Department of Civil Engineering & Management (CEM)

Bachelor Thesis

Submitted for the degree of

Bachelor of Science

A METHODOLOGY FOR SELECTING WATERPROOFING TECHNIQUES IN UNDERGROUND CAR PARKS FOR PREVENTING GROUNDWATER LEAKAGE

by

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Abstract

Underground car parks face increasing challenges from groundwater leakage, a growing issue exacerbated by rising groundwater levels and intensified rainfall caused by urbanization and climate change. These leaks not only threaten the structural integrity of these facilities but also pose safety hazards, disrupt operation, and lead to substantial financial losses for property owners. Traditional drainage systems and existing waterproofing measures often fall short of addressing the complex and site-specific conditions of preventing groundwater infiltration. As urbanization continues and extreme weather events become more frequent, there is an urgent need for a systematic approach to evaluate and select effective waterproofing techniques.

This thesis aims to address this gap by developing a structured methodology to evaluate and select the most suitable waterproofing techniques for preventing groundwater leakage in underground car parks. The proposed approach employs a Multi-Criteria Decision Analysis (MCDA), supported by the Analytical Hierarchy Process (AHP), to compare alternative solutions systematically. The methodology introduces a set of evaluation sub-criteria, divided into main-criteria: performance, environmental impact, efficiency, and applicability.

To demonstrate the applicability of the methodology, a case study was conducted at P6 Uitgaansdriehoek in Amsterdam, a site facing persistent operational challenges from groundwater infiltration. The study assessed multiple waterproofing solutions, including cementitious, bituminous, and crystalline techniques, using expert surveys to determine the relative importance of criteria and a scoring model to rank the alternatives. The results identified *Sika® Igolflex 301* as the best-performing solution due to its superior waterproofing capabilities and high applicability, *while SikaTop® Seal-107* was deemed the most cost-effective option, offering an optimal balance of performance and cost.

This report provides a practical and adaptable decision-making framework on the selection of waterproofing techniques. While the methodology demonstrates significant promise, areas for future refinement include the incorporation of advanced decision-making models, such as fuzzy logic systems, and the exploration of new innovative waterproofing materials to enhance durability and sustainability.

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1. Introduction

1.1. Problem statement

Urbanization levels are being expected to rise to 70% by 2050 (Un-Habitat, 2008). This goes hand in hand with the current overexploitation of natural resources (Lampert, 2019), including urban water sources. Depletion and deterioration of fresh water resources by heavy industry caused dropping of groundwater levels in urban areas (Hernández et al., 1997). To break this trend, deindustrialization in urban areas played an important role. Cities have ever since witnessed rising groundwater levels due to this deindustrialization process. Studies also show a correlation between urbanization, climate change and groundwater rise. Global temperature increases due to urbanization, thus increasing atmospheric moisture levels. Consequently, there is a higher risk of extreme weather, such as heat waves, drought, but most importantly heavy rainfall. Not only increase of precipitation amounts is witnessed, but also shorter interval time in between rain storms (Medicine et al., 2016). Poor infiltration levels in urban areas due to high amounts of paved areas cause a high rainfall runoff rate (Hillel, 1998). Consequently, gravitational force enable high percentages of rainwater, unable to infiltrate into the soil, to flow into lower altitudinal areas, such as gutters, uneven paved areas and underground infrastructure. Eventually the rainwater is drained and stored as groundwater. Together with deindustrialization, this is one of the causes of the increase of piezometric levels in urban areas.

Maximizing exploitation of space, vertical urban development also has occurred over the past few decades. On the one hand often witnessed above sea level, underground infrastructure has on the other hand developed drastically to comply with residential and transportation demands. Rising groundwater levels and higher rainfall runoff rates can become a serious threat to this underground infrastructure, such as subways, basements and underground car parks (Attard et al., 2016). Although this threat applies to all underground infrastructure, this report focuses on the consequences on *underground car parks,* see Figure 1.1

Due to water leakage in underground car parks, several underground parking garages real estate managers suffer several problems. Inundation due to water infiltration has serious consequences, such as risk of electrocution and fire. Water penetrates into electrical devices and circuits causing electrical short. Also cars and other valuable items can suffer damage due to water leakage. Not only direct contact with water, but also mold can cause severe damage to construction, health of personnel and visitors, and devices. Furthermore, dropping of visitor rates occur. All this together has a negative impact on the structural integrity of the underground car parks, health of staff and visitors, financial status and turnover, finally creating reputational damage to real estate owners of the car parks.

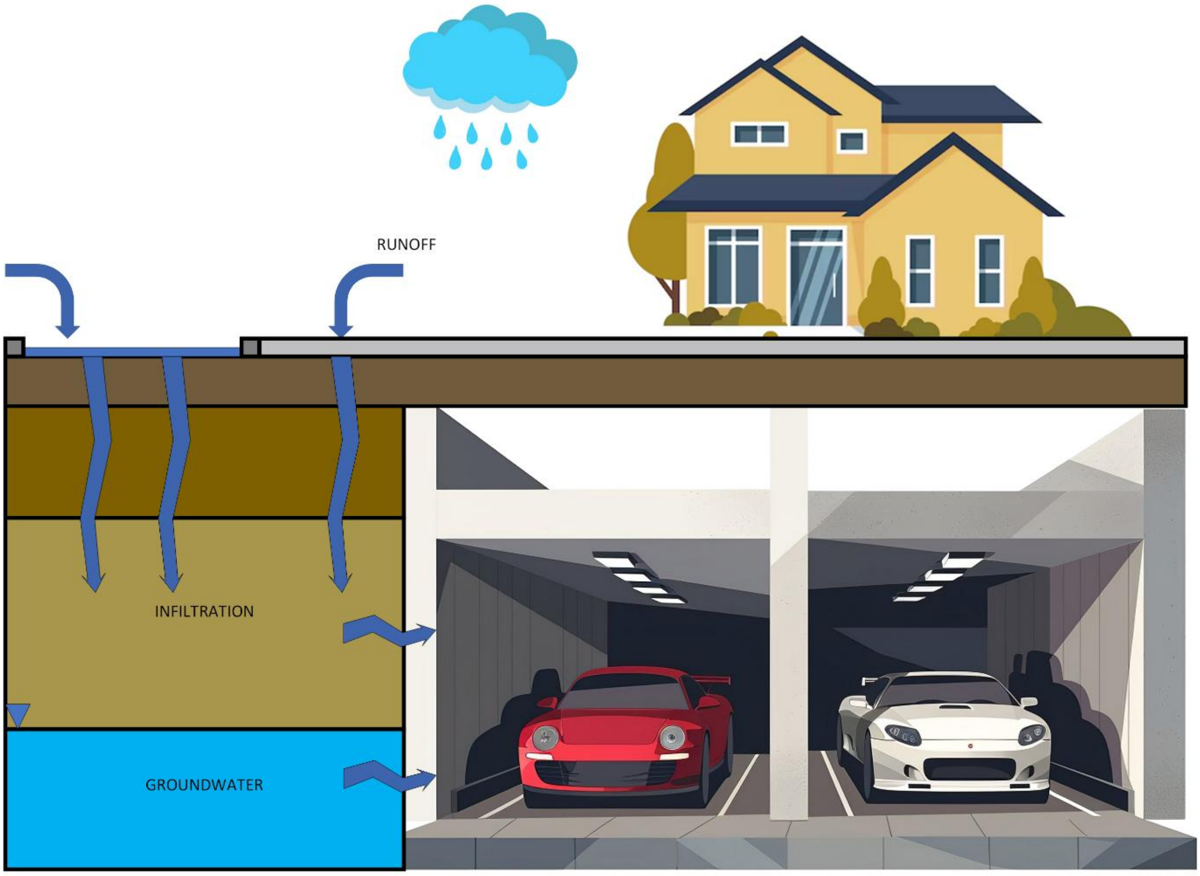

Figure 1.1. Graphical representation of problem statement.

At this very moment multiple measures exist to drain water in underground car parks. These are designed to drain rainwater dripping from just parked vehicles, which is contaminated with e.g. gasoline, oil, coolant or rubber. Also gutters and vortexes are placed to drain water flowing down from ramps. Structural waterproofing agents such as coatings are used to create a hydrophobic concrete or steel structure, ensuring a water repellent environment.

However, several underground car parks still suffer from water leakage. Walhout Group received several requests from real estate managers of car parks to provide counsel on this problem. It has been diagnosed by Walhout Group that the water leakage is caused by infiltration of rising groundwater and excess rainwater runoff. The next step is to research availability of suitable waterproofing techniques and their application in underground infrastructure. This process of selection and elimination implies serious challenges. Various preventive measures are difficult to implement, due to limited available space around the structure of the underground car park, impeding adequate interventions. Additionally, some interventions can become costly, depending on the parameters of the case study. Also chemical properties of coating agents prohibit excessive use in public spaces (Xue et al., 2017). To conclude, the problem can be formally stated in the following way:

At the moment, a methodology for selecting the best fit waterproofing design technique to prevent groundwater leakage in underground car parks is missing.

1.2. Research aim and objectives

The research aim of this thesis can be formulated as follows:

To evaluate waterproofing techniques to prevent groundwater leakage in underground car parks.

The research aim can be translated into four different objectives:

- *Carry out a literature study on waterproofing techniques, performance criteria and decision-making analysis;*
- *Develop a methodology for evaluating the most fitting waterproofing techniques;*
- *Select and provide information on a suitable case study and demonstrate the application of the proposed methodology to it;*
- *Provide recommendations based on results of case study and limitations of proposed methodology, which drives discussion and draws a conclusion.*

1.3. Scope

This Bachelor Thesis focuses on evaluating different waterproofing techniques to prevent water leakage in underground car parks. Firstly, a literature study has been carried out to critically examine the state of the field of the introduced problem, and to gather data needed to develop this thesis. This includes studies on decision-making management, waterproofing techniques, performance criteria, etc. A methodology will be developed to support the research aim. It should be said that this methodology is to be considered as a general approach to evaluate waterproofing techniques for any given situation. One case will be studied in the thesis, after which the proposed methodology will be applied to the case.

Based on the results of the MCDA, a recommendation will be given as a most suitable solution to prevent the stated problem. This thesis does not examine the cause of the water leakage, nor does it provide a diagnose of the problem. It is assumed, based on examination done by Walhout Civil and literature study, the water leakage is solely caused by groundwater and excess rainfall runoff leakage due to climate change and global urbanization (She et al., 2018). Lastly, due to limited access to stakeholders, no stakeholder analysis is included in this report. Instead, 8 experts working at Walhout Group function as stakeholder representatives by filling in criteria weight surveys.

2. Literature study

2.1. Hydrophobic surface treatment

Since Portland Cement Concrete (PCC) is naturally a hydrophilic material (Monteiro et al., 2017), water spontaneously fills the pores of concrete and penetrates deeply into its structure. This can cause severe damage to the structure of concrete, as penetrating water could transport chemicals into the pores, potentially initiating corrosion due to chlorine and sulfate attacks, as well as affecting the steel reinforcements, initiating rust forming (Y. Li et al., 2019). Rust occupies a greater volume than concrete, resulting in expansion and tensile stress. Cracks and delamination of concrete are consequences of this increase in tensile stress. This all together has a negative effect on the structural integrity of the concrete and decreasing its durability, as well as initiating water leakage through cracks, emphasizing the need for a hydrophobic surface treatment. Different methods for concrete super hydrophobic or hydrophobic treatment are currently introduced in literature. The water absorption rate is dependent on the Water Equilibrium Contact Angle (WECA, θ_e). The Contact Angle can be described by the Classical Young´s equation and can be seen in Figure 2.1, which is given as (Adam, 1957):

$$\gamma_{sv} - \gamma_{sl} = \gamma_{sl}\cos(\theta_e) \quad (1)$$

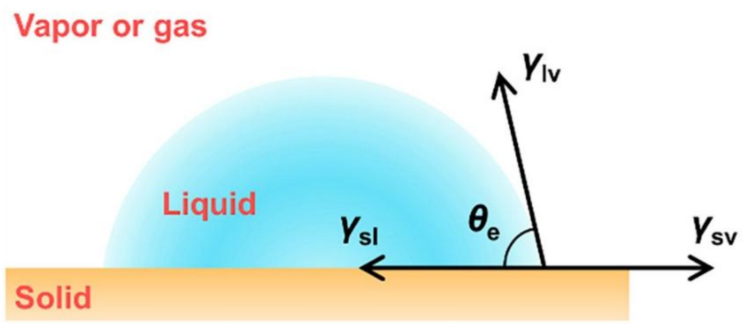

Figure 2.1. Illustration of the equilibrium contact angle formed by a certain vapor-liquid-solid system (Song & Fan, 2021).

Assumptions to this equation include the solid surface is glazed, chemically heterogeneous and undissolved. However, as most structures do not present a homogeneous solid surface – concrete being a great example due to the high amount of pores – this equation is much idealized. It is therefore advisable to increase the amount of measurements of the equilibrium contact angle, to be able to obtain a more reliable outcome of the wettability of the surface.

The water contact area can be either hydrophilic ($\theta_e < 90°$) or hydrophobic ($\theta_e > 90°$). Also so called super-states exist, being superhydrophilic ($\theta_e < 10°$) or superhydrophic ($\theta_e > 150°$) (Yao & He, 2014) (She et al., 2018) (Song & Fan, 2021). A graphical overview of these states can be found in Figure 2.2.

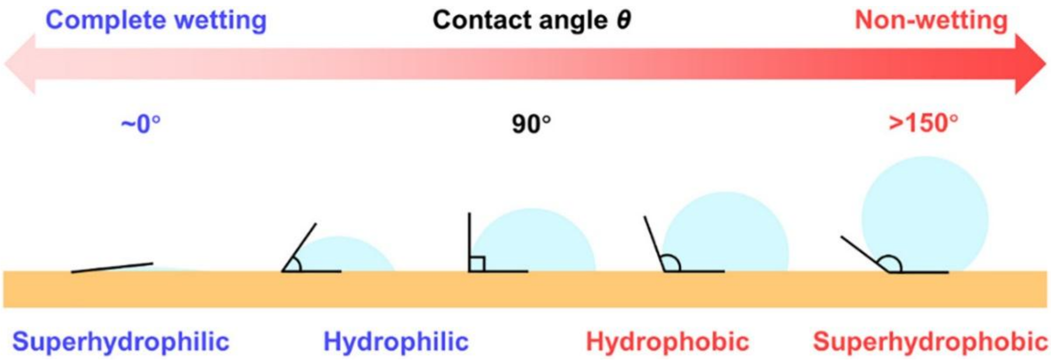

Figure 2.2. Classification of the wettability of a surface using contact angle (Song & Fan, 2021).

To achieve a water repellant surface, a CA θ of at least 90˚ is desired.

2.2. Waterproofing alternatives

Most common agents to achieve a water repellant surface are surface treatment and hydrophobic admixture method. Surface treatment implies the processing of finished concrete. The surface of the concrete is made hydrophobic by applying (a mixture of) coating agents. Coatings can be applied by respectively brushing, spraying, impregnation, etc. (Wang et al., 2020)

Most coatings consist of a mixture of silane/siloxanic resin. A study by She et al. (2018) fabricated and analyzed a superhydrophobic surface on concrete by applying nano-silica gel. This gel consists of a mixture of N-propyltrimethoxysilane (NP) and polymethyl-hydrogen siloxane oil (PMHS) with silica nanoparticles. The application of this coating resulted in a contact angle CA of 162˚, ensuring superhydrophobic properties of the concrete. Outstanding for this study is the combination of process simplicity, breathability and coating durability, which has not been reported for superhydrophobic studies: ´´*This exceptional water repellent offers advantages of simplicity in fabrication, high adaptation to a cement-based substrate, cost-effectiveness, self-breathability, and applicability to a large area surface* (She et al., 2018).´´

However, other studies show using silica nanoparticles is not quite a cost-effective solution, preventing increased application in construction (Pacheco-Torgal & Jalali, 2011). Recently, studies aim to seek for a replacement of silica nanoparticles. A study by Husni et al. (2017) investigates feasibility of the use of rice husk as nanoparticles in coating. Rice husk ash, being naturally rich in silica as a by-product, contains more than 90% of amorphous silica, which serves as an excellent replacement for synthetic silica nanoparticles (Simanjuntak et al., 2025). A mixture of rice husk ash and fluoroalkyl silane is applied to the concrete with help of a ethanolic solution, to ensure successful forming of a superhydrophobic coating. Measuring the CA of the concrete surface resulted in a θ = 152˚, being a theoretically proved superhydrophobic coating. The coating reduced water absorption up to 40.38%. It should be noted that this coating, although reducing water absorption, did not fully prevent it. The study suggests that increasing the number of ash coating would further improve the coating.

Another major drawback of silica-based nanoparticle agents is the breathability of the concrete. Although literature suggest advantageous aspects, it allows water vapor to enter the pores of the concrete, overtime creating (minor) water leakage (Tittarelli & Moriconi, 2008). Especially when there is an outside hydraulic head difference, excessive pore pressure due to rising groundwater can contribute to this water leakage. Pore pressure of water present at the concrete surface has to be closely monitored, as well as establishing certain boundary conditions to be able to examine the feasibility of silica-based nanoparticle agents. Studies also show potential toxicity due to human absorption of nanoparticles. Symptoms can be compared to those caused by asbestos inhalation, such as lung inflammation and DNA damage, resulting in later cancer development (Pacheco-Torgal & Jalali, 2011). Extreme caution is therefore recommended, as there is a lack of literature regarding this subject (Singh et al., 2009).

To further bring down costs of hydrophobic agents, replacements for silanes or siloxanes nanoparticles have been further investigated. Studies have examined the effectiveness of mortar surface treatment, impregnating the concrete surface with alkyl-alkoxy-silane. However, successful performance does not seem self-evident. Literature investigating alkyl-alkoxy-silane as hydrophobic agent is either quite outdated (Gislason, 1999) (Wong et al., 1983), or does not provide adequate evaluation of performance. There exist one study by Xue et al. (2017) that investigates the waterproofing performance and chloride resistance of a silane-replaced agent. In this study, the water repelling performance of waterborne systems as impregnation is investigated. Opposed to coating, impregnation offers cost-effective benefits, as it does not interrupt construction work. Furthermore, appearance of concrete is less affected, which can be an essential criterium. The study highlights significant suppressing of water absorption by the hydrophobic agent, as well as having great thermal and acid resistance. The coating also significantly reduced chloride ion penetration, thus postponing corrosion initiation. However, relative low penetration depth of the waterborne hydrophobic agent, primarily due to large micelle size, causes a small barrier for outside chemicals. This results in a higher risk of early malfunction of the hydrophobic agent, decreasing durability of the concrete.

Finally, ensuring a hydrophobic surface of concrete, hydrophobic agents are added to the admixture of concrete. Studies show a significant decrease in water absorption during tests, reducing it to almost 0% (Al-Kheetan et al., 2018). In this study by Al-Kheetan, crystallizing minerals were mixed with concrete components during mixing stage. According to this study, using crystallizing minerals instead of silane- and siloxane-based materials, is a more environmentally friendly option. However, compressive strength of concrete with 2% crystallizing agent admixture reduced with 19% compared to non-treated concrete. Studies examined other hydrophobic agents that does not significantly reduce compressive strength, and found out that using sodium acetate 4% even increases compressive strength compared to untreated concrete (Jahandari et al., z.d.) (!). In this case however, due to a hydrophilic contact angle of < 20˚, water absorption rate is higher, which is not desired.

2.3. Criteria

Literature provides a variable set of criteria to rate the performance of silane/siloxane based waterproofing agents. Table 2.1 below gives a clear insight into performance criteria used in literature. The criteria are ranked from top to bottom starting with the criterium supported by the most number of sources and ending with the criteria supported by the least number of sources.

Table 2.1. Criteria to rate the performance of waterproofing agents proposed by literature.

Criteria	Sub-criteria	Symbol	Unit	Source	Nr. of sources	Remarks
Water-proofing performance	***Water Contact Angle***	θ	°	(She et al., 2018) ('Effect of PDMS on the Waterproofing Performance and Corrosion Resistance of Cement Mortar', 2020) (R. Li et al., 2018) (Y. Li et al., 2019) (Zhao et al., 2018) (G. Li et al., 2018) (Wang & Fang, 2015) (Arabzadeh et al., 2017) (Husni et al., 2017) (Song & Fan, 2021)	9	-
	Water absorption ratio	W	$kg/(m^2 \cdot h^{0.5})$	(R. Li et al., 2018) (Al-Kheetan et al., 2018) (She et al., 2018) (Husni et al., 2017) **EN 1062-1**	4	Mass increase divided by exposed surface

				EN 1062-3		
	Water absorption ratio	B	%	(Xue et al., 2017) (Jahandari et al., z.d.) (Tittarelli & Moriconi, 2011)	3	Treated surface water absorption divided by untreated surface water absorption x 100
Durability	***Concrete compressive strength***	-	MPa	(Al-Kheetan et al., 2018) (Y. Li et al., 2019) (Husni et al., 2017)	3	-
	Durability, Tape peeling test	θ (checking contact angle after employing tape on coating surface)	°	(She et al., 2018)	1	-
	Penetration depth of agent	h	mm	(Xue et al., 2017)	1	Guarantees durability
	Durability, weathering conditions	θ	°	(Wang et al., 2020)	1	-
Breathability	***Gas permeability test***	-	g/d*m²	(R. Li et al., 2018) **EN 1062-1**	1	Breathability of concrete surface
Roughness	*Skid resistance*	BPN (British Pendulum Number)	J	(Arabzadeh et al., 2017)	1	

Five performance criteria stand out due to the high number of studies utilizing it or having interesting potential, being respectively:

- *Water contact angle CA;*
- *Water absorption ratio;*
- *Concrete compressive strength.*
- *Tape peeling test*

- *Breathability*

The water contact angle (CA, θ), used to measure the wettability of a concrete surface, is key in measuring the hydrophobic properties of a waterproofing agent. It is therefore a crucial criterion to measure the performance of a waterproofing agent.

Water absorption ratio is linearly related to the measured CA: a low CA ensures hydrophilicity, a high CA ensures hydrophobicity. It seems therefore measuring both the water absorption ratio and water contact angle are redundant. However, as the CA is a highly theoretically idealized equation, reliability of claims on water repellant properties of concrete can be greatly increased by supporting it with empirical tests, such as water absorption ratio. Two different approaches are given to measure water absorption ratio, respectively mass increase of concrete after being immersed into water relative to oven-dried concrete, divided by the exposed surface; and the mass of surface water absorption divided by the *untreated* surface water absorption. Both approaches describe a comparison between treated and untreated concrete surfaces. However, the mass increase divided by exposed surface seems more accurate, as it also takes into account the immersed surface.

Measuring **concrete compressive strength** is a crucial test to assess the durability and degree of safety of the treated concrete. Although waterproofing agents might have a positive influence on water absorption ratio, the structural integrity of the concrete might be damaged. Keeping record on compressive strength of treated concrete and comparing the results to untreated concrete is thus an important criterium to consider. Also the **tape peeling test** is a crucial test to perform. Bond strength ensures adhesion between the waterproofing agent and the concrete surface, creating both performance and durability.

Finally, assessing the **breathability** of the concrete surface is an important factor to consider. Certain coatings do allow water vapor to enter the pores of the concrete surface, creating (minor) water leakage. The amount of water leakage is linearly related to the hydraulic head difference outside of the structure. Increased pore pressure can result in more vapor entering the pores, increasing water leakage (Tittarelli & Moriconi, 2008). Therefore, testing gas permeability is crucial to test the performance of waterproofing agents.

Other criteria brought forward by literature are either rejected for this report due to limited research (nr. of sources <2), or because other tests are already being carried out in its accessory class.

2.4. Decision-management groundwater infiltration

Currently, multiple decision-making procedures exist. Some of these procedures are monetary, such as cost-benefit analysis, some of them take into account other factors, such as social or environmental impact. As there are also non-monetary criteria to be evaluated, such as temperature dependency or chemical resistance (An & Kim, 2023b), performance criteria cannot always be measured in money. Thus, any analysis solely based on cost-benefit will be rejected for this research.

As literature and data produced by Walhout Civil do provide a variable set of waterproofing options to choose from, as well as to some extent performance criteria to score the different options, it would be more convenient to seek for a decision making process that takes into account both monetary (costs of options) and non-monetary criteria. A convenient and suitable approach would be to perform a Multi-Criteria Decision Analysis, or MCDA.

A MCDA is a way of looking at a complex problem with different monetary and non-monetary objectives. The aim is not to take a decision, but to provide an insight into the performance of different options, ranking them from most-preferred to least-preferred. An advantage of this analysis is that it provides a relative rate of importance to each criterion. In this way, performance of options can be analyzed in a systematic and comprehensive way. Additionally, weighting ensures hierarchy in criteria: certain criteria might have a greater impact or importance, hence a higher weight. Another great advantage of a MCDA is the ability to incorporate criteria, despite heterogenous units (Pereira et al., 2019). Especially regarding the context of the problem addressed in this thesis – where both objective and subjective criteria will be considered – a MCDA is convenient option to consider

However, there are also downsides to a MCDA. Despite correct argumentation behind the establishment of the objectives and criteria, scoring the options remains a human choice. This could potentially create a bias element in decision-making, as there is no evidence for the scoring, solely human judgement. Another drawback is the complexity of ''weighing'' the criteria. It can be difficult and time-consuming to estimate weights and scoring the alternatives. However, multiple software exist to execute this process, to minimize time and effort, and reduce the risk of human error.

Although on the one hand literature suggests the major disadvantage of a MCDA is human intervention to score the available options, on the other hand, it could provide excellent insight into performance of different waterproofing techniques. Therefore it is concluded that conducting a MCDA is a suitable and convenient approach for evaluating the most fitting waterproofing techniques.

2.5. Conclusion

Based on the finding in this literature study, the following conclusions are reached:

- The need for a hydrophobic concrete surface treatment, achieving a contact angle CA (θ) of at least 90 ˚.
- The use of silane/siloxanic resin in combination with *silica nano-particles* as a waterproofing agent. This offers excellent water repellant properties (θ = 162˚)

and coating durability. Implementing this technique is however not quite cost effective.

- *Impregnating hydrophobic agents* into concrete surface does not interrupt construction work, making it a cost effective solution. Appearance of concrete surface is minimally altered. Offers great reduction in water absorption. May however not be durable due to low penetration depth, with risks of early cracking and malfunction of the waterproofing agent.
- Applying hydrophobic agents as *admixture* to concrete decreases water absorption rate, but also decreases compressive strength of the concrete. It must be noted that adding hydrophobic agents into concrete admixture implies a surface treatment during construction. Although offering great waterproofing opportunities prior to/during construction, it does not fit in the scope of this report to offer the use of this treatment, as the case study implies an already existing underground parking garage.

Based on the documented amount per criterion and classification relevance, the following criteria will be used for this report:

- Water Contact Angle;
- Water Absorption Ratio;
- Concrete Compressive Strength;
- Bond strength;
- Breathability.

To be able to select the most suitable waterproofing technique for underground car parks, a fitting decision-making model has to be used. Based on the literature study, conducting a MCDA is the most convenient way to achieve this aim.

3. Case study

A case study is introduced to demonstrate the developed methodology. The study area of this Bachelor Thesis is ‘’P6 Uitgaansdriehoek, located at Corridor 15, Amsterdam. This parking garage is located in the South-East of Amsterdam, as can be seen in Figure 3.1 and Figure 3.2. This area is home to Pathé Arena, AFAS Live, Ziggo Dome, Shopping Centre Amsterdamse Poort, Hilton Arena Boulevard and the Johan Cruijff Arena. It is known as a busy area, especially during football games played at the Johan Cruijff Arena and events at AFAS Live and Ziggo Dome. Consequently, the parking garage has a high social and financial demand, thus potential problems concerning the parking garage have to be taken serious.

Figure 3.1. P6 "Uitgaansdriehoek" relative location, indicated by red circle.

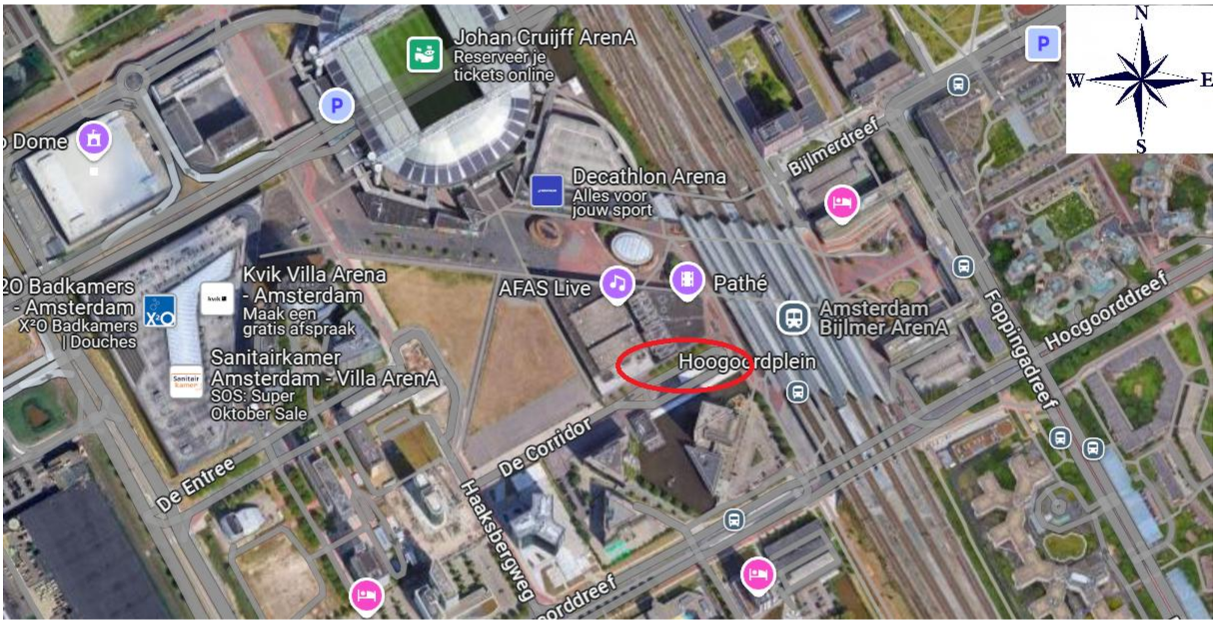

Figure 3.2. P6 "Uitgaansdriehoek" location, indicated by red circle.

The surrounding environment of P6 is non-saline. According to the soil quality chart Amsterdam Arena (Municipality of Amsterdam, 2022), the present chemical substances in the soil do not exceed standards for the destination plan, which is *agricultural/nature*, see Figure 3.3.

Bodemkwaliteitskaart Gemeente Amsterdam 2022
Berekende waarden 1,0 - 2,0 m-mv (in mg/kg)

Zone 1 Humus 5,62%, lutum 6,68%	**Laag 1,0 tot 2,0 m-mv**						**Bodemkwaliteitsklasse (gem.):** **Kwaliteit bij ontgraven (P80):**				**Landbouw/natuur** **Landbouw/natuur**		
Stoffen	N	Min	P5	P50	P75	P80	P90	P95	P99	Max	Gem	VC	HI
Barium	1164	10	30	54	57,25	76	119	173,85	479,43	868	72,69	1,10	NVT
Cadmium	1164	0,05	0,15	0,24	0,24	0,24	0,32	0,47	0,83	2,06	0,26	0,59	0,03
Cobalt	1164	0,76	3,7	7,4	9,1	9,94	12,27	15,1	26,45	83,10	8,47	0,62	0,07
Koper	1164	1,60	6,1	7,2	13,9	16,14	25,34	37,47	109,95	1303,40	16,12	3,20	0,21
Kwik	1164	0,03	0,04	0,05	0,1	0,12	0,23	0,42	1,87	20,11	0,14	4,50	0,01
Lood	1164	3,89	10	11	25	31	57,7	100,85	265,11	1159,09	30,51	2,30	0,19
Molybdeen	1164	0,35	0,35	1,05	1,05	1,05	1,05	1,5	2,44	24	0,88	0,97	0,01
Nikkel	1164	2,98	8,2	17,8	22,63	23,74	29	35,43	53,28	113,8	19,38	0,48	0,42
Zink	1164	8,00	29	33	69,04	81	122,4	178,85	486,33	3559	71,21	2,01	0,26
PAK	1164	0,03	0,07	0,35	0,44	0,56	1,3	3,18	22,74	345,14	1,48	7,89	0,08
Minerale olie	1164	0,00	26	100	123	123	188,5	321,8	819,98	11500	142,98	3,20	0,06
PCB (som7)	1164	0,00	0,002	0,025	0,025	0,025	0,025	0,04	0,11	0,31	0,02	0,99	0,04

Figure 3.3. soil quality chart Amsterdam Arena. (Municipality of Amsterdam, 2022). Calculated values 1,0 – 2,0 m-mv (in mg/kg).

The figures below depict one of the witnessed water leakages in P6.

Figure 3.5. Water leakage P6.

Figure 3.4. Water leakage P6, zoomed in.

4. Methodology

In order to adequately perform a multi-criteria decision analysis, different steps should be taken. A general overview of the applied methodology in this report can be found in Figure 4.1. In the following sections, every phase is consecutively introduced and explained.

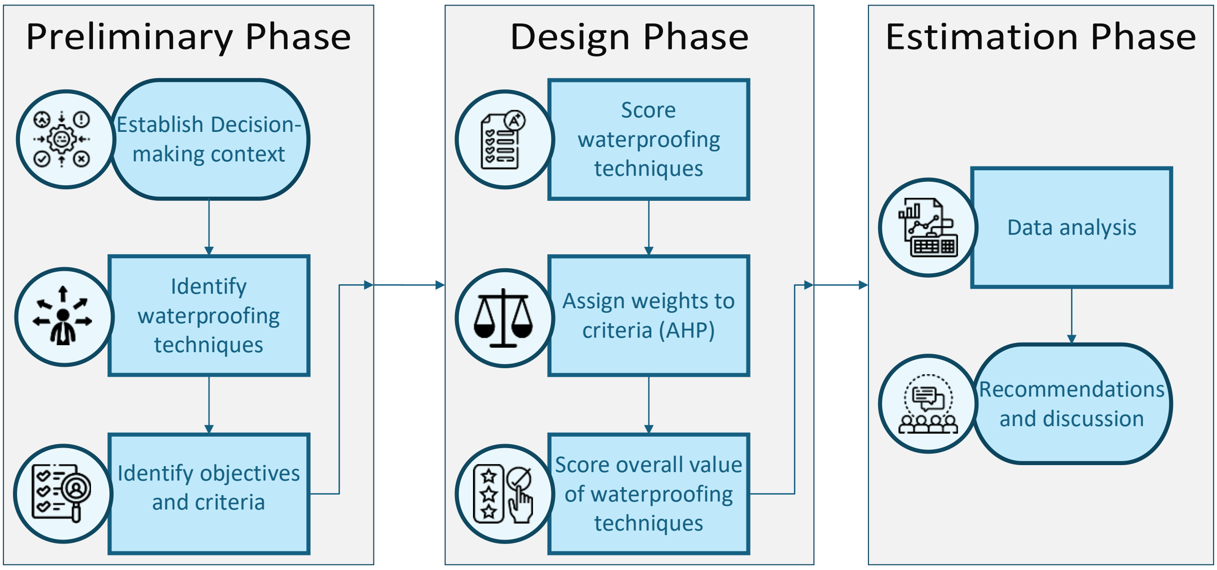

Figure 4.1. Proposed methodology.

4.1. Preliminary phase

As displayed in Figure 4.2, firstly decision-making context is established. This part can be found in Chapter 1, Problem context. To examine the further context of waterproofing techniques, a literature study has been carried out. In here, hydrophobic surface treatment is elucidated, explaining the theory behind the methods of hydrophobic surface treatment. Also, several waterproofing options brought forwards by literature are introduced and explained, as well as complementary pros and cons. The availability of these products is then checked on the market. Some of the options suggested by literature may be costly or difficult to implement, imposing unnecessary barriers when implementing the waterproofing technique, and may thus be rejected from the MCDA. After this reciprocal analysis is completed, a selection of waterproofing techniques is proposed.

Additionally, an overview of criteria to assess the waterproofing techniques introduced in literature is given. Performance criteria is accepted or rejected based on documentation (number of sources using it) and relevance to the scope of the report. Furthermore, additional criteria are introduced by expert interviews, done internally with several experts within Walhout Group. Lastly, certain criteria can be rejected due to limited product documentation. Although limited information of market products regarding certain criteria cannot be entirely avoided, yet a complete and fully documented scoring model should be strived for.

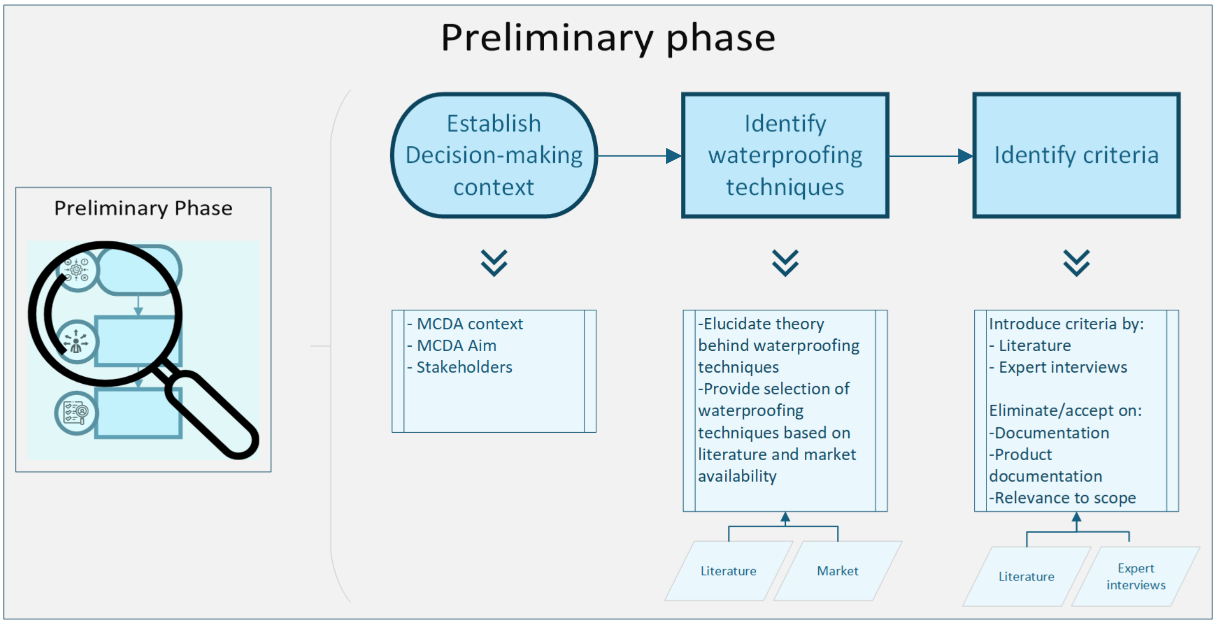

Figure 4.2. (zoomed in) Preliminary phase.

4.2. Design Phase

After the options and criteria have been established, the Design phase is introduced, see Figure 4.3. The aim of this phase is to create a convenient scoring model and accurate weights of criteria, to give a representative benefit-score to each option. The phase starts with creating a performance matrix, in which the options are scored on the introduced criteria, based on product documentation. Additionally, the consistency of the criteria is checked. This avoids the use of unreliable and unverified data. In case of unreliable or incomplete data, the usage of certain criteria or waterproofing options may be rejected. After this step, a final choice of criteria and waterproofing options is given, displayed in a hierarchical objective-criteria tree, to ensure a comprehensive overview of objectives and criteria.

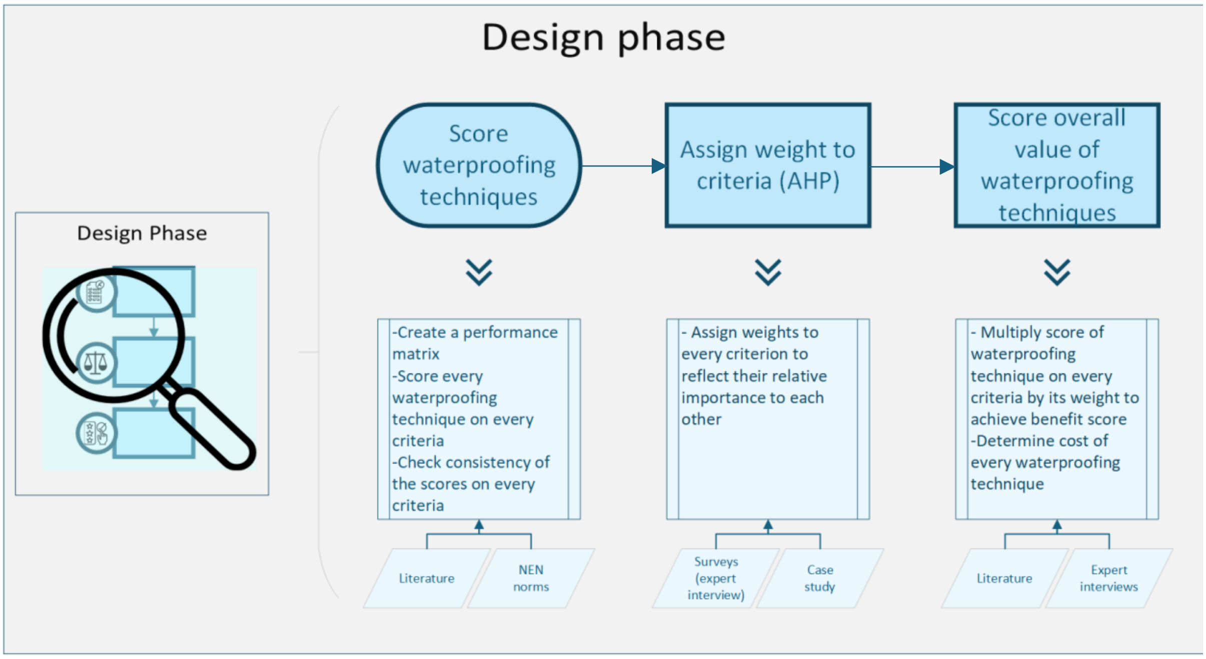

Figure 4.3. (zoomed in) Design phase

To translate the heterogeneity of the scores of each option into a homogeneous unit (0-100), three different performance assessments are used, respectively: Component Value Assessment, Direct Rating, Absolute Rating. Depending on the class of each criterion, one of these performance assessments is chosen, see Table 4.1. Overview of different performance assessments.Table 4.1.

Table 4.1. Overview of different performance assessments.

Performance assessment	Criteria class	Documentation	Objective/subjective	Reliability
Component Value Assessment(CVA)	(Non-linear) numerical criteria, officially documented (NEN-EN)	Officially documented (NEN-EN)	Objective	Very high
Direct Rating (DR)	Subjective criteria, undocumented	Undocumented (preferable: expert rating)	Subjective	Low
Absolute rating	Binary criteria, documented	Officially documented (NEN-EN),	Objective	High

As Direct Rating is highly subjective, it is strived for to minimize this performance assessment for this report.

4.2.1. Analytical Hierarchy Process (AHP)

The importance of certain criteria might be greater than other criteria, thus a suitable approach has to be identified to ensure relative weights of criteria. However, weights of criteria are usually determined by stakeholders. This is outside the scope of this research. Instead, weights are determine by up to 8 experts working at Walhout Civil, each having its own expertise. While also creating a basic representation of stakeholders, these experts all have background knowledge concerning the case study, and use this knowledge while determining weights.

Weighing criteria is done by using the Analytical Hierarchy Process (AHP). This approach, which has been introduced by Saaty (1987), describes a method to use both psychological and mathematical components to ensure a representative weight for each criterion. As ranking of criteria is a highly-subjective process, its success rate relies on the degree of human expertise and their interpretation of linguistic variables (Shapiro & Koissi, 2017). To ensure this, two expert interviews have been conducted (in form of surveys), to establish weights for criteria and sub-criteria.

The strengths of the AHP method lies in its ability to incorporate both quantitative and qualitative criteria. This ensures a broad range of criteria, such as monetary, social and technological concerns. It also decreases bias, as pairwise comparisons force decision makers to make a relative choice of importance between the pairs, with no other factors influencing the decision. AHP also may assist in decision-making as choosing between a wide range of criteria at once is prone to missing essential criteria or balancing them incorrectly (Issa et al., 2022) (Abadi et al., 2025).

The major drawback of the AHP method is its mathematical complexity, as it makes use of relatively complex matrix algebra to calculate the relative weight per criterion. It could make it difficult to use and understand for non-experts. Additionally, increasing the number of criteria involved increases the pairwise combinations with 0,5n(n-1), where n is number of criteria. This exponential relationship makes it laborious to incorporate a high number of criteria, as it is time-consuming to answer all accessory pairwise questions. Lastly, changing, eliminating or adding criteria or options influences the weights of the criteria. This demands a new weighing round, being once again rather time-consuming.

Although its drawbacks, the AHP method is a suitable and convenient approach to weigh the established criteria in this study. It incorporates both the present quantitative and qualitative criteria as one homogeneous unit, and is relatively easy to use for non-experts. To reduce its mathematical complexity, a great alternative to the eigenvector method is the use of the geometric mean of the rows of the matrix to calculate the weights of the criteria. Finally, to reduce the time to pairwise-assess all criteria at once, the criteria will be split up into main-criteria, and for each main-criteria accessory sub-criteria.

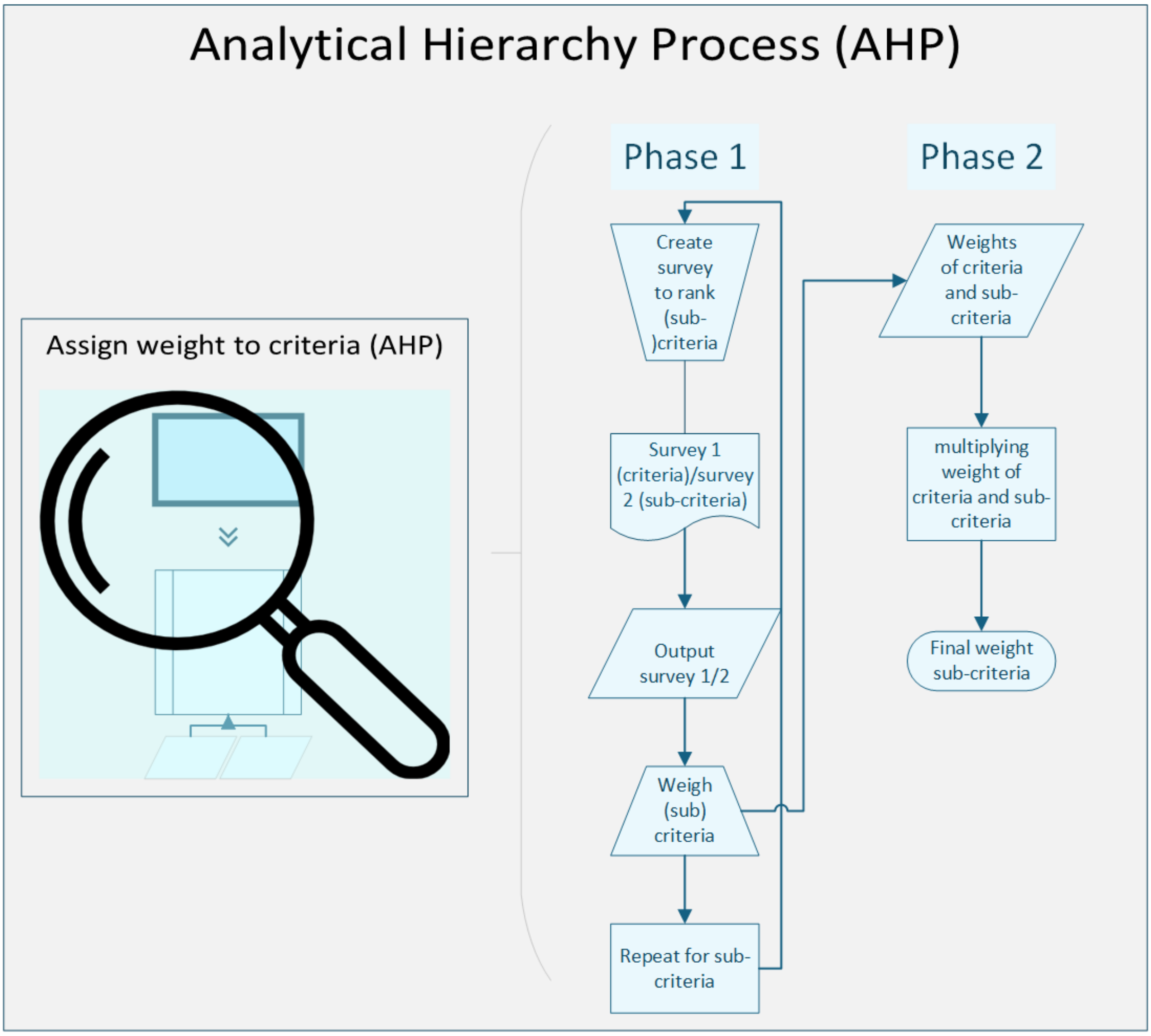

Figure 4.4. (zoomed in) Analytical Hierarchy Process (AHP).

In the flowchart in Figure 4.4, an overview of the AHP method can be found. To eliminate a too extensive and complex survey where all different sub-criteria are compared pairwise, a hierarchy in the form of an upside-down tree is ensured.

Sub-criteria are grouped in criteria-categories, so called main-criteria. Survey 1 is created to rank these main-criteria relative to each other. These rankings are then translated into weights per main-criterion. After these weights are determined, the ranking of sub-criteria per main criterion is assessed in survey 2. Once again, these rankings are translated into weights per sub-criterion. Finally, the weight of the main-criteria are multiplied by the weight of their accessory sub-criteria. The final output is the relative weight of every sub-criteria.

Once the weight of the sub-criteria is determined, the waterproofing options can be scored. This is done by multiplying the score of each option for every criterion by its weight. The final output is then the benefit-score of each waterproofing option.

The last step to take in the design phase is to determine the cost for every waterproofing option. This is done simply as a monetary representative value.

4.3. Estimation phase

Now that the score of each waterproofing option is obtained, the last phase of the methodology is reached: Estimation phase, Figure 4.5. This phase consists of data analysis, discussion of results, and finally a recommendation on the most suitable waterproofing option to use. The data analysis incorporates both the score of the benefits and the cost of each waterproofing option, displayed in an adequate graph. With help of a drawn Pareto front, the best waterproofing option is determined, based on the best combination of cost and benefit. Two recommendations of the most suitable waterproofing option to use will be provided, respectively one including both cost and benefit, and one solely based on benefit score. Finally, a discussion of results is included, to critically evaluate methodology and results, as well as the limitations of the methodology.

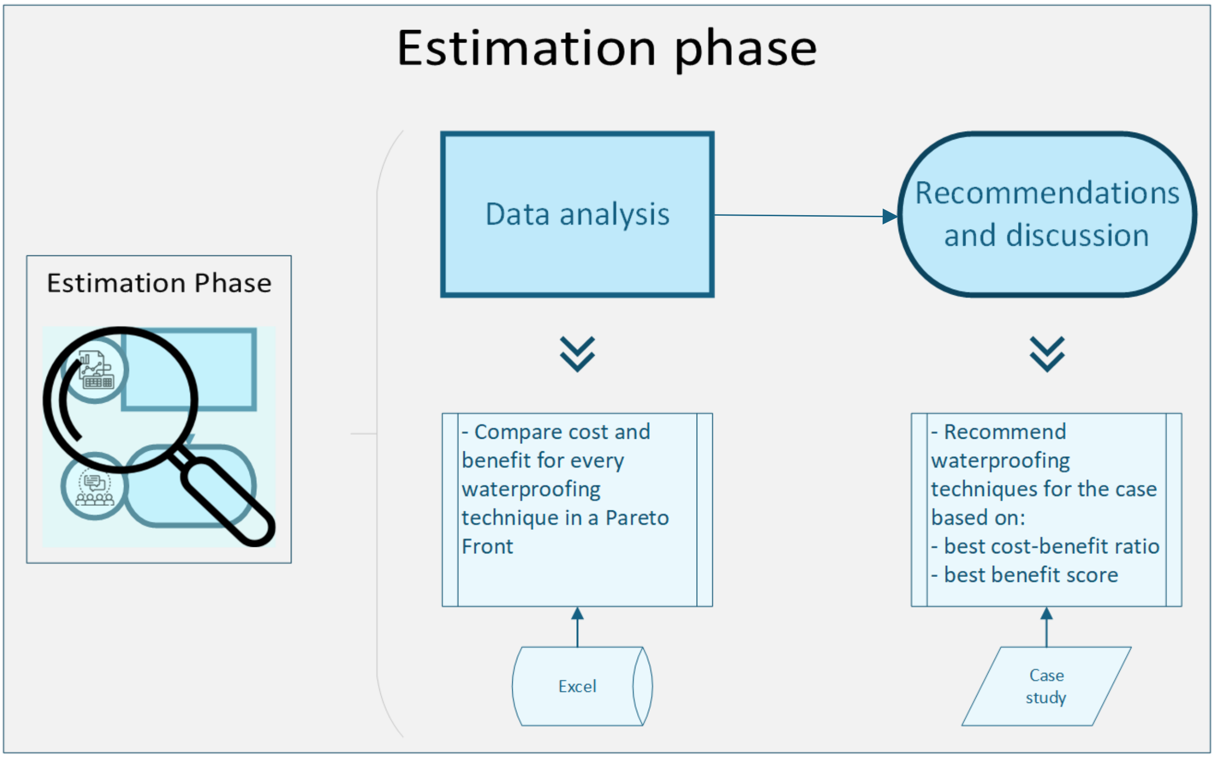

Figure 4.5. (zoomed in) Estimation phase.

4.4. Expected results

-An overview of all considered **waterproofing techniques**.

-An overview of all accepted **criteria**.

- **A performance matrix**. This matrix includes the numerical/linguistic values of every waterproofing technique scored on every criteria. No scores are calculated yet, as criteria weight is not yet determined. From this stage, this matrix is applicable to a great range of scenarios where a choice of a waterproofing technique has to be made to be implemented.

- **Weights of criteria and sub-criteria**. Data assembled by the two surveys are translated into weights for every criterion and sub-criterion. Note that the weights are established based on the case study in P6 Amsterdam, and therefore not applicable for all scenarios, as described in the previous section.

- A **score matrix**, providing an overview of all waterproofing options and criteria and their accessory scores.

- **Benefit scores and cost** for every waterproofing techniques, as well as a recommendation of the most suitable waterproofing technique, based on respectively cost-benefit relation and solely benefit.

5. Results

This section contains the results obtained following the described methodology of this research. The analyzed waterproofing alternatives together with the criteria will be presented, as well as a performance matrix. This matrix includes the numerical/linguistic values of every waterproofing technique scored on every criteria. Furthermore, the weights of criteria and sub-criteria is provided, based on the case study and expert interviews. Finally, a score matrix is presented, as well as the final benefit scores and cost for every waterproofing technique.

5.1. Waterproofing alternatives

Waterproofing techniques will be selected in two different types: surface treatment and impregnation. Based on market availability, reliability of product and frequency of usage, several products have been selected carefully.

Most of the waterproofing techniques for this report are supplied by Sika®. The Swiss company with offices in up to 104 countries is known for its production of excellent products to glue, seal, reinforce and protect concrete. *On 15-01-2025 at InfraTech Rotterdam, the choice for Sika® was validated and ratified by VDB Vochtwering. This company offers a wide range of services in waterproofing concrete, using Sika® products.* An overview of the surface treatment waterproofing alternatives can be found below:

Cementitious:

- *Sikalastic – 1K ES;*
  Product information (Sika.com):
  Mono-component cementitious waterproofing agent, modified with polymers. To be applied, only water is added. Offers excellent prolapsing resistance, crack filling abilities and bond strength.
- *SikaTop Seal – 107 (Polymer-modified Portland cement coating);*
  Product information (Sika.com):
  Two component cementitious waterproofing agent, modified with polymers. Offers good water repellant properties and temperature resistance.
- *SikaTop – 144 (Polymer-modified Portland cement coating);*
  Product information (Sika.com):
  Two component cement coating, modified with polymers. Offers great adhesion to concrete surface, water repellant properties and is not vulnerable to chemical reactions.
- *P3 Industrial (nano-particle based).*
  Product information (exteriorcoatings.com):
  Permanent concrete waterproof and physical protection with only 1 component. Applied to surface by spraying. Offers excellent water repellant properties. Not a filler for cracks in surface.

Bituminous:

- *Sika Igolflex – 201;*
  Product information (Sika.com):
  Two-component bitumen coating. Offers great adhesion strength and resistance against water vapor penetration, as well as crack-filling properties.
- *Sika Igolflex – 301*.
  Product information (Sika.com):
  One component bituminous waterproofing coating. Offers great crack-filling properties and adhesion, together with waterproofing the concrete surface.

Due to low amount of alternatives available on the market, only one **impregnation** agent is analyzed in this report:

- *CEM-KOTE CW PLUS (Crystalline waterproofing agent)*
  Product information (www.wrmeadows.com):
  CEM-KOTE CW PLUS is a one-component (add water only), Portland cement based coating (slurry) containing silica-based materials. Under water pressure (negative or positive), the soluble silicate penetrates (due to osmotic pressure) into the substrate, where it reacts with lime and forms insoluble calcium silicate crystals which "plug" the capillary pores and waterproofs the concrete while allowing water vapor to pass.

5.2. Criteria

The following criteria brought forward in the literature study are accepted for this MCDA:

- *Water absorption rate;*
- *Bond strength;*
- *Breathability*.

During the construction of the performance matrix, it was discovered that several criteria lacked product documentation. (Almost) no information was available on respectively *water contact angle*, *concrete compressive strength* and *carbon emission*. Chosen was therefore to exclude these criteria from the MCDA, to establish a complete and convenient scoring system.

Furthermore, it was decided criteria regarding environmental impact and efficiency should be included being respectively:

- *Toxicity* of the waterproofing technique: the amount of toxic substances in the waterproofing technique and their impact on the overall health of humans and animals.
- *Appearance* alteration of the surface: The extent to which the treated surface appearance changes, e.g., in terms of color, roughness, reflectivity, etc.

- *Application feasibility*: How easy it is to apply the waterproofing technique (e.g., through spraying, trowelling, spreading, etc.).
- *Harden/dry time*: The duration required for the waterproofing technique to harden or dry.

During an expert session at Walhout Group it was suggested to include more criteria on applicability of the waterproofing agent:

- *Temperature application* – to what extent is the waterproofing technique applicable in (extreme) temperature changes;
- *Saline attack* – to what extent is the waterproofing technique resistant to salt, or a saline environment;
- *Pore pressure resistance* – to what extent is the waterproofing technique resistant to increasing water pressure, e.g. capillary rise, increasing groundwater tables;
- *Chemical resistance* – to what extent is the waterproofing technique resistant to chemical substances, e.g. chlorine and sulfur attack.

The final considered sub-criteria, divided into main-criteria are displayed in Table 5.1 below, with accessory unit and assessment:

Table 5.1. Final considered main-criteria and sub-criteria.

Main criteria	Sub-criteria	Unit	Assessment
Performance	*Water absorption rate*	$kg/m^2h^{0.5}$	Component value Assessment
	Bond strength	N/mm^2	Component value Assessment
	Gas permeability	kg/m^2d	Component value Assessment
Environmental impact	*Toxicity*	H-norm	Component value Assessment
	Appearance alteration	-	Direct rating
Efficiency	*Application feasibility*	-	Absolute rating
	Harden/dry time	days, hour	Component value Assessment
Application	*Temperature application*	˚C	Component value Assessment
	Saline attack	yes/no	Absolut rating
	Pore pressure resistance	yes/no	Absolute rating
	Chemical resistance	yes/no	Absolute rating

5.3. Scoring of waterproofing alternatives

In this section, the introduced waterproofing alternatives are scored based on the criteria. The results are displayed in a performance matrix, see Table 5.2 below.

Table 5.2. Performance matrix.

			CRITERIA										
			Performance			**Environmental impact**		**Efficiency**		**Durability**			
			Water absorption ratio	*Bond strength*	*Gas permeability*	*Toxicity*	*Appearance alteration*	*Application feasability*	*Harden time*	*Temperature application*	*Saline attack*	*Pore pressure resistant*	*Chemical resistance*
		Performance assessment	Component value assessment	Component value assessment	Component value assessment	Component value assessment	Direct rating	Absolute rating	Component value assessment	Component value assessment	Absolute rating	Absolute rating	Absolute rating
ALTERNATIVES	**Surface treatment**	*Sikalastic ® - 1 K ES*	0.02 kg/m2h^0.5	0.8 N/mm2	Sd < 5, V > 4.08	H318*	Light-grey, white	Brush, trowel	2-7 days	+5˚C < T < +35˚C	yes	yes	additional treatment
		SikaTop ® Seal - 107	0.0 kg/m2h^0.5	1.25 N/mm2	V = 107	H317, H335, H350, H372*	Non-aesthetic coating	Trowel, brush, spray	2 days	+7˚C < T < +35˚C	Unknown	yes	Yes, avoid aluminium
		SikaTop ® - 144	Unknown	unknown	no vapor barrier, V = 451.656	H314, H317, H318, H335, H350, H372*	Cement-grey	Brush/roller	3 days	+4˚C < T < +35˚C	yes, deicing salt	no	Yes, avoid aluminium
		P3 industrial (silica-nano)	0.0 kg/m2^h0.5	Unknown	Unknown	Unclassified	White, transparant	Spray	1 hour	+2˚C < T < +32˚C	Unknown	yes	Unknown
		Sika ® Igolflex® - 201	0.057 kg/m2^h0.5	unknown	Sd > 117 m, V=<0.17	-	Black/grey	Trowel	2-3 days	+5˚C < T < +25˚C	no	no	yes
		Sika ® Igolflex® - 301	0.0 kg/m2^h0.5	1.5 N/mm2	5 < Sd < 50 m klasse II, V = 4.08	H317*	Black, seamless	Spray, brush	4 days	+5˚C < T < +35˚C	yes	yes	chemicals in soil, groundwater
	Impregnation	*CEM-KOTE CW PLUS*	0.5 kg/m2^h0.5	1.4 N/mm2	1.8 perms, V = 16.3	H314, H317, H318, H335, H350, H372*	Grey, not a decorative material	Spray, brush	5 days	>5˚C	yes	yes	Chemicals in soil and groundwater

*H314, Causes severe skin burns and eye damage. H317, may cause allergic skin reaction. H318, causes serious eye damage. H335, may cause respiratory irritation. H350, may cause cancer by inhalation. H372, causes damage to organs (Lungs) through prolonged or repeated exposure. **All data used to fill in this matrix is derived from the product data sheet coming with every product.

To transform the performance measurements depicted in Table 5.2 into numerical scores, a performance assessment is needed (Table 4.1). For every scored that has to be determined with CVA (Component Value Assessment), a scoring model has been developed. Figure 5.1 displays the scoring model for Water absorption, based on the norms for concrete coatings, paints and varnishes described in NEN-EN 1504-2:2004 en. The scoring models of the other criteria that use CVA can be found in Appendix C – Component value assessment sub-criteria.

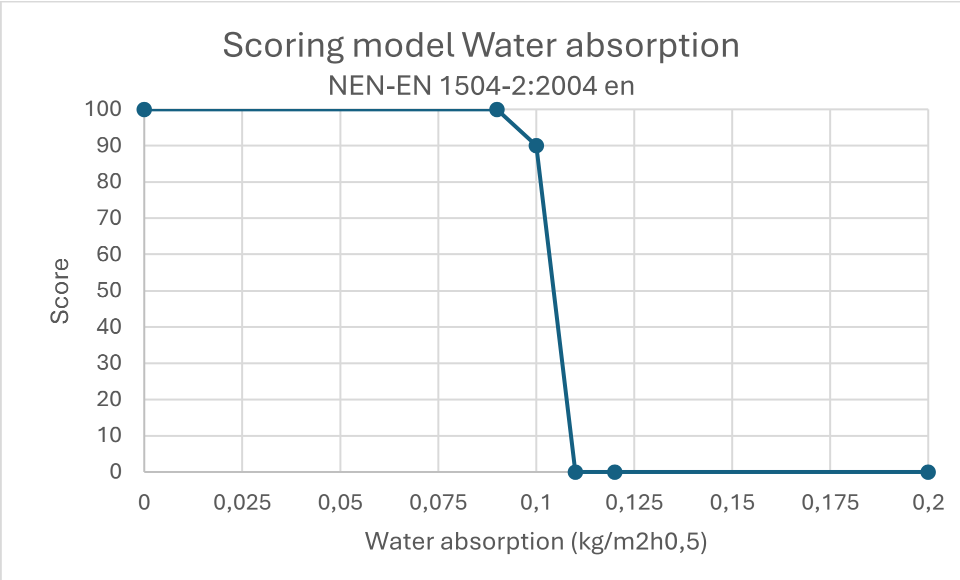

Figure 5.1. Component Value Assessment Water absorption.

As the criterion *appearance alteration* is a highly subjective criterion and no performance assessment is available, this is the only criterion that uses direct rating to be determined.

5.4. Weight of criteria

Furthermore, the weights of the criteria have to be determined to ensure hierarchy between criteria. The pairwise-combination surveys and the results used to determine the weights can be found in Appendix A – survey 1 and Appendix B – Survey 2. Extensive weight calculations can be found in Appendix D – Criteria weight calculations. In Figure 5.2 the weights for all main-criteria and sub-criteria are depicted in form of a hierarchical criteria tree.

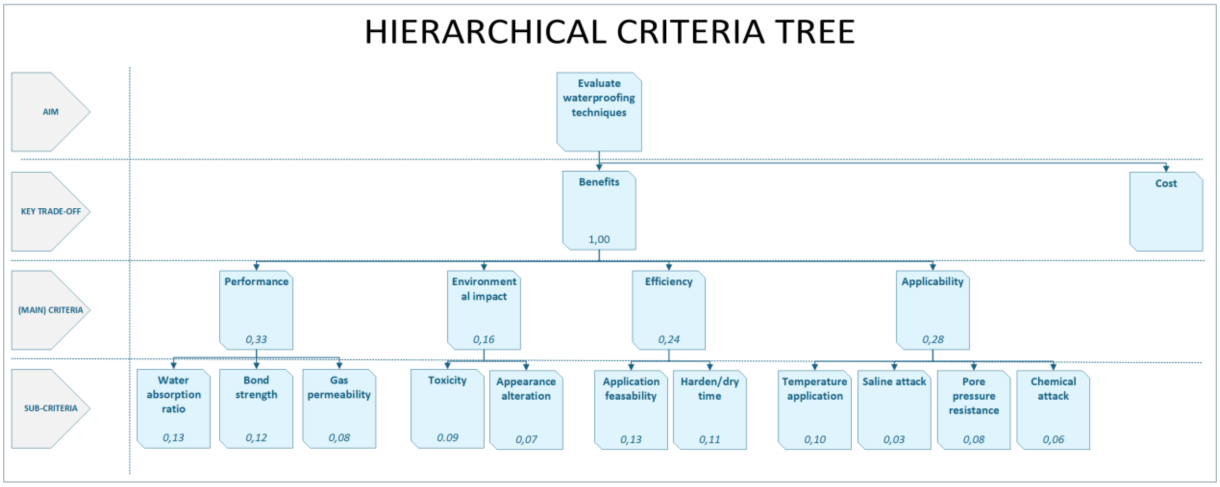

Figure 5.2. Hierarchical criteria tree.

Performance is allocated the highest score by experts at Walhout Group: *0,33*, while environmental impact is allocated the lowest score: *0,16*. Elaboration on filled in answers was not mandatory after filling in the survey. It seems however self-evident that the fulfillment of its fundamental purpose, which is protecting certain structures from water damage, outweighs long-term environmental considerations. However, this does not imply that environmental concerns are unimportant. Even more so, as sustainability gains prominence in construction, excluding this criterion from this report is unthinkable. Both *Efficiency* and *Applicability* are rated respectively *0,24* and *0,28*, both having rather equal influence on the final scores of the alternatives.

5.5. Scoring model

After translating all values into scores for every criterion and multiplying it by its accessory weight, a final representative score for every waterproofing option is determined. The scores are depicted in the red column of the scoring model on the next page in Figure 5.3. The highest and lowest scores are respectively *6,94* (Sika® Igolflex 301) and *3,18* (Sika® Igolflex 201). The low scores are mainly due to lack of documentation on the product data sheets (given score 1). The reason for this is lack of research on the coatings, and rather outdated products. Also poor performance on *performance* and *environmental impact* is observed, causing a low overall score. On the other hand, strengths of high scoring waterproofing techniques are the fully documented values, as well as excellent performance on *performance* and *applicability*. These main-criteria are allocated with the highest weights. Consequently, scoring high on these criteria result in relative higher scores.

			CRITERIA											
			Performance			Environmental impact		Efficiency		Applicability				
			Water absorption ratio	***Bond strength***	***Gas permeability***	***Toxicity***	***Appearance alteration***	***Application feasability***	***Harden time***	***Temperature application***	***Saline attack***	***Pore pressure resistant***	***Chemical resistance***	
		Criteria weight	*0,33*			*0,16*		*0,24*		*0,28*				
		Sub-criteria weight	*0,40*	*0,35*	*0,25*	*0,58*	*0,42*	*0,55*	*0,45*	*0,38*	*0,12*	*0,29*	*0,20*	
		Final Criteria weight	***0,13***	***0,12***	***0,08***	***0,09***	***0,07***	***0,13***	***0,11***	***0,10***	***0,03***	***0,08***	***0,06***	
ALTERNATIVES	**Surface treatment**	*Sikalastic ® - 1 K ES*	100	80	97	90	80	60	10	90	100	100	50	**6,93**
		SikaTop ® Seal - 107	100	100	44	35	20	90	80	60	1	100	90	**6,62**
		SikaTop ® - 144	1	1	0	0	50	60	60	90	100	0	90	**3,26**
		P3 Industrial	100	1	1	1	80	30	100	80	1	100	1	**4,55**
		Sika ® Igolflex® - 201	100	1	36	1	40	30	60	0	0	0	100	**3,18**
		Sika ® Igolflex® - 301	100	100	97	90	20	60	0	90	100	100	100	**6,94**
	Impregnation	*Polymer-modified Portland cement coating*	0	100	90	0	50	60	0	95	100	100	100	**5,18**

Figure 5.3. Scoring model overview for all alternatives.

5.6. Cost-benefit analysis

Finally, the cost of every waterproofing technique have been added, depicted in Table 5.3. Outstanding is the high cost of silica nano-particle based coating. A reason for this is the relative young technology behind this coating, as well as the costly synthesis of the product itself. High purity silica is needed, together with certain sophisticated binders (Al, 2018). Furthermore, no (linear) relationship is visible between high scoring alternatives and higher cost as well as low scoring alternatives and lower cost: cost-benefit relation seems randomly distributed for every waterproofing technique.

Table 5.3. Cost and benefit per alternative.

			Price per kg €	Scored benefit
ALTERNATIVES	**Surface treatment**	*Sikalastic ® - 1 K ES*	€ 8,96	6,93
		SikaTop ® Seal - 107	€ 4,00	6,62
		SikaTop ® - 144	€ 13,73	3,26
		P3 Industrial	€ 26,00	4,55
		Sika ® Igolflex® - 201	€ 3,98	3,18
		Sika ® Igolflex® - 301	€ 5,75	6,94
	Impregnation	*Polymer-modified Portland cement coating*	€ 6,01	5,18

From the results depicted in Table 5.3, a Pareto Front is drawn, see Figure 5.4. In this way, best cost-benefit scoring alternatives can be easily determined.

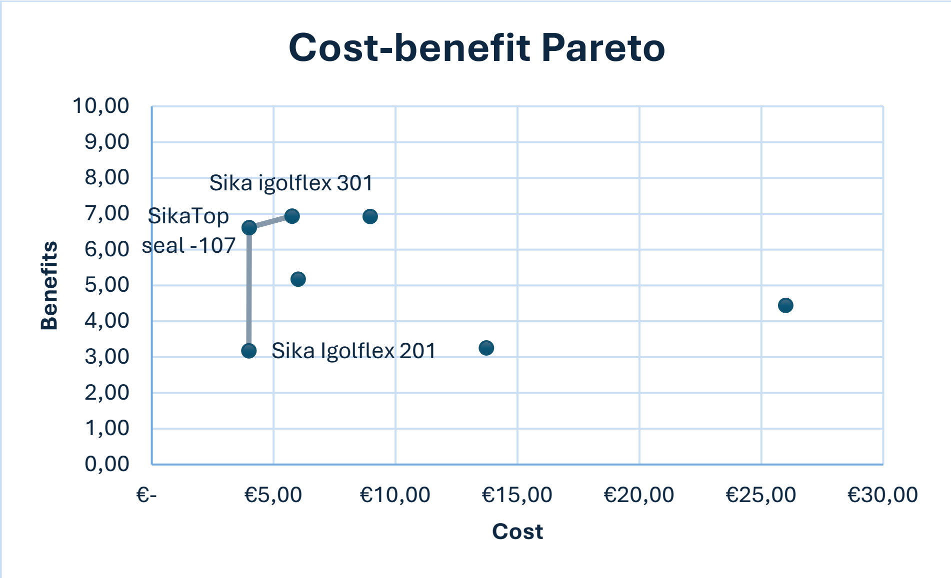

Figure 5.4. Cost-benefit Pareto Front.

From this figure can be derived, taking into account solely *benefits*, Sika® Igolflex 301 scores the highest overall score: 6,94. This is 33% higher than the average score of all alternatives (5,24)

Taking into account both cost and benefits, Sika®Top seal -107 scores the highest: a score of 6,62 with a relative low cost: €4.00,-. Assuming an equally distributed cost-benefit weight (0,50 – 0,50), Sika® Igolflex 201's score hands in more than twice of its value compared to Sika®Top seal -107, although being the cheapest alternative (€3.98,-). On the other hand, while offering only minimal extra benefit score (+0,32), Sika® Igolflex 301 costs +€1.75 more compared to Sika®Top seal -107.

5.7. Discussion

Firstly, the carried out MCDA in this report successfully met the project aim. Using MCDA as a decision-making tool to evaluate and select a suitable waterproofing technique incorporates weights and scores, excellently representing the hierarchical nature of criteria. Especially regarding the scope of the project, where a great portfolio of criteria is analyzed, incorporating relative importance for criteria is a logical step. On the other hand, weights of criteria have to be determined by human selection. This can create a biased and unreliable set of weights. To overcome this problem, using human expertise to set up weights is a valuable option. To further diminish biased data, this report uses data from up to 8 experts within Walhout Group. Each person has its own expertise, being e.g. juridical, construction, engineering, project planning. Taking the mean of the survey outcomes of every experts creates a reliable and unbiased final weight for every criterion. Finally, the absence of a detailed stakeholder analysis (as described in project scope) might also badly affect the results of this research. However, introducing a broad scala of experts also creates a considerable alternative for incorporating stakeholders.

Secondly, a limit of this MCDA is the recurring lack of documentation. This can be clearly seen in both the performance matrix and the scoring model (figure X and figure X). Especially *P3 Industrial*, which uses innovative silica-nanoparticles, lacks product information. Although literature provides promising performance perspectives on this technique, it is a relatively new and thus rarely investigated and used. Additionally, there is currently a very low market availability, which increases product price.

For this MCDA, lack of documentation on a criteria has been scored a 1 (on scale 100). However, if this product data would be available and accessible, this score most likely would increase. There seems to be no adequate solution to solve this problem, except incorporating a certain amount of uncertainty score rate (in this case 1). Obviously, this is not representative value. Additionally, product documentation remains a theoretical and sometimes idealized and abstract representation of reality. In practice, several idealized parameters of criteria are not ''ideal'', and might deviate from theoretical values. Examples are properties of the treated concrete surface, which is almost impossible to capture in theoretical equations. In short, some (undesired) assumptions are unavoidable.

Lack of documentation also had its influence on the selection of criteria. Several potential interesting criteria could not be incorporated, such as carbon emissions of waterproofing techniques and the compressive strength of the concrete surface after the application of the waterproofing technique. This could create a biased element in scoring the alternatives, as criteria is not introduced based on stakeholder involvement, but solely on what data is available.

5.8. Limitations

Finally, the limitations of the MCDA have to be thoroughly examined. This is crucial, as it provides transparency towards potential future users of the model, as well as identifying certain areas of improvement.

To make the MCDA more accessible to users, complex mathematical matrix calculations are avoided. Instead, a more user-friendly approach has been taken to calculated the weights. The geometric mean for every row, representing scores for every criteria, has been calculated. Although being a very accurate representation of the traditional MCDA weight calculation, which makes use of eigenvector calculations, resulting weights are not exactly the same. Also secondary consistency calculation of criteria weights is not included, making the matrix prone to error.

Furthermore, the alternatives analyzed in this MCDA are subject to ''tunnel vision''. To be more specific, one type of waterproofing technique is selected and analyzed, while additional agents or products are neglected. This can be illustrated by for example Sika®Top 144. For this product, an additional coating of Sika is recommended, potentially having a great (positive) impact on the score of this waterproofing technique in the scoring model.

Lastly, introducing additional or deducting certain criteria to or from the described MCDA, demands an entirely new weighing process of criteria. As all criteria are relevant to each other, new surveys have to be carried out, as well as additional calculations. This is a very time-consuming process; however, it is not impossible. Introducing new waterproofing techniques to the MCDA is less time-consuming, as no new weighing process is demanded, and is therefore a more accessible step.

5.9. Recommendations for further study

A suggestion for improvement of this research to potentially overcome certain limitations, might be to include additional waterproofing agents or binders to already introduced waterproofing techniques. This potentially increases the benefit score of the considered alternative, although also increasing the costs. Furthermore, the rather simplistic weight calculations could be replaced with eigenvector calculations, to increase reliability of the results. Lastly, an alternative for the used AHP method could be used. There exist multiple elaborated ''fuzzy'' MCDA-approaches, such as *fuzzy VIKOR*, *fuzzy RANCOM,* and *fuzzy TOPSIS* (Papathanasiou, 2021; Saoud et al., 2025; Więckowski et al., 2025). VIKOR, RANCOM and TOPSIS are all different approaches to systematic decision-making. However, adding *fuzzy logic* to the decision-making process adds a whole new universe of scoring alternatives and weighing criteria. Binary scoring of alternatives and criteria is considered impossible when using fuzzy logic, as the truth of a possibility can be interpreted differently by any arbitrary person. Rather than either 0 or 1 (binary), the truth is represented as a linguistic variable, once again translated into a semantic value. Although on some areas of this research this fuzzy logic is already applied (such as Component Value Assessment), more could be applied to other criteria or alternatives.

6. Conclusion

This thesis developed a systematic methodology for selecting effective waterproofing techniques to prevent groundwater leakage in underground car parks. By employing a Multi-Criteria Decision Analysis (MCDA) framework supported by the Analytical Hierarchy Process (AHP), various waterproofing alternatives were evaluated against carefully defined criteria. These criteria, derived from literature and expert input, included performance, environmental impact, efficiency, and applicability. A case study, P6 Uitgaansdriehoek in Amsterdam, was used to apply and demonstrate the methodology.

The key steps of the research included a comprehensive literature study on waterproofing techniques and their performance metrics, the development of an evaluation methodology, and a case study analysis. The MCDA methodology prioritized the criteria based on expert surveys, providing weighted scores for each alternative.

The results highlighted two key recommendations:

1. **Best-performing technique (based on benefit score only):** *Sika® Igolflex 301*, scoring a benefit-score of 6,94, significantly above the average score of 5.24. Its superior waterproofing properties and high applicability make it the optimal choice when cost is not the primary concern.
2. **Best cost-benefit technique:** *SikaTop® Seal-107*, scoring a benefit-score of 6,62 with a competitive cost of €4.00/kg, offers an effective balance between performance and affordability.

The methodology demonstrated its utility as a decision-making tool, providing a robust framework adaptable to various scenarios. However, the study acknowledged certain limitations, including incomplete product documentation for some innovative waterproofing techniques, potential subjectivity in criteria weighting, and the absence of a detailed stakeholder analysis. Future research could address these limitations by integrating advanced decision-making models like fuzzy logic and incorporating additional waterproofing technologies or criteria.

In summary, this study successfully achieved its objectives by proposing a structured approach to evaluate and select waterproofing techniques, offering actionable insights for addressing groundwater leakage in underground car parks. The developed methodology provides a replicable framework for similar challenges, fostering informed and sustainable decision-making in civil engineering practices.

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A. Appendix A – survey 1

Note that the survey and the results are presented in Dutch, as the official spoken language at Walhout Group is Dutch. A translation of the survey is also added.

ENQUÊTE RANKING CRITERIA

Mede door toenemende neerslaghoeveelheden en hogere grondwaterstanden is water lekkage in ondergrondse parkeergarages een veelvoorkomend probleem. Water van buitenaf sijpelt door de wanden de parkeergarage binnen: door beton en/of connecties tussen damwanden/beton. In mijn afstudeeropdracht onderzoek ik de haalbaarheid van het toepassen van verschillende coatings op de betonnen wand van ondergrondse parkeergarages om deze waterlekkage te voorkomen. Ik voer hiervoor een Multi-Criteria Decision Analysis uit. Hierbij worden verschillende alternatieven becijferd onder bepaalde criteria. Het alternatief met de hoogste score wordt vervolgens aanbevolen. Onderstaand wordt elke criteria toegelicht.

Performance: De prestatie van de waterdichte techniek. Afhankelijk van o.a. de hoeveelheid water die het opneemt/afstoot, hechtsterkte, waterdampdoorlatendheid.

Milieu impact: De invloed van de waterdichte techniek op het milieu. Afhankelijk van o.a. giftigheid van de stof en verandering van het uiterlijk van het behandelde oppervlak.

Efficiëntie: De mate van efficiëntie van de waterdichte techniek. Afhankelijk van o.a. gemakkelijkheid van het aanbrengen van de waterdichte techniek en de uithardingstijd.

Toepasbaarheid: De mate van toepasbaarheid van de waterdichte techniek. Afhankelijk van o.a. temperatuurbestendigheid, zoutbestendigheid, weerstand tegen chemische reacties, weerstand tegen waterdruk.

Deze enquête is bestemd voor het bepalen van de relatieve belangrijkheid tussen deze criteria.

Bij elke vraag krijgt u telkens 2 keuzes uit 4 mogelijkheden, de **criteria**. Hieruit kiest u wat u denkt dat de belangrijkste criteria van de twee is, met het oog op de waterdichte techniek.

ENGLISH VERSION

SURVEY RANKING CRITERIA

Due to increasing rainfall and rising groundwater levels, water leakage in underground car parks has become a common issue. Water from outside seeps into the car park through the walls: either through the concrete itself and/or through the connections between retaining walls and concrete. In my graduation project, I am investigating the feasibility of applying various waterproofing techniques to concrete walls of underground car parks to prevent this water leakage. I am conducting a Multi-Criteria Decision Analysis (MCDA), *where various alternatives are evaluated based on specific criteria. The alternative with the highest score will then be recommended. Below, each criterion is explained:*

- ***Performance**: The effectiveness of the waterproofing technique. This depends on factors such as the amount of water absorbed/repelled, bond strength, and water vapor permeability.*
- ***Environmental Impact**: The impact of the waterproofing technique on the environment. This includes factors such as the toxicity of the material and changes in the appearance of the treated surface.*
- ***Efficiency**: The degree of efficiency of the waterproofing technique. This involves factors such as the ease of application and the curing time of the waterproofing material.*
- ***Applicability**: The extent to which the waterproofing technique is suitable for use. This depends on factors such as temperature resistance, salt resistance, resistance to chemical reactions, and resistance to water pressure.*

This survey aims to determine the relative importance of these criteria.

In each question, you will be presented with two options out of the four criteria listed above. You are asked to choose the criterion you believe is more important in the context of waterproofing techniques.

***

Vragen:

1. Hoe belangrijk vindt u [A] Performance ten opzichte van [B] Milieu-impact?
   To what extent is [A] Performance important relative to [B] Environmental impact?
2. Hoe belangrijk vindt u [A] Performance ten opzichte van [C] Efficiëntie?
   To what extent is [A] Performance important relative to [C] Efficiency?
3. Hoe belangrijk vindt u [A] Performance ten opzichte van [D] Toepasbaarheid?
   To what extent is [A] Performance important relative to [D] Applicability?
4. Hoe belangrijk vindt u [B] Milieu-impact ten opzichte van [C] Efficiëntie?
   To what extent is [B] Environmental impact important relative to [C] Efficiency?
5. Hoe belangrijk vindt u [B] Milieu-impact ten opzichte van [D] Toepasbaarheid?
   To what extent is [B] Environmental impact important relative to [D] Applicability?
6. Hoe belangrijk vindt u [C] Efficiëntie ten opzichte van [D] Toepasbaarheid?
   To what extent is [C] Efficiency important relative to [D] Applicability?

RESULTS

1. To what extent is [A] Performance important relative to [B] Environmental impact?

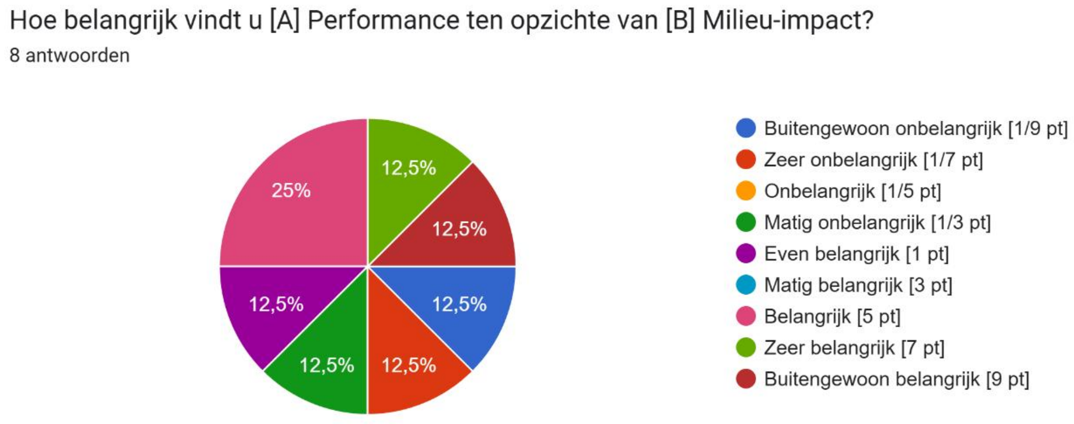

Figure A.1. Survey 1, question 1.

2. To what extent is [A] Performance important relative to [C] Efficiency?

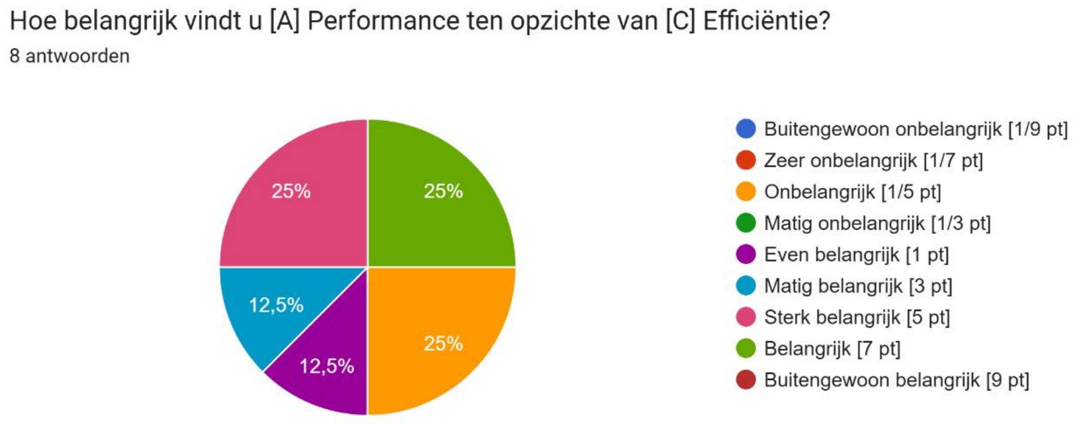

Figure A.2, Survey 1, question 2.

3. To what extent is [A] Performance important relative to [D] Applicability?

Hoe belangrijk vindt u [A] Performance ten opzichte van [D] Toepasbaarheid?
8 antwoorden

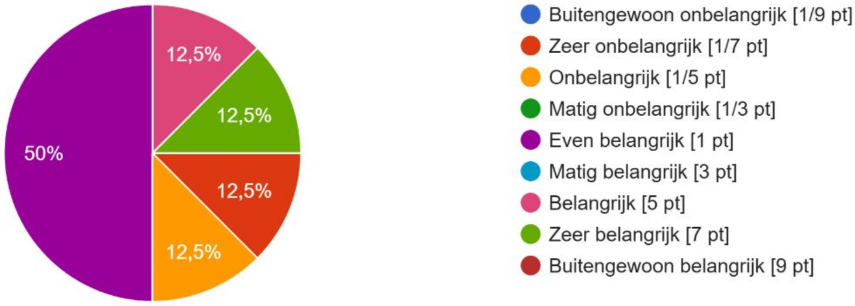

Figure A.3, Survey 1, question 3.

4. To what extent is [B] Environmental impact important relative to [C] Efficiency?

Hoe belangrijk vindt u [B] Milieu-impact ten opzichte van [C] Efficiëntie?
8 antwoorden

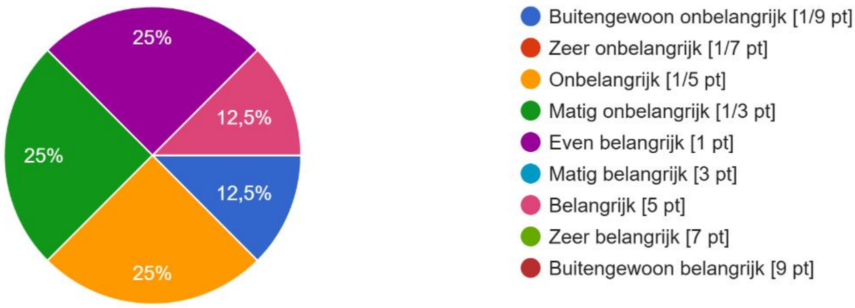

Figure A.4, Survey 1, question 4.

5. To what extent is [B] Environmental impact important relative to [D] Applicability?

Hoe belangrijk vindt u [B] Milieu-impact ten opzichte van [D] Toepasbaarheid?
8 antwoorden

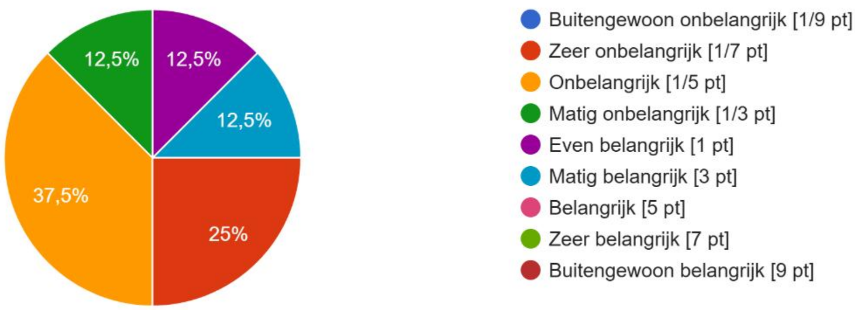

Figure A.5, Survey 1, question 5.

6. To what extent is [C] Efficiency important relative to [D] Applicability?

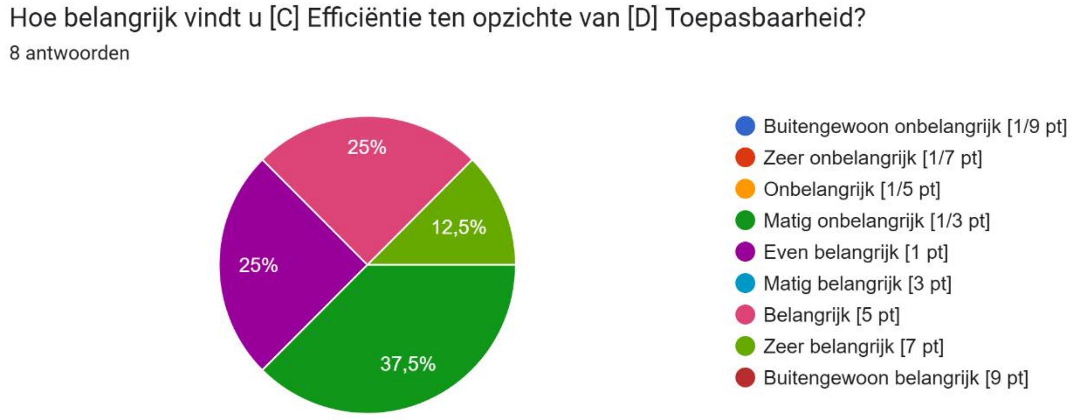

Figure A.6, Survey 1, question 6.

B. Appendix B – Survey 2

Note that the survey and the results are presented in Dutch, as the official spoken language at Walhout Group is Dutch. An English version is also added.

Deze enquête is het vervolg van de Ranking criteria enquête. Het doel van deze enquête is om de wegingsfactor vast te stellen van de **sub-criteria**.

De wegingsfactor van de volgende hoofdcriteria zijn vastgesteld in de vorige enquête:

1. Performance;
2. Milieu-impact;
3. Efficiëntie;
4. Toepasbaarheid.

Onder elke hoofdcriteria vallen zogeheten **sub-criteria**. Dit zijn criteria die samen een gedetailleerd beeld geven voor elk hoofdcriteria. Bij elke vraag per hoofd-criteria kunt u kiezen tussen twee verschillende sub-criteria binnen deze hoofd-criteria. Hieruit kiest u wat u denkt dat de belangrijkste criteria van de twee is, met het oog op de waterdichte technieken.

Vragen:

1. Performance criteria
Deze criteria bepalen de (mate van) prestatie van de waterdichte techniek:

[A1]: Waterdoorlaatbaarheid. De hoeveelheid water wat de waterdichte techniek doorlaat.

[A2]: Hechtsterkte. De hechtsterkte van de waterdichte techniek aan de te behandelen oppervlak.

[A3]: Waterdampdoorlaatbaarheid. De hoeveelheid waterdamp wat de waterdichte techniek doorlaat.

1. Hoe belangrijk vindt u [A1] Waterdoorlaatbaarheid ten opzichte van [A2] Hechtsterkte?
2. Hoe belangrijk vindt u [A1] Waterdoorlaatbaarheid ten opzichte van [A3] Waterdampdoorlaatbaarheid?
3. Hoe belangrijk vindt u [A2] Hechtsterkte ten opzichte van [A3] Waterdampdoorlaatbaarheid?

2. Milieu-impact
Deze criteria bepalen de impact van de waterdichte techniek op het milieu:

[B1]: Toxiciteit: de hoeveelheid giftige stoffen in de waterdichte techniek en hun impact op de algemene gezondheid van mens en dier.

[B2]: Uiterlijke verandering. De mate van de uiterlijke verandering van het behandelde oppervlak, bijvoorbeeld kleur, ruwheid, weerspiegeling, etc.

4. Hoe belangrijk vindt u [B1] Giftigheid ten opzichte van [B2] Uiterlijke verandering?

3. Efficiëntie
Deze criteria bepalen de efficiëntie van de waterdichte techniek:
[C1]: Gemakkelijkheid van het aanbrengen van de waterdichte techniek. Afhankelijk van de hoeveelheid mogelijkheden tot sprayen, verven, smeren, etc.

[C2]: Uithardingstijd/droogtijd. Afhankelijk van de duur van drogen/uitharden van de waterdichte techniek.

5. Hoe belangrijk vindt u [C1] gemakkelijkheid van het aanbrengen ten opzichte van [C2] Uitharding/droogtijd?

4. Toepasbaarheid
De volgende sub-criteria bepalen de toepasbaarheid van de waterdichte techniek:

[A]: Temperatuursbestendigheid. Het bereik van de omgevingstemperatuur waarin de waterdichte techniek kan worden aangebracht en verblijven.

[B]: Zoutbestendigheid. Is de waterdichte techniek bestand tegen zout water, zoute lucht, zoute omstandigheden?

[C]: Drukbestendigheid. Is de waterdichte techniek bestand tegen hoge druk, bijvoorbeeld door capillaire werking, hoge grondwaterstanden, etc.

[D]: Chemische bestendigheid. Is de waterdichte techniek bestand tegen chemische stoffen, zoals chloor, zwavel, etc.

6. Hoe belangrijk vindt u [D1] Temperatuursbestendigheid ten opzichte van [D2] Zoutbestendigheid?
7. Hoe belangrijk vindt u [D1] Temperatuursbestendigheid ten opzichte van [D3] Drukbestendigheid (capillaire werking)?
8. Hoe belangrijk vindt u [D1] Temperatuursbestendigheid ten opzichte van [D4] Chemische bestendigheid (Chloor, zwavel, etc.)?
9. Hoe belangrijk vindt u [D2] Zoutbestendigheid ten opzichte van [D3] Drukbestendigheid (Capillaire werking)?
10. Hoe belangrijk vindt u [D2] Zoutbestendigheid ten opzichte van [D4] Chemische bestendigheid (Chloor, zwavel, etc.)?
11. Hoe belangrijk vindt u [D3] Drukbestendigheid (capillaire werking) ten opzichte van [D4] Chemische bestendigheid (Chloor, zwavel, etc.)?

ENGLISH VERSION

This survey is a continuation of the Ranking Criteria survey. The purpose of this survey is to determine the weighting factor of the sub-criteria.

The weighting factors for the following main criteria have already been established in the previous survey:

1. ***Performance**;*
2. ***Environmental Impact**;*
3. ***Efficiency**;*
4. ***Applicability**.*

Each main criterion consists of sub-criteria, which together provide a detailed view of each main criterion. For each question within a main criterion, you can choose between two different sub-criteria. From these, you select the one you consider to be the most important in the context of waterproofing techniques.

Questions:

1. Performance Criteria

These criteria determine the (level of) performance of the waterproofing technique:

- *[A1] Water Absorption Ratio: The amount of water the waterproofing technique absorbs*
- *[A2] Bond Strength: The adhesive strength of the waterproofing technique to the treated surface.*
- *[A3] Gas Permeability: The amount of water vapor that the waterproofing technique allows to pass through.*

1. *How important is [A1] Water Absorption Ratio relative to [A2] Bond Strength?*
2. *How important is [A1] Water Absorption Ratio relative to [A3] Gas Permeability?*

3. *How important is [A2] Bond Strength relative to [A3] Gas Permeability?*

2. Environmental Impact

These criteria determine the environmental impact of the waterproofing technique:

- *[B1] Toxicity: The amount of toxic substances in the waterproofing technique and their impact on the overall health of humans and animals.*
- *[B2] Appearance Alteration: The extent to which the treated surface's appearance changes, e.g., in terms of color, roughness, reflectivity, etc.*

4. *How important is [B1] Toxicity relative to [B2] Appearance Alteration?*

3. Efficiency

These criteria determine the efficiency of the waterproofing technique:

- *[C1] Application Feasibility: How easy it is to apply the waterproofing technique (e.g., through spraying, painting, spreading, etc.).*
- *[C2] Harden/Dry Time: The duration required for the waterproofing technique to harden or dry.*

5. *How important is [C1] Application Feasibility relative to [C2] Harden/Dry Time?*

4. Applicability

The following sub-criteria determine the applicability of the waterproofing technique:

- *[D1] Temperature Resistance: The temperature range in which the waterproofing technique can be applied and remain effective.*
- *[D2] Saline Attack Resistance: The ability of the waterproofing technique to resist saline environments (e.g., saltwater, salty air).*
- *[D3] Pore Pressure Resistance: The ability of the waterproofing technique to resist high pressure, such as those caused by capillary rise or rising groundwater levels.*
- *[D4] Chemical Resistance: The ability of the waterproofing technique to resist chemical substances, such as chlorine or sulfur.*

6. *How important is [D1] Temperature Resistance relative to [D2] Saline Attack Resistance?*
7. *How important is [D1] Temperature Resistance relative to [D3] Pore Pressure Resistance?*
8. *How important is [D1] Temperature Resistance relative to [D4] Chemical Resistance?*
9. *How important is [D2] Saline Attack Resistance relative to [D3] Pore Pressure Resistance?*
10. *How important is [D2] Saline Attack Resistance relative to [D4] Chemical Resistance?*
11. *How important is [D3] Pore Pressure Resistance relative to [D4] Chemical Resistance?*

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RESULTS

1. To what extent is [A1] Water absorption ratio important relative to [A2] Bond strength?

Figure B.1, Survey 2, question 1.

2. To what extent is [A1] Water absorption ratio important relative to [A3] Gas permeability?

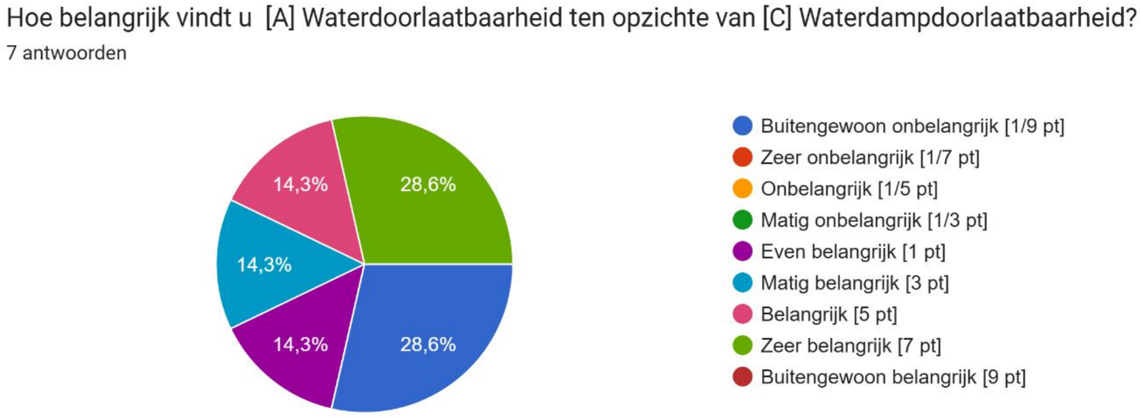

Figure B.2, Survey 2, question 2.

3. To what extent is [A2] Bond strength important relative to [A3] Gas permeability?

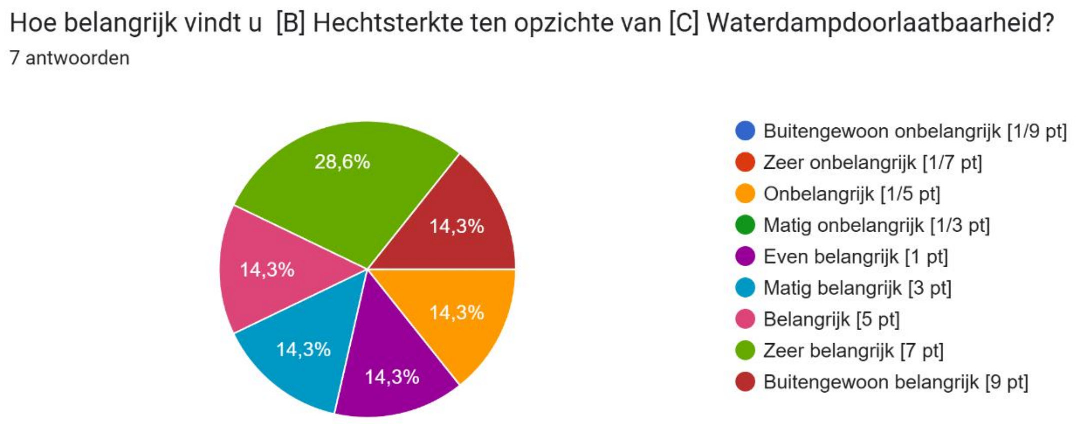

Figure B.3, Survey 2, question 3.

4. To what extent is [B1] Toxicity important relative to [B2] Appearance alteration?

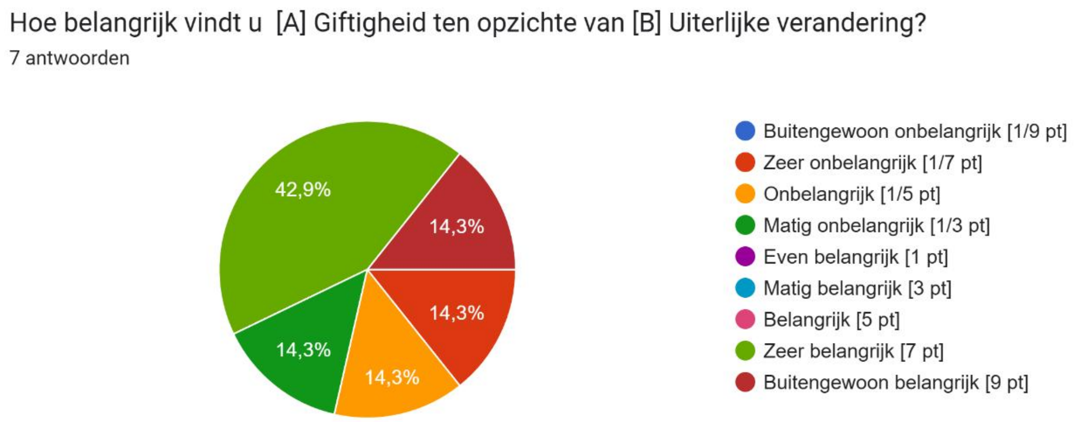

Figure B.4, Survey 2, question 4.

5. To what extent is [C1] Application feasibility important relative to [C2] Harden/dry time?

Hoe belangrijk vindt u [A] gemakkelijkheid van het aanbrengen ten opzichte van [B] Uitharding/droogtijd?

7 antwoorden

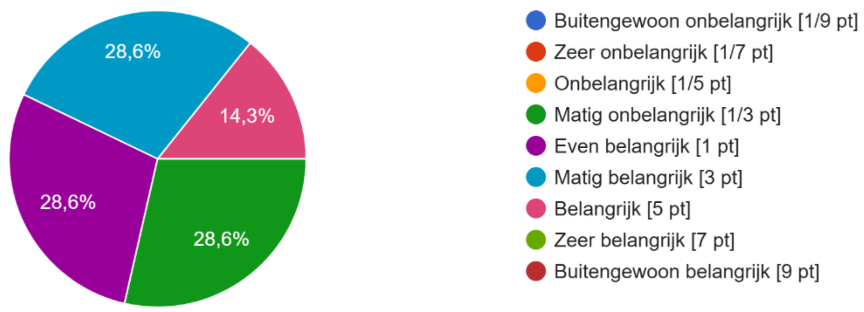

Figure B.5, Survey 2, question 5.

6. To what extent is [D1] Temperature resistance important relative to [D2] Saline attack?

Hoe belangrijk vindt u [A] Temperatuursbestendigheid ten opzichte van [B] Zoutbestendigheid?

7 antwoorden

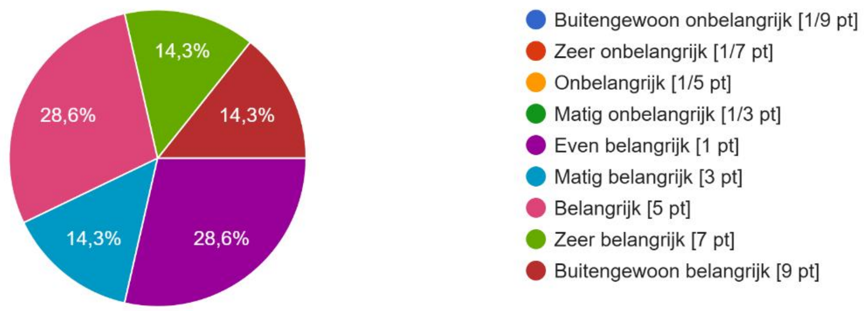

Figure B.6, Survey 2, question 6.

7. To what extent is [D1] Temperature resistance important relative to [D3] Pore pressure resistance?

Hoe belangrijk vindt u [A] Temperatuursbestendigheid ten opzichte van [C] Drukbestendigheid (capillaire werking)?

7 antwoorden

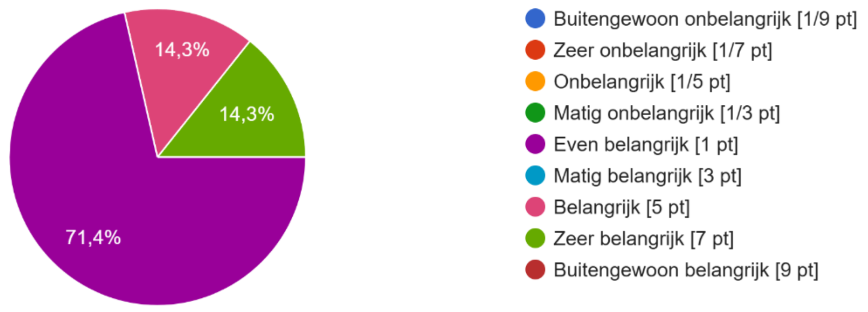

Figure B.7, Survey 2, question 7.

8. To what extent is [D1] Temperature resistance important relative to [D4] Chemical attack?

Hoe belangrijk vindt u [A] Temperatuursbestendigheid ten opzichte van [D] Chemische bestendigheid (Chloor, zwavel, etc.)?

7 antwoorden

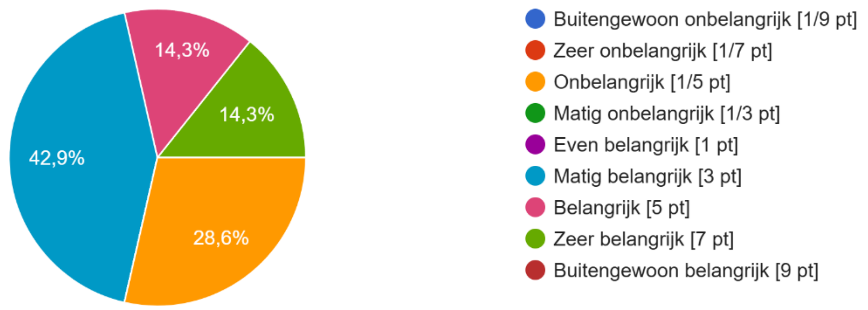

Figure B.8, Survey 2, question 8.

9. *To what extent is [D2] Saline attack important relative to [D3] Pore pressure resistance?*

Hoe belangrijk vindt u [B] Zoutbestendigheid ten opzichte van [C] Drukbestendigheid (Capillaire werking)?
7 antwoorden

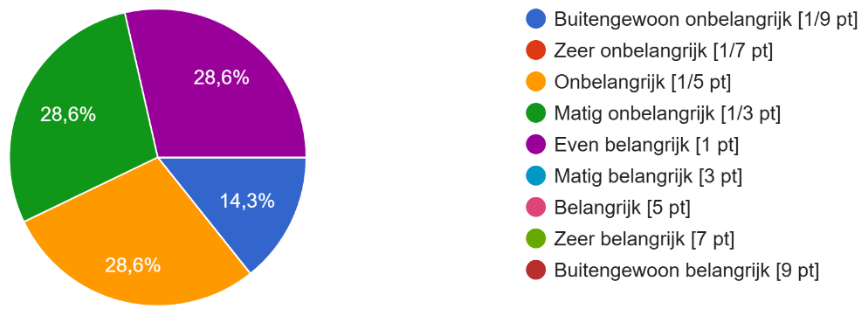

Figure B.9, Survey 2, question 9.

10. *To what extent is [D2] Saline attack important relative to [D4] Chemical attack?*

Hoe belangrijk vindt u [B] Zoutbestendigheid ten opzichte van [D] Chemische bestendigheid (Chloor, zwavel, etc.)?
7 antwoorden

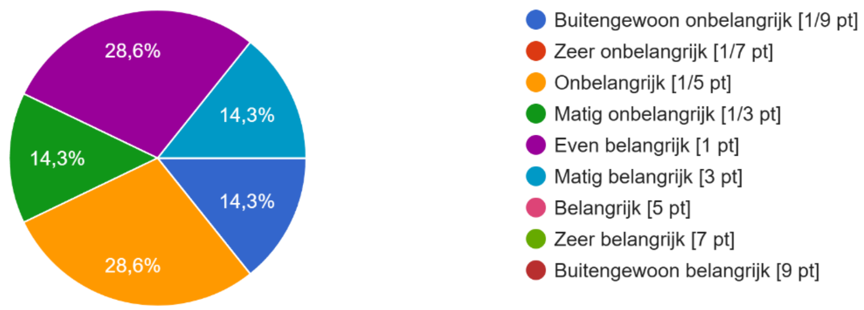

Figure B.10, Survey 2, question 10.

11. To what extent is [D3] Pore pressure resistance important relative to [D4] Chemical attack?

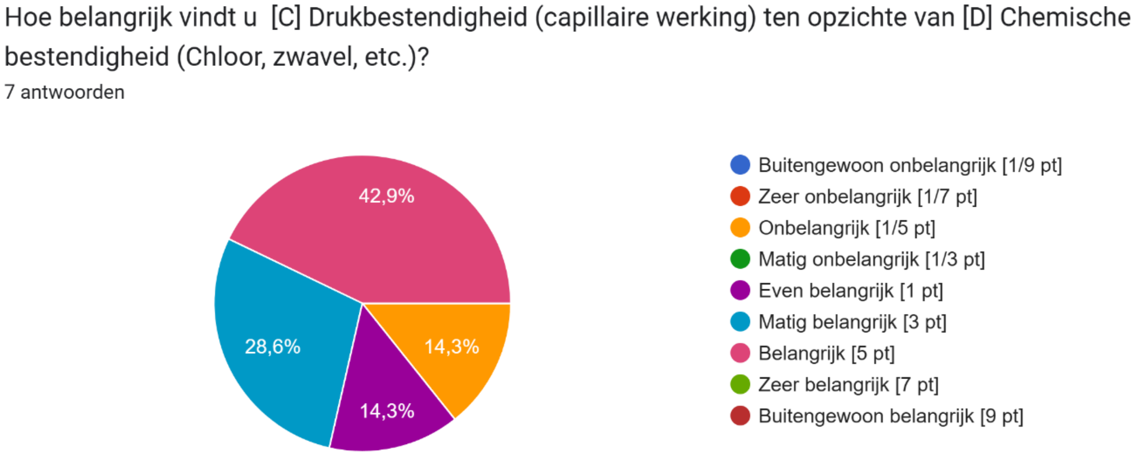

Figure B.11, Survey 2, question 11.

C. Appendix C – Component value assessment sub-criteria

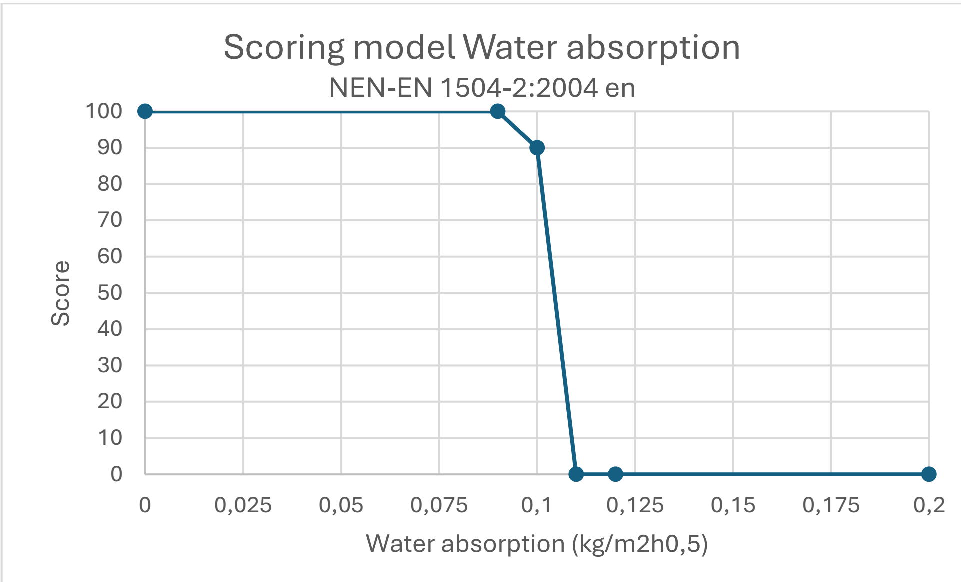

Figure C.1, Component Value Assessment Water absorption.

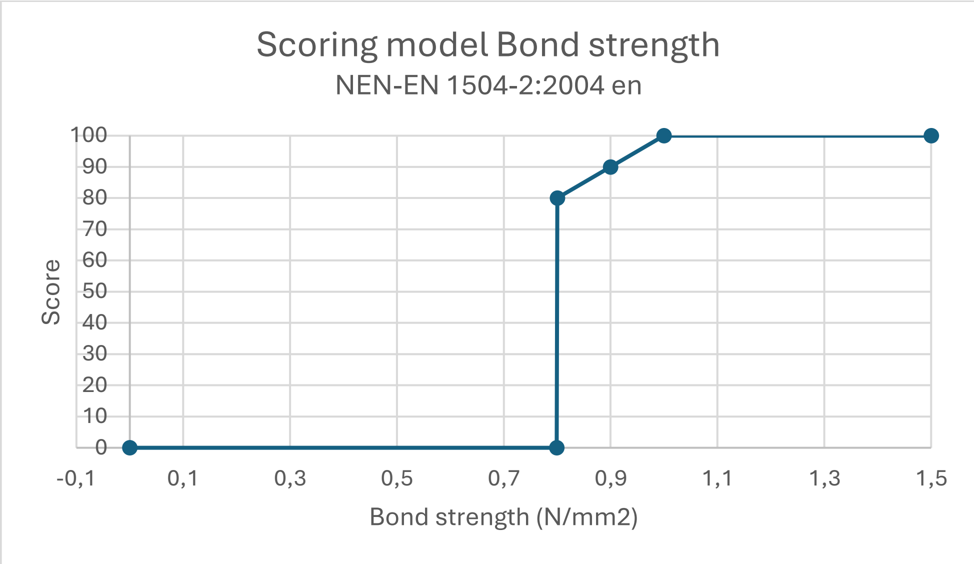

Figure C.2, Component Value Assessment Bond strength.

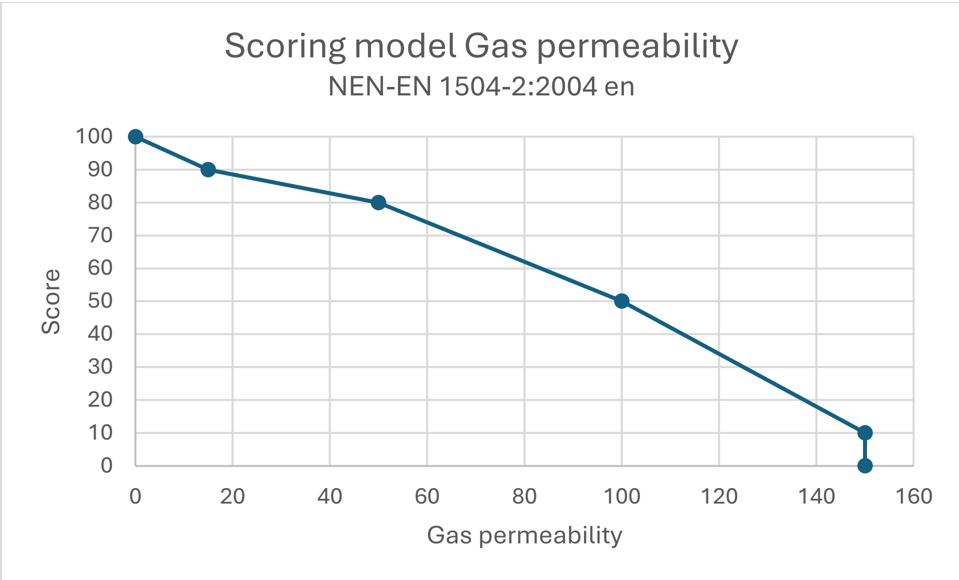

Figure C.3, Component Value Assessment Gas permeability.

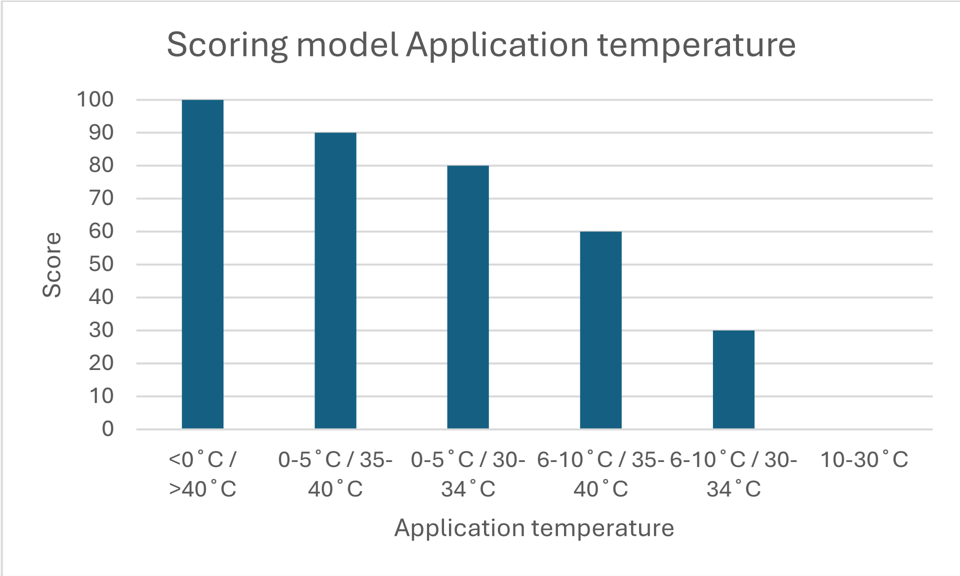

Figure C.4, Component Value Assessment Bond Application temperature.

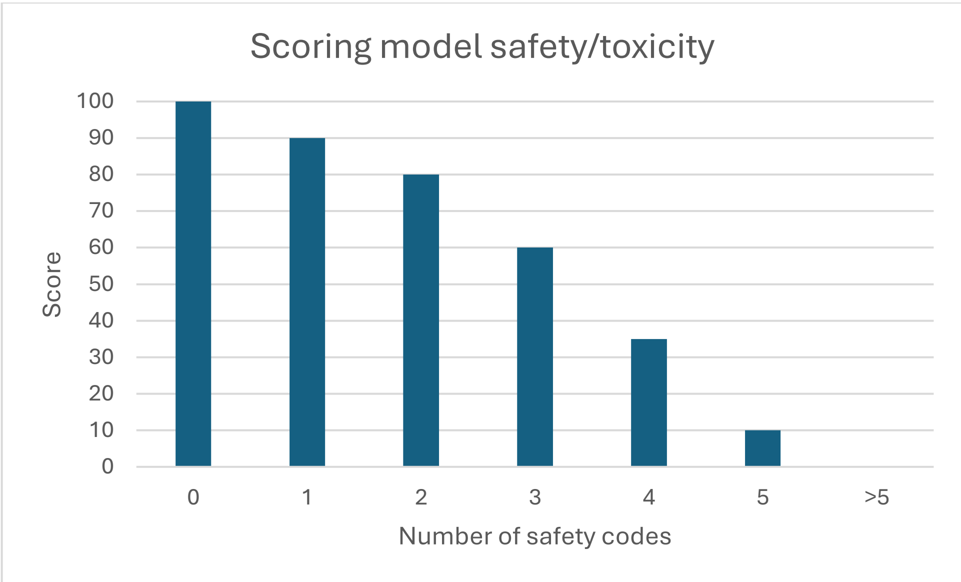

Figure C.5, Component Value Assessment Toxicity.

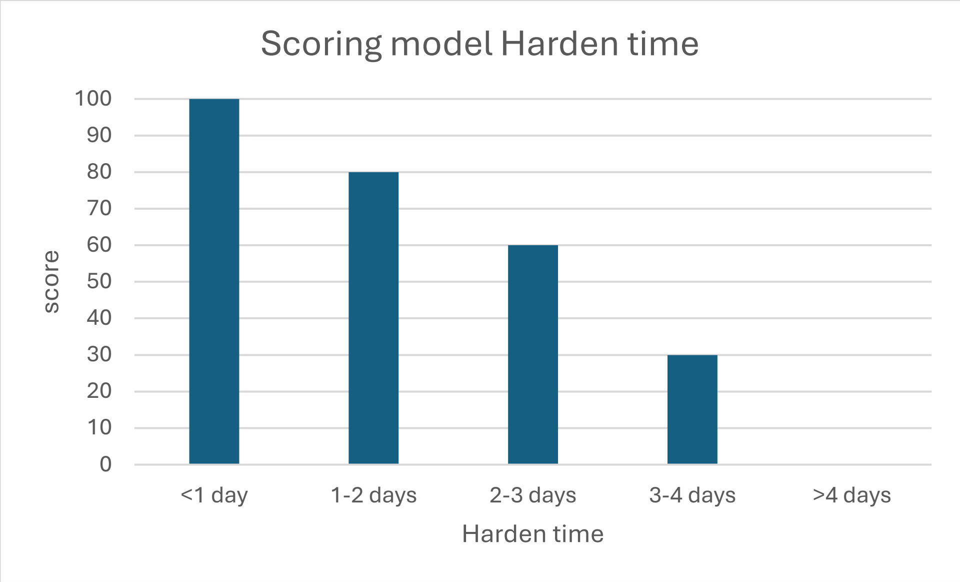

Figure C.6, Component Value Assessment Harden time.

D. Appendix D – Criteria weight calculations

The values in the matrices are directly derived from the results of survey 1&2 in appendix A&B.

1. Main criteria

Table D.1. Weighing matrix main criteria expert 1.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 1	A	B	C	D	Geometr. mean	Weights	
A	1,00	0,33	0,20	0,14	0,31	0,06	
B	3,00	1,00	5,00	3,00	2,59	0,49	
C	5,00	0,20	1,00	7,00	1,63	0,31	
D	7,00	0,33	0,14	1,00	0,76	0,14	
					5,29	*1,00*	TOT

Table D.2. Weighing matrix main criteria expert 2.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 2	A	B	C	D	Geometr. mean	Weights	
A	1,00	0,14	0,20	1,00	0,41	0,08	
B	7,00	1,00	0,20	0,14	0,67	0,14	
C	5,00	5,00	1,00	1,00	2,24	0,45	
D	1,00	7,00	1,00	1,00	1,63	0,33	
					4,94	*1,00*	TOT

Table D.3. Weighing matrix main criteria expert 3.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 3	A	B	C	D	Geometr. mean	Weights	
A	1,00	1,00	5,00	0,20	1,00	0,22	
B	1,00	1,00	1,00	1,00	1,00	0,22	
C	0,20	1,00	1,00	0,33	0,51	0,11	
D	5,00	1,00	3,00	1,00	1,97	0,44	
					4,48	*1,00*	TOT

Table D.4. Weighing matrix main criteria expert 4.

EXPERT 4	A	B	C	D	Geometr. mean	Weights	
A	1,00	9,00	7,00	5,00	4,21	0,66	
B	0,11	1,00	0,33	0,33	0,33	0,05	
C	0,14	3,00	1,00	5,00	1,21	0,19	
D	0,20	3,00	0,20	1,00	0,59	0,09	
					6,34	*1,00*	TOT

Table D.5. Weighing matrix main criteria expert 5.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 5	A	B	C	D	Geometr. mean	Weights	
A	1,00	5,00	1,00	1,00	1,50	0,31	
B	0,20	1,00	0,33	0,20	0,34	0,07	
C	1,00	3,00	1,00	0,33	1,00	0,21	
D	1,00	5,00	3,00	1,00	1,97	0,41	
					4,80	*1,00*	TOT

Table D.6. Weighing matrix main criteria expert 6.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 6	A	B	C	D	Geometr. mean	Weights	
A	1,00	7,00	3,00	1,00	2,14	0,42	
B	0,14	1,00	1,00	0,20	0,41	0,08	
C	0,33	1,00	1,00	0,33	0,58	0,11	
D	1,00	5,00	3,00	1,00	1,97	0,39	
					5,10	*1,00*	TOT

Table D.7. Weighing matrix main criteria expert 7.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 7	A	B	C	D	Geometr. mean	Weights	
A	1,00	0,11	5,00	1,00	0,86	0,20	
B	9,00	1,00	0,11	0,14	0,61	0,14	
C	0,20	9,00	1,00	5,00	1,73	0,40	
D	1,00	7,00	0,20	1,00	1,09	0,25	
					4,30	*1,00*	TOT

Table D.8. Weighing matrix main criteria expert 8.

WEIGHING CRITERIA (AHP METHOD)							
EXPERT 8	A	B	C	D	Geometr. mean	Weights	
A	1,00	5,00	7,00	7,00	3,96	0,65	
B	0,20	1,00	0,20	0,20	0,30	0,05	
C	0,14	5,00	1,00	1,00	0,92	0,15	
D	0,14	5,00	1,00	1,00	0,92	0,15	
					6,09	*1,00*	TOT

Table D.9. , Final mean weight main criteria

FINAL WEIGHT MAIN CRITERIA		
	FINAL MEAN WEIGHT	
A (PERFORMANCE)	**0,33**	
B (ENVIRONMENTAL IMPACT)	**0,16**	
C (EFFICIENCY)	**0,24**	
D (APPLICABILITY)	**0,28**	
	1,00	**TOT**

2. Sub-criteria

Table D.10. Weighing matrix sub-criteria – Performance expert 1.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 1	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	7,00	7,00	3,61	0,76	
A2	0,14	1,00	3,00	0,76	0,16	
A3	0,14	0,33	1,00	0,37	0,08	
				4,73	*1,00*	TOT

Table D.11. Weighing matrix sub-criteria -- Performance expert 2.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 2	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	1,00	0,11	0,48	0,14	
A2	1,00	1,00	9,00	2,06	0,58	
A3	9,00	0,11	1,00	1,00	0,28	
				3,55	*1,00*	TOT

Table D.12. Weighing matrix sub-criteria – Performance expert 3.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 3	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	1,00	3,00	1,44	0,41	
A2	1,00	1,00	5,00	1,70	0,48	
A3	0,33	0,20	1,00	0,41	0,12	
				3,55	*1,00*	TOT

Table D.13. Weighing matrix sub-criteria -- Performance expert 4.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 4	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	1,00	7,00	1,90	0,47	
A2	1,00	1,00	7,00	1,90	0,47	
A3	0,14	0,14	1,00	0,28	0,07	
				4,08	*1,00*	TOT

Table D.14. Weighing matrix sub-criteria -- Performance expert 5.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 5	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	1,00	1,00	1,00	0,33	
A2	1,00	1,00	1,00	1,00	0,33	
A3	1,00	1,00	1,00	1,00	0,33	
				3,00	*1,00*	TOT

Table D.15. Weighing matrix sub-criteria -- Performance expert 6.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 6	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	3,00	5,00	2,44	0,60	
A2	0,33	1,00	7,00	1,32	0,32	
A3	0,20	0,14	1,00	0,31	0,08	
				4,08	*1,00*	TOT

Table D.16. Weighing matrix sub-criteria -- Performance expert 7.

WEIGHING SUB-CRITERIA (AHP METHOD) --- PERFORMANCE						
EXPERT 7	A1	A2	A3	Geometr. mean	Weights	
A1	1,00	1,00	0,11	0,48	0,11	
A2	1,00	1,00	0,20	0,59	0,13	
A3	9,00	5,00	1,00	3,51	0,77	
				4,58	*1,00*	TOT

Table D.17. Weighing matrix sub-criteria – Environmental impact expert 1.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 1	B1	B2	Geometr. mean	Weights	
B1	1,00	0,33	0,58	0,25	
B2	3,00	1,00	1,73	0,75	
			2,31	*1,00*	TOT

Table D.18. Weighing matrix sub-criteria – Environmental impact expert 2.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 2	B1	B2	Geometr. mean	Weights	
B1	1,00	0,20	0,45	0,17	
B2	5,00	1,00	2,24	0,83	
			2,68	*1,00*	TOT

Table D.19. Weighing matrix sub-criteria – Environmental impact expert 3.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 3	B1	B2	Geometr. mean	Weights	
B1	1,00	7,00	2,65	0,88	
B2	0,14	1,00	0,38	0,13	
			3,02	*1,00*	TOT

Table D.20. Weighing matrix sub-criteria – Environmental impact expert 4.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 4	B1	B2	Geometr. mean	Weights	
B1	1,00	7,00	2,65	0,88	
B2	0,14	1,00	0,38	0,13	
			3,02	*1,00*	TOT

Table D.21. Weighing matrix sub-criteria – Environmental impact expert 5.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 5	B1	B2	Geometr. mean	Weights	
B1	1,00	9,00	3,00	0,90	
B2	0,11	1,00	0,33	0,10	
			3,33	*1,00*	TOT

Table D.22. Weighing matrix sub-criteria – Environmental impact expert 6.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 6	A	B	Geometr. mean	Weights	
A	1,00	0,14	0,38	0,13	
B	7,00	1,00	2,65	0,88	
			3,02	*1,00*	TOT

Table D.23. Weighing matrix sub-criteria – Environmental impact expert 7.

WEIGHING SUB-CRITERIA (AHP METHOD) --- ENVIRONMENTAL IMPACT					
EXPERT 7	B1	B2	Geometr. mean	Weights	
B1	1,00	7,00	2,65	0,88	
B2	0,14	1,00	0,38	0,13	
			3,02	*1,00*	TOT

Table D.24. Weighing matrix sub-criteria – Efficiency expert 1.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 1	C1	C2	Geometr. mean	Weights	
C1	1,00	3,00	1,73	0,75	
C2	0,33	1,00	0,58	0,25	
			2,31	*1,00*	TOT

Table D.25. Weighing matrix sub-criteria – Efficiency expert 2.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 2	C1	C2	Geometr. mean	Weights	
C1	1,00	1,00	1,00	0,50	
C2	1,00	1,00	1,00	0,50	
			2,00	*1,00*	TOT

Table D.26. Weighing matrix sub-criteria – Efficiency expert 3.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 3	C1	C2	Geometr. mean	Weights	
C1	1,00	0,33	0,58	0,25	
C2	3,00	1,00	1,73	0,75	
			2,31	*1,00*	TOT

Table D.27. Weighing matrix sub-criteria – Efficiency expert 4.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 4	C1	C2	Geometr. mean	Weights	
C1	1,00	5,00	2,24	0,83	
C2	0,20	1,00	0,45	0,17	
			2,68	*1,00*	TOT

Table D.28. Weighing matrix sub-criteria – Efficiency expert 5.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 5	C1	C2	Geometr. mean	Weights	
C1	1,00	0,33	0,58	0,25	
C2	3,00	1,00	1,73	0,75	
			2,31	*1,00*	TOT

Table D.29. Weighing matrix sub-criteria – Efficiency expert 6.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 6	C1	C2	Geometr. mean	Weights	
C1	1,00	1,00	1,00	0,50	
C2	1,00	1,00	1,00	0,50	
			2,00	*1,00*	TOT

Table D.30. Weighing matrix sub-criteria – Efficiency expert 7.

WEIGHING SUB-CRITERIA (AHP METHOD) --- EFFICIENCY					
EXPERT 7	C1	C2	Geometr. mean	Weights	
C1	1,00	3,00	1,73	0,75	
C2	0,33	1,00	0,58	0,25	
			2,31	*1,00*	TOT

Table D.31. Weighing matrix sub-criteria – Applicability expert 1.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 1	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	5,00	5,00	7,00	3,64	0,62	
D2	0,20	1,00	0,33	1,00	0,51	0,09	
D3	0,20	3,00	1,00	5,00	1,32	0,22	
D4	0,14	1,00	0,20	1,00	0,41	0,07	
					5,87	*1,00*	TOT

Table D.32. Weighing matrix sub-criteria – Applicability expert 2.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 2	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	1,00	1,00	0,20	0,67	0,16	
D2	1,00	1,00	1,00	1,00	1,00	0,24	
D3	1,00	1,00	1,00	1,00	1,00	0,24	
D4	5,00	1,00	1,00	1,00	1,50	0,36	
					4,16	*1,00*	TOT

Table D.33. Weighing matrix sub-criteria – Applicability expert 3.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 3	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	1,00	1,00	3,00	1,32	0,30	
D2	1,00	1,00	1,00	3,00	1,32	0,30	
D3	1,00	1,00	1,00	3,00	1,32	0,30	
D4	0,33	0,33	0,33	1,00	0,44	0,10	
					4,39	*1,00*	TOT

Table D.34. Weighing matrix sub-criteria – Applicability expert 4.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 4	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	9,00	1,00	3,00	2,28	0,38	
D2	0,11	1,00	0,11	0,11	0,19	0,03	
D3	1,00	9,00	1,00	5,00	2,59	0,44	
D4	0,33	9,00	0,20	1,00	0,88	0,15	
					5,94	*1,00*	TOT

Table D.35. Weighing matrix sub-criteria – Applicability expert 5.

EXPERT 5	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	7,00	1,00	3,00	2,14	0,42	
D2	0,14	1,00	0,33	0,20	0,31	0,06	
D3	1,00	3,00	1,00	3,00	1,73	0,34	
D4	0,33	5,00	0,33	1,00	0,86	0,17	
					5,05	*1,00*	TOT

Table D.36. Weighing matrix sub-criteria – Applicability expert 6.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 6	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	3,00	7,00	0,20	1,43	0,30	
D2	0,33	1,00	0,20	0,20	0,34	0,07	
D3	5,00	0,20	1,00	5,00	1,50	0,31	
D4	5,00	5,00	0,20	1,00	1,50	0,31	
					4,76	*1,00*	TOT

Table D.37. Weighing matrix sub-criteria – Applicability expert 7.

WEIGHING CRITERIA (AHP METHOD) --- APPLICABILITY							
EXPERT 7	D1	D2	D3	D4	Geometr. mean	Weights	
D1	1,00	5,00	1,00	5,00	2,24	0,46	
D2	0,20	1,00	0,20	0,33	0,34	0,07	
D3	1,00	5,00	1,00	0,20	1,00	0,20	
D4	0,20	3,00	5,00	1,00	1,32	0,27	
					4,89	*1,00*	TOT

Table D.38. Final mean weight sub-criteria.

FINAL WEIGHT SUB-CRITERIA		
	FINAL MEAN WEIGHT	
A1 (WATER ABSORPTION RATIO)	**0,40**	
A2 (BOND STRENGTH)	**0,35**	
A3 (GAS PERMEABILITY)	**0,25**	
	1,00	**TOT**
B1 (TOXICITY)	**0,58**	
B2 (APPEARANCE ALTERATION)	**0,42**	
	1,00	**TOT**
C1 (APPLICATION FEASABILITY)	**0,55**	
C2 (HARDEN/DRY TIME)	**0,45**	
	1,00	**TOT**
D1 (TEMPERATURE RESISTANCE)	**0,38**	
D2 (SALINE ATTACK)	**0,12**	
D3 (PORE PRESSURE RESISTANCE)	**0,29**	
D4 (CHEMICAL ATTACK)	**0,20**	
	1,00	**TOT**

Table D.39. Final weight all criteria (sub-criteria multiplied by main criteria).

FINAL WEIGHT ALL CRITERIA		
	FINAL WEIGHT	
A1 (WATER ABSORPTION RATIO)	0,13	
A2 (BOND STRENGTH)	0,12	
A3 (GAS PERMEABILITY)	0,08	
B1 (TOXICITY)	0,09	
B2 (APPEARANCE ALTERATION)	0,07	
C1 (APPLICATION FEASABILITY)	0,13	
C2 (HARDEN/DRY TIME)	0,11	
D1 (TEMPERATURE RESISTANCE)	0,10	
D2 (SALINE ATTACK)	0,03	
D3 (PORE PRESSURE RESISTANCE)	0,08	
D4 (CHEMICAL ATTACK)	0,06	
	1,00	TOT