responses, separate interview sessions were arranged with each respective interviewee whereby both direct interviews were conducted (i.e. face-to-face) during early April 2010.
Due to sensitivity of the information provided, confidentiality was promised to the interviewees taking part in this study.

Chapter 4: Interview Findings

This section discusses the findings obtained from the interviews conducted with two companies. The focus of the interviews was to understand the essential factors considered in the selection of appropriate waterproofing systems as it will prove useful for the formulation of the selection guide, which will be discussed in the following chapter.

4.1 Profiles of interviewees

Out of the interview requests sent to supplier companies providing waterproofing services, only two companies agreed to the request of direct interviews - BSAF and Fosroc. The profile details of the interviewees and the interviews are shown in Table 17.

Table 17 Details of interviewees and interviews

Name	Designation	Company	Years of experience	Date of interview	Mode of interview
Mr Y	Sales Manager	Fosroc	> 20 years	07 April 2010	Direct
Mr X	Business Development Manager	BASF	12 years	09 April 2010	Direct

4.2 Interview Discussion

4.2.1 Integral system unsuitable as waterproofing system for roofs

According to the experts, integral system is not a suitable candidate for waterproofing on roof as cracks will be formed easily due to the thermal expansion and contraction effects. This system is more widely used for basement construction as there is minimal thermal movement on the basement as compared to roof. However, in certain circumstances when waterproofing on roof is extremely crucial, this system could still be used as a waterproofing protection with additional liquid or preformed membrane application so as to insure full protected of water ingress.

Thus in the subsequent chapters, the types of waterproofing systems discussed and considered for the selection guide will only be constrained to the liquid and preformed waterproofing systems. Such option is in accordance to industry practice since these two waterproofing systems are undeniably the most common types applied on roofs in Singapore.

4.2.2 Speed of installation

The speed of installation differs between the two types of waterproofing systems. As mentioned by Mr X, liquid applied system using the spraying method is more suitable for large roofs as it is more effective in terms of time and cost considerations. Moreover, liquid membranes usually set faster which could therefore reduce the time taken to complete the whole waterproofing layering. Mr Y agreed that liquid waterproofing system is much faster as compared to preformed waterproofing regardless the size of the roof. As he repeatedly emphasized, the correct application of the preformed membrane is especially critical, and requires more skilled workmanship, precision and time. A rough guide on the speed of installation suggested by the Mr X shows that liquid application could cover $1000m^2$ on the roof area per day while the speed for preformed waterproofing installation is slower with coverage of $750m^2$ area per day.

4.2.3 Aesthetics

Exposed waterproofing system that uses liquid applied could help improve the aesthetics of the roof through the addition of colouring pigments to the liquid applied mixture. During the interview, Mr X revealed that the colour of the roofing membrane could be tailored to suit the building aesthetic and this is commonly popular with the clients since they are willing to be a little more generous in spending to enhance the visual effect of the roof. One example of having a nice roof is on a high-end residential carpark. Mr Y also acknowledged that this type of aesthetic enhancements is commonly applied to carpark roof decks. However, clients need to note that the colour will change eventually due to the effect of chemical reactions under constant weathering.

4.2.4 Costs of waterproofing systems

Both interviewees emphasized that cost is one of the upmost considerations when it comes to the selection of waterproofing systems. Usually, the planned budget would somehow determine the types of products used after the type of waterproofing system has been identified.

It is apparent that clients who wish to have a good quality membrane would have to decide to spend more. However, having a good quality membrane does not assure long life span of the waterproofing system as the experts emphasized the need for good workmanship, detailing and maintenance for sustaining the lifespan of the systems. Hence, the choice of having the most expensive waterproofing system does not, at anytime, imply that it is the best alternative available.

According to Mr X of BASF, liquid membranes are more costly than preformed ones. In contrast, for FOSROC, preformed membranes are more expensive as compared to liquid membranes. It is explicable that the costs of waterproofing systems vary among companies as different companies produce unique products and that their specialties differ. Table 18 shows a comparison on the cost of the membranes as stated by the experts. The figures provided are supply-and-install costs.

Table 18 Variation of Prices of Waterproofing Systems between Suppliers

Companies	BASF	Fosroc
Preformed membrane ($\$/m^2$)	$18	$50 – $60
Liquid membrane ($\$/m^2$)	$ 40 – $45	$15 – $20

4.2.5 Feasibility of using combined waterproofing systems

The selection on the type of waterproofing system is dependent on a few criteria which include the function of roof, client's budget and the level of detailing. As highlighted by the experts, more often than not, a roof uses only one type of waterproofing system as it could be expensive to accommodate different types of waterproofing systems. For instance, the use of both liquid and preformed systems requires more specialized workers with relevant know-how to apply each individual system. Furthermore, using additional resources and equipment would certainly incur new cost should different systems be used. Additionally the experts mentioned that the introduction of combined waterproofing systems could be ineffective as the transport of equipment could be tedious.

But the use of combined waterproofing systems is essential on critical areas where these areas require extremely good and special waterproofing application. For instance, it can be used when a swimming pool is located on the rooftop, or if the space use beneath the roof sells luxurious merchandise.

4.2.6 Environmental Considerations

From the interviews conducted, it seems that both companies have several products with Green Label approved. However, these environmentally friendly products are limited to just liquid membranes. As addressed by the experts, these products are usually solvent-free liquid or contain low solvent content and such products are usually popular for buildings that wish to achieve Green Mark Certification.

4.2.7 Maintenance issues

The maintenance of waterproofing takes place over a period of time or when any defects pertaining to roof waterproofing arises. From the interview, Mr X mentioned that re-roofing of waterproofing membrane on public housings takes place approximately every 12 years while re-roofing on other buildings like commercials or shopping malls take place every 10 to 15 years. The warranty for re-roofing on any roof is standardized to be around 5 years.

As mentioned earlier, the durability of waterproofing systems also depends on good detailing and workmanship of workers, which have huge influence in maintenance of the systems as well. As highlighted by Mr Y, problems usually occur due to poor workmanship and improper detailing which therefore create defects causing short lifespan of the system. Moreover, good gradient and drainage system on roof play an essential part in sustaining the lifespan of the waterproofing membranes.

Chapter 5: Formulation of Selection Guide

Flat roofs in Singapore have commonly utilized space in the form of rooftop gardens, carparks, or even plain roofs for storage of mechanical and electrical equipment. According to these different usages, three separate selection guides have been formulated.

To derive the selection guide modelled after an expert, it is critical to first establish some form of problem statement structuring, so that the flow of questions would better facilitate the process of decision analysis.

5.1 Factors of Consideration

5.1.1 General

Firstly, the factors governing the selection of waterproofing systems will have to be addressed. The basic ones include:

a. Type of Application

The type of application may be generally categorized as either new application or remedial works. In brief, both systems are compatible regardless of the application type. But according to the interview responses garnered, it seems that the preformed is preferred to liquid systems for remedial works. As it is usually tough to identify or trace the specific area of membrane failure, the industry practice would be to avoid localised patching and instead re-apply a new coat of membrane. In such instances, a preformed membrane is more convenient for remedial works, although it would require the removal of the existing membrane- only if it was preformed.

b. Roof Size

For the purpose of standardization, the experts have given a classification of roof sizes: small (less than 20,000m^2), medium (20,000-40,000m^2) and large (above 40,000m^2).

Generally, liquid system may be used regardless of the roof size. Preformed system, however, is more suitable for use of small areas to a certain degree of roof size. One such reason may be due to the lapping required for large roof areas, which makes preformed membranes less appealing as compared to the liquid membrane which promises continuity and uniformity. Lapping would require not only skilled and careful workmanship to avoid membrane failure, it would also require much more materials as compared to liquid membranes. Therefore, because of reasons to do with practicality and cost efficiency, liquid system would be more appropriate for roof sizes between medium to large.

c. Roof Perimeter

Classified into regular and non-regular, the shape of the roof perimeter is able to distinguish between the choices of liquid or preformed membranes. The latter is not preferred for irregular roof shape due to the discontinuity and lapping required, which again would demand skilled and careful workmanship. Finishing works are also more difficult if preformed membranes are chosen for irregular perimeters. Hence, having liquid membranes are much easier and at the same time, allows for continuity and uniformity throughout the roof surface and its perimeters.

d. Level of Detailing (M&E Services/Excessive Joints)

Level of detailing present on the roof will influence the selection of membranes to be used. When there is a high level of detailing, preformed membranes are generally not recommended. Although preformed membranes may also be formed to contours, it would require a high level of precision and workmanship to ensure uniformity, without which, causes a potential occurrence of roofing defects. Figure 6 shows an example of uniformity of membrane on the corners and step.

Figure 6 Example of Uniformity of Membrane

Liquid system is thus preferred regardless of the level of detailing, due to its continuity between horizontal and vertical planes, around projections and penetrations. Certain liquid membranes are enhanced with self-levelling property, which adds on to its advantage for use in such roofing applications. Being seamless and monolithic, including field joints, the liquid system is typically more appropriate for roofs in Singapore since most of the M&E services are stored on the roofs due to shortage of space in the building itself.

e. Exposure of Waterproofing System

Normally, the waterproofing system of a roof is concealed within the slab to reduce the probability of destruction by weathering and movements. Both liquid and preformed membranes are able to cater to this requirement. But contrary to belief, waterproofing systems do not always require concealment for roofs that experience heavy traffic flow, or even vehicular traffic. In the case of carparks, liquid membranes could be used as an exposed waterproofing system provided that the elongation for the membranes is designed to take on heavy vehicular loads. As such, elongation required should be around 300-400%. Thus, unless the roof deck is abused to improper usage (i.e. heavy vehicles or dragging bulky items across the surface), the membrane is unlikely to fail. Additional factors would have to be considered if the waterproofing is used as an exposed roof surface.

f. Expected Life Span

For remedial roof works, the re-installation of waterproofing system, either liquid or preformed, is expected to last for 5 years. In terms of new application, the expected lifespan of both waterproofing systems can be up to 10 years, while only liquid membrane is capable of offering up to 20 years of lifespan. Although the expectation of their lifespan is long, it is also subjected to other factors which would influence the waterproofing system's duration of function. The amount of traffic on the roof, problems with drainage, wrong installation process, entrapped moisture between membranes and others may result in defects to occur which would shorten the lifespan of the waterproofing system.

g. Application Time for Waterproofing System

The application time required for each type of membrane differs. Hence, the time factor would be able to help determine whether to opt for liquid or preformed. In addition to the requirement of skilled and careful workmanship, preformed membrane has a longer installation time. On average, only 750 m^2 of preformed membrane can be installed per day in contrast to liquid membrane of 1,000 m^2. Thus, for projects which are constrained to a tight schedule, or falls behind schedule, the application of liquid membrane as roof waterproofing might prove to be a better option, provided if both systems are applicable.

h. Rate of Membrane

The budget available obviously affects the selection of membrane. The prices of the membranes obtained from the experts required adjustments to accommodate for the difference in rates given. The final rates suggested are: Preformed membrane costing about \$20-40/m^2, while the liquid membrane at a higher price of \$40-60/m^2. Hence with a higher budget, users are able to choose either the liquid or preformed membrane according to their roof's requirement, while only the preformed membrane could be adopted for projects of lower budget. Users, however, should not allow their budget to restrict the type of waterproofing membranes used. As compared to other building elements, the cost of investing in a good and effective waterproofing membrane is much smaller. Thus, by investing in the right waterproofing membrane suited to the roof's requirements, future costs on repairs and maintenance can be saved.

i. Environmental Considerations

With the increased emphasis on sustainability in the built environment today, environmental considerations are undeniably a significant concern to many. The BCA Green Mark scheme, initiated to drive Singapore's construction industry towards more environmental-friendly buildings, helps provide a meaningful differentiation of buildings in the real estate market. As a form of benchmarking scheme, it incorporates internationally recognized best practices in environmental design and performance. The adoption of the Green Product Certification is not only favorable to the environment; it also brings about benefits to the consumers in terms of positive effect on corporate image, leasing and resale value of buildings.

Having a priority of environmental consideration is considerable because it would determine the choice of either the liquid or preformed system. To date, and as affirmed by the experts, there is no Green Label certification for any of the preformed systems. In contrast, examples of liquid systems such as Acrylic and Polyurea are Green Label approved.

5.1.2 Carpark

a. Aesthetic Considerations

Aesthetic requirements could help govern the choice of waterproofing membrane, provided the system is left exposed. As earlier mentioned, this consideration is left applicable to only carparks since plain RC roofs are generally not required to be aesthetically pleasing due to it being a form of impractical, additional spending. Liquid membranes would be more aesthetically pleasing than preformed ones, since the preferred colouring could be easily customized.

5.1.3 Rooftop garden

a. Types of Flora Present (Intensive and Extensive)

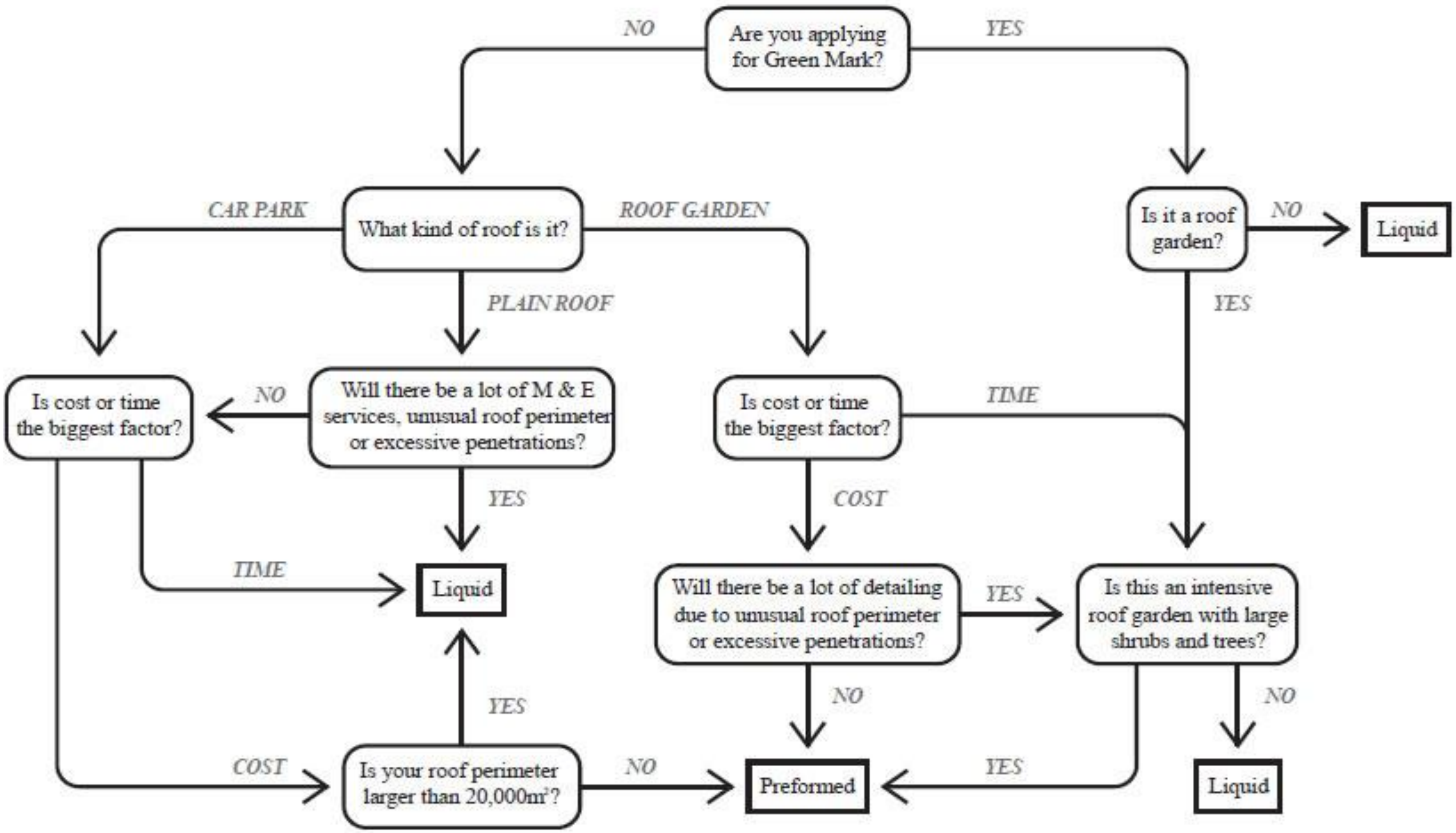
The types of plants to be located on the rooftop garden would affect the choice of membrane. For large flora like trees that are to be planted on the rooftop garden (i.e. Intensive rooftop gardens), the preformed system is strongly recommended. This is so because preformed systems are able to provide the extra security of waterproofing due to the lapping of membranes and it is more resistant to root penetration, unlike the liquid membranes. On the other hand, rooftop gardens or green roofs planted with small vegetation like shrubs and grass (i.e. Extensive rooftop gardens) are recommended to use liquid membranes due to its light weight on roof, and since these plants do not usually produce large roots, there is little concern over the membranes getting destroyed due to root and rot issues.

b. Pedestrian Use

Depending on the usage of the roof, the requirements to resistance differs. For example, as earlier mentioned, carparks would require a traffic deck-like system designed to provide added level of protection to heavily trafficked areas such that the membrane is made to withstand excellent impact, abrasion and puncture. These would relate to characteristics such as tensile strength and elongation. Since the requirements are not as strict for less severe cases such as moderate human traffic, both the liquid and preformed are capable of handling low to high foot traffic.

5.2 Decision Structuring

To better establish the relationship between the factors and the system selection, the following flowchart was derived.



5.3 Selection Guide

Having derived the flow of the questions, it was converted to a less tedious checklist guide. The selection guide was formulated such that it addresses all the main factors of consideration (as discussed in the earlier chapter) in a straightforward manner. It specifically avoided unnecessary or lengthy descriptions/questions and evaded the process of having to deal with heavy technical terms. The bypassing was made possible since the technical characteristics of the systems were analyzed beforehand, so as to relate the requirements of a project directly to the system selection. As such, the guide provides a simplified rendition of the complex decision-making an expert is required to make. By abiding to such concrete guideline, it is not only time-saving but also helps ensure that an appropriate waterproofing system is being put in place – The user of the checklist is merely required to answer quick, simple and short questions, without having to be burdened by technical terms, to decide on a system most appropriate.

In brief, the steps to using the selection guide may be summarized as such:

1. Sectionalize the roof according to the different requirements/usages (if required)

2. Using the appropriate guideline, answer the questions by filling the bubble(s) accordingly.
   For example, the checklist would appear to be…

Function of roof - Rooftop gardens	**Liquid**	**Preformed**
Type of application		
New application	●	●
Remedial Works	O	O
Roof Size		
< 20,000 m2	O	O
20,000 - 40,000 m2	O	
> 40,000 m2	●	
Roof Perimeter		
Regular shape	●	●
Irregular shape	O	
Level of detailing		
High	●	
Low	O	O

If the new roof is intended to be a rooftop garden of size greater than $40,000m^2$, with a squared shape perimeter of high detailing due to the presence of excessive joints.

3. After working down the list of questions, total up the number of filled bubbles for each system. The system with a greater number of filled bubbles would be the system suggested. Should there be a tie, one may also consider the use of a combined system of both liquid and preformed, as appropriate.

The target users for the checklist are the contractors. One may argue that the contractors have experience relevant enough to not rely on such guidelines. However, judging from the many waterproofing defects commonly witnessed, it proves to show that it is insufficient to generally rely on experience, or gut feeling of the contractors. To select a right waterproofing system is crucial and this selection guideline could, at the very least, help contractors affirm, if not influence, their decisions made.

Appendix B provides the selection guideline for different function of roofs and Appendix C presents the specifications of the products for the users to help them better decide on the specific product to use when they have derived a suitable system from the primary checklist.

Chapter 6: Conclusion

A comprehensive selection guide was formulated after extensive literary research and in-depth interviews with experienced local suppliers. A decision flow chart which encompassed the major considerations in the selection of the most appropriate waterproofing system for a specific roof function was used in the derivation of the selection guide.

It is clear that the decision for a waterproofing system is an extremely important one, and includes many complexities, including the current availability of the product in Singapore. Despite this, the developed selection guide can be a crucial tool, along with its accompanying sheet of detailed performance specifications of both common liquid and preformed waterproofing membranes utilized in Singapore.

6.1 Evaluation of selection guide

The selection guide provides a simple and clear-cut interface that can be easily used by both professional and amateurs. Users of the selection guide can not only indicate, according to the specifications of a particular roof function, their requirements in the checklist, but also are able to rightfully justify their selection of best waterproofing alternative to their clients, especially when the cost, as revealed by the interviews, is a major concern. With the provision of the selection guide, the whole life cycle costing of a waterproofing system is also taken into account so as to facilitate future maintenance, replacement or repair during the operation of a building. This would in turn, help the users in evaluating the most cost-effective waterproofing system for their building of interest.

However, the performance specifications of the different waterproofing systems as well as waterproofing materials can differ from supplier to supplier. This is due to the competitive nature within the industry that encourages suppliers to improvise new technologies in order to possess a competitive edge over their competitors in the market. Therefore, the performance specifications provided in the selection guide can only be taken as a generic guideline, which may be subjected to changes in areas such as the composition and properties of the materials used that can ultimately affect the performance of a particular waterproofing system.

6.2 Significance of study

This paper helps to set a basis for the development of a more complex and comprehensive software that may be used for the selection of waterproofing systems for roofs. By developing a system that incorporates many other significant factors featuring the contributing elements to a successful or failed waterproofing system, users of the software are able to simulate the effects of using the different types of waterproofing systems on different types of roofs. Uncertainties, for example, the deterioration rate of a waterproofing system, whether is it exposed to extreme weathering or due to improper usage of the roof, could also be verified with the use of the software to suggest the time period for maintenance as well as replacement.

Crucial areas can also be identified so that the integration of different waterproofing systems on a single roof can be made possible and introduced to the industry for consideration, since the concept of doing so is less seen today.

6.3 Recommendations for future research

Further research on these factors of consideration may be tested out with an increased sample size of experts. With a greater number of respondents, more meaningful comparisons can be made by analyzing the results according to aspects such as the organizational backgrounds of the respondents, types of project and so on. This will in turn provide for the development of a more applicable toolkit.

If time permits, future research can also include the other project participants in the industry, such as the subcontractors and manufacturers to involve a broader scope of perspectives to develop an even more comprehensive and complete list, which can not only cover flat roofs, but roofs of all shapes and sizes.

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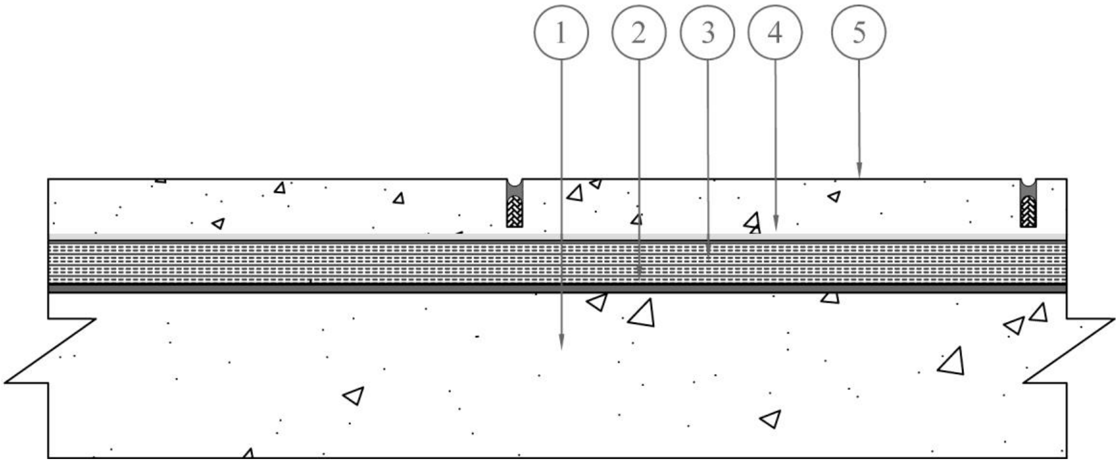
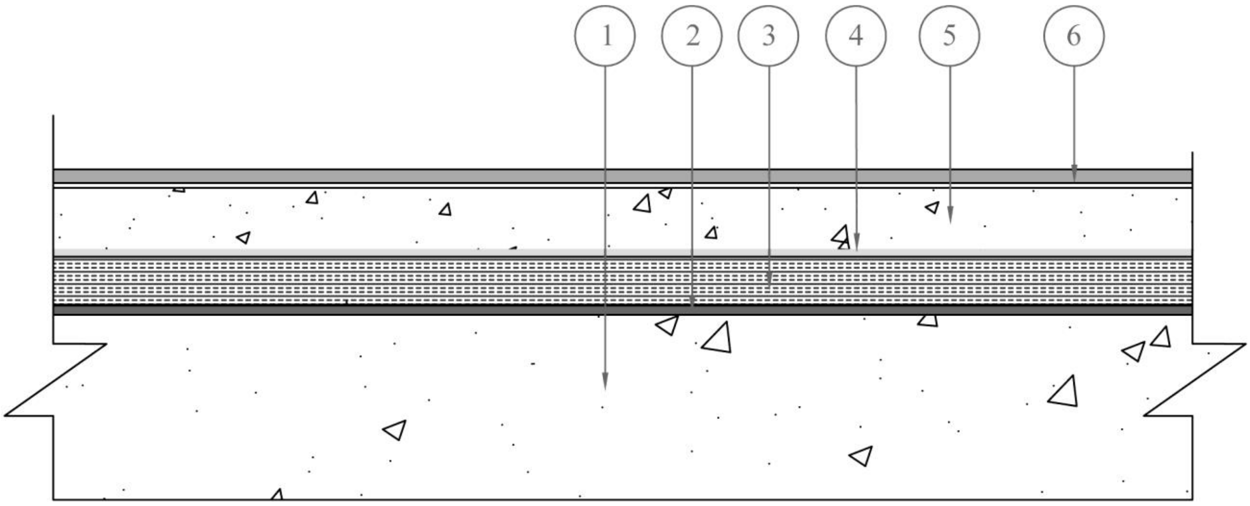
Appendix A – Construction Details

Typical waterproofing detail – Polyurethane membrane



1. RC Slab
2. 1.3mm polyurethane waterproofing membrane
3. 50mm extruded polystyrene insulation foam
4. Geotextile separation layer
5. 50mm concrete protective panel

Typical waterproofing detail – exposed Acrylic membrane



1. RC Slab
2. 1.3mm polyurethane waterproofing membrane
3. 50mm extruded polystyrene insulation foam
4. Geotextile separation layer
5. 50mm concrete protective panel
6. Liquid applied acrylic waterproofing membrane

Source: FOSROC

Appendix B – Selection Guide

Function of Rooftop – Plain Roof		Liquid	Preformed
Type of Application	New application	○	○
	Remedial works	○	○
Roof Size	< 20,000 m^2	○	○
	20,000 – 40,000 m^2	○	
	> 40,000 m^2	○	
Roof Perimeter	Regular shape	○	○
	Irregular shape	○	
Level of Detailing	Low	○	○
	High	○	
Exposure of Waterproofing System	Concealed	○	○
	Exposed	○	
Expected Life Span	5 years warranty	○	○
	10 years warranty	○	○
	20 years warranty	○	
Application Time or Waterproofing System	750 m^2 / day		○
	1000 m^2 / day	○	
Budget	\$20 - \$40 / m^2		○
	\$40 - \$60 / m^2	○	○
Environmental Considerations	Green Label approved	○	
Aesthetics	Important	○	

Total		

Function of Rooftop – Carpark		Liquid	Preformed
Type of Application	New application	○	○
	Remedial works	○	○
Roof Size	< 20,000 m^2	○	○
	20,000 – 40,000 m^2	○	
	> 40,000 m^2	○	
Exposure of Waterproofing System	Concealed	○	○
	Exposed	○	
Expected Life Span	5 years warranty	○	○
	10 years warranty	○	○
	20 years warranty	○	
Application Time or Waterproofing System	750 m^2 / day		○
	1000 m^2 / day	○	
Budget	\$20 - \$40 / m^2		○
	\$40 - \$60 / m^2	○	○
Environmental Considerations	Green Label approved	○	
Aesthetics	Important	○	

Total		

Function of Rooftop –Rooftop Garden		Liquid	Preformed
Type of Application	New application	○	○
	Remedial works	○	○
Roof Size	< 20,000 m^2	○	○
	20,000 – 40,000 m^2	○	
	> 40,000 m^2	○	
Roof Perimeter	Regular shape	○	○
	Irregular shape	○	
Level of Detailing	Low	○	○
	High	○	
Exposure of Waterproofing System	Concealed	○	○
	Exposed	○	
Expected Life Span	5 years warranty	○	○
	10 years warranty	○	○
	20 years warranty	○	
Application Time or Waterproofing System	750 m^2 / day		○
	1000 m^2 / day	○	
Budget	$\$20 - \$40 / m^2$		○
	$\$40 - \$60 / m^2$	○	○
Environmental Considerations	Green Label approved	○	
Pedestrian Use	High foot traffic	○	○
	Low foot traffic	○	○
Type of Plants	Small plants [shrubs & grass]	○	
	Large plants [trees]		○

Total			

Appendix C – Waterproofing Products

Attributes	Preformed	
	Modified - bitumen	PVC
Thickness	60 mils	3 in
Flexibility	Unaffected	Not tested
Tensile Strength	250 – 320 PSL	1,600 psi
Elongation	300 %	250 % longitudinal 270 % transverse
Cracking Cycling at - 32ºC, 100 cycles	Unaffected	Not tested
Lap Adhesion at Min Application Temperature	4 to 7 ib / in	Not tested
Peel Strength 16 / in	7.5 to 9	Not tested
Puncture Resistance Membrane (lbs)	40	66.74
Resistance to Hydrostatic Head (ft)	150 to 230	Not tested
Exposure to Fungi in Soil, 16 weeks	Unaffected	Not tested
Root Resistance	No	Yes
Permeance (perms)	0.05 perms	Not tested
Water Absorption (by wt)	0.1 to 0.25	0.11
Suitable as exposed / concealed	Concealed	Exposed & Concealed
Cost	$15 – 20	$30 – 40

Attributes	Liquid	
	Acrylic	Polyurethane
Thickness per coat	0.4 – 1.0 mm	Not tested
Viscosity	Not tested	200 p
Tensile Strength	> 2.0 N / mm^2	1.6 N / mm^2
Elongation	300 – 400 %	500 – 700 %
Crack bridging	5mm maximum	Not tested
Recovery from 200 % elongation	Not tested	95 %
Crack bridging	5mm max	Not tested
Tack free time at 25 ºC	Not tested	15 – 24 hrs
Viscosity	Not tested	200 p
Solids content	62 ±3 %	92 %
Tear resistance	Not tested	10 N
Water vapor transmission	Not tested	9.5
Cost	$30 – 40	$30 – 40