buildings

MDPI

Article

Waterproofing Performance Evaluation and Grading Methods for Lowest Level Floor Slabs and Positive-Side Walls of Residential Underground Structures

Ki-won An [1] and Byoungil Kim [2,*]

[1] Institute of Construction Technology, Seoul National University of Science & Technology, Seoul 01811, Republic of Korea; ankiwon@seoultech.ac.kr

[2] School of Architecture, Seoul National University of Science & Technology, Seoul 01811, Republic of Korea

* Correspondence: bikim@seoultech.ac.kr; Tel.: +82-2-970-6512

Abstract: In Korea, large-scale apartment projects often give rise to disputes among residents, which have prompted implementation of the "Apartment Performance Rating System" by the Ministry of Land, Infrastructure, and Transport. In addition, disputes related to leakage defects in apartment structures are increasing, especially in underground spaces of joint residential complexes. This study aims to identify waterproofing materials and methods for specific underground structure components through experimental evaluations and to assign waterproofing performance ratings similar to existing apartment house grades. These performance ratings will serve as foundational data to prevent leakage in joint residential complexes. This study proposes composite and self-adhesive sheet waterproofing as effective methods, emphasizing the significance of sheet waterproofing materials for excellent performance. The need for improved waterproofing materials to address long-term permeability issues is also highlighted. This research provides essential data for future waterproofing performance ratings; therefore, contributing to construction quality and safety in joint residential complexes.

Keywords: performance grade; waterproofing; basement floor slab; positive-side walls; evaluation technique

Citation: An, K.-w.; Kim, B. Waterproofing Performance Evaluation and Grading Methods for Lowest Level Floor Slabs and Positive-Side Walls of Residential Underground Structures. *Buildings* **2023**, *13*, 2679. https://doi.org/10.3390/buildings13112679

Academic Editor: Daxu Zhang

Received: 22 August 2023
Revised: 7 October 2023
Accepted: 18 October 2023
Published: 24 October 2023

1. Introduction

In Korea, when new town developments or urban planning projects are designed, construction plans for apartment housing are typically established to accommodate large numbers of people [1,2]. Since these apartment buildings house a significant population in close proximity, disputes and complaints often arise, leading to frequent lawsuits. To address this issue and to provide residents with useful information, the Ministry of Land, Infrastructure, and Transport has established the "Apartment Performance Rating System", which informs prospective residents of building performances according to five categories: "noise performance", "structural performance", "environmental performance", "living environment performance", and "fire and firefighting performance" [3]. This system aims to enable residents to make informed choices and to prevent safety accidents and conflicts [4].

However, despite implementation of this system, conflicts and legal proceedings regarding seepage issues in apartment construction are annually on the rise [5]. The main cause of these problems is the recent trend of large-scale and spacious underground parking lots in joint residential complexes, which has led to extensive underground spaces [6]. Cracks caused by movement and vibrations in these underground spaces, as well as increased water pressure due to groundwater blockage, have created vulnerabilities for leakage issues in the underground areas [7]. As the significance of underground spaces continues to grow, the absence of clear directives and follow-up actions for seepage issues has contributed to the increasing incidence of such problems [8]. Moreover, the current legal and institutional indicators in Korea have insufficient provisions for preventing leaks [9]. The limited time residents spend in underground spaces and the concealed nature of the walls make it challenging to recognize defects unless direct property damage occurs [10].

Additionally, if a small leak develops into a significant defect, the underground space may already have experienced severe structural damage due to leakage, and aging of the structure can further compromise safety [11,12]. Considering the time involved in disputes, litigation, and defect repair, the damage caused by structural leakage can escalate [13]. Hence, there is a pressing requirement for legislation, organizational steps, leak prevention mechanisms, and protocols that are tailored to avert seepage in the subterranean areas of collaborative residential compounds in Korea [14,15].

Therefore, this study aims to identify waterproofing materials and construction methods applicable to specific parts of an underground structure, such as the underground outer walls and the lowest level floor slab. The selected materials and methods undergo experimental evaluations to determine waterproofing performance ratings for each component of the underground structure. The waterproofing performance ratings are classified similarly to the existing performance grades set for apartment houses, and could be used as foundational data for waterproofing performance grades to prevent leakage in joint residential complexes.

2. Rating System for Apartment Housing Performance

The Apartment Performance Rating System in Korea has undergone several changes and transitions. It was initially introduced in January 2006 and underwent revisions to enhance standards in July 2007 and January 2009. It was removed from the housing performance rating requirement in February 2013 and began operating as a green building certification system from June of the same year. Currently, the Ministry of Land, Infrastructure and Transport (Notification No. 2014-705) and the Ministry of Environment (Notification No. 2014-213) oversee the system according to the "Apartment Certification Review Standards" (Table 1) [16].

Table 1. Waterproofing materials and methods used for a basement structure's lowest level floor slab and positive-side walls.

Item (Code)	Materials (Composition)	Note (Waterproofing Position)
A Material	Composite waterproofing material (adhesive flexible sealant + modified asphalt sheet waterproofing)	Composite waterproofing (positive side)
B Material	Self-adhesive waterproofing sheet (rubber asphalt based or butyl rubber based)	Sheet waterproofing (positive side)
C Material	Modified asphalt waterproofing sheet (rubber asphalt based)	Sheet waterproofing (positive side)
D Material	Membrane waterproofing material (rubber asphalt based or polyurethane rubber based)	Membrane waterproofing (positive side and negative side)
E Material	Silicate-based coating waterproofing material or liquid waterproofing material	Concrete waterproofing (negative side)
F Material	Untreated	-

The performance rating evaluation system for apartment houses consists of 56 items which are divided into 26 crucial elements and 30 discretionary components. In addition, regarding the method of setting the performance grade, 19 items have been calculated according to the selection of applied materials or construction methods, and 14 items have been calculated to calculate the performance ratio [17]. Furthermore, nine performance configurations are incorporated into the lower tier to elevate it compared to the higher tier, while the remaining classifications are stratified based on factors such as area, proximity, material/build quality, and the assessment and scoring of the tier [18]. Since the top three items comprise 42 of the total 56 items, i.e., about 75% of the total, it is judged that the performance rating plan for the waterproofing field can be used stably in the performance grade utilization process if the above rating setting method is carried out [19].

In conclusion, the performance grade of apartment houses included as preliminary certification in an eco-friendly building certification has been determined using design drawings, plans, quality certificates, etc., [20] of apartment houses, or the performance grade has been measured by the quality and high performance of materials used in constructed [21]. Specifically, during the rating establishment process, the performance assessment was conducted through diverse approaches including the quantity of materials utilized, area-based ratios, proximity, scoring, and the enhancement of performance grades through the inclusion of additional materials in earlier phases [22]. In addition, the performance grade has been evaluated taking into consideration various conditions such as structure and the environment, but it has been confirmed that environmental pollution and inconvenience among users' lives have not been considered at all [23,24].

3. Waterproofing Performance of Underground Structures in Apartment Buildings Verification Plan and Test Method

Various waterproofing materials such as sheets, coatings, and composite waterproofing materials are applied to the lowest level floor slab and outer walls of underground structures of apartments, and even if similar raw materials are used, their physical properties vary. For example, since the correlation between tensile strength and elongation in tensile performance is inversely proportional, there is a limit to judging the excellence of the materials with quantitative results. Accordingly, this study investigates and analyzes the application method applied to the bottom floor slab and outer walls of an underground structure, and plans and conducts a test to establish performance ratings of materials to be used as a constructive performance evaluation method.

For this study's tests, the construction method of the waterproofing materials was carried out by referring to the construction manual, any material property degradation resulting from the use of construction equipment, such as torches or hot air welders, as specified in some construction methods, was not considered, and the test was conducted accordingly.

3.1. Checking the Waterproofing Method and Type of Test Evaluation

In Korea, waterproofing methods for the lowest level floor slabs of residential underground structures can be classified based on the construction area or the application method of the materials. Depending on the construction area, applicable construction methods include positive side waterproofing applied between the upper surface of the foundation mat and the lower surface of the lowest level floor slab, negative side waterproofing applied to the upper surface of the lowest level floor slab, and a non-treated method where no waterproofing treatment is applied.

Regarding the trend of materials used in the above-mentioned methods, synthetic polymer-based waterproofing sheets (such as PVC, TPO, and EPDM) are commonly used for waterproofing the top surfaces of the uppermost slabs in underground structures or as exposed waterproofing methods on the roofs of residential buildings. For underground applications, asphalt-based waterproofing sheets are primarily used to achieve a tight bond with the structure. Additionally, for sheet waterproofing, asphalt or asphalt-urethane-based sheet waterproofing materials are widely used. In terms of liquid waterproofing, materials like acrylic-based coatings that are easy to apply to the negative side of structures are frequently used.

Finally, waterproof concrete with enhanced impermeability has waterproofing capabilities, but it constantly absorbs moisture, such as groundwater, due to its permeable nature. This can potentially lead to long-term effects on the corrosion of a structure's reinforcement.

Additionally, assuming that both negative side and positive side waterproofing methods create a pathway for leakage due to concrete cracks, waterproof concrete exhibits similar waterproofing performance to non-treated methods. Based on this assumption, the test was conducted.

Therefore, we distinguished between composite waterproofing methods and single waterproofing methods (sheets, membranes) used on the lowest level floor slabs and outer walls of underground structures and focused on materials with high construction frequency and preference, as listed in Table 1.

After scrutinizing the testing and assessment approaches for waterproofing materials and construction techniques used to grade the waterproofing efficacy of ground-level slabs and the positive-side walls of apartment complexes, we verified that a performance appraisal system for these materials and methods is overseen by the National Construction Standards Center (KCSC). In this performance evaluation method, a waterproofing performance evaluation method is applied to the outer walls and lowest level floor slab, and a basic lower pad subsidence stability test is added as a waterproofing performance evaluation for the lowest level floor slab in case reverse installation of waterproofing materials is required on the foundation mat.

Accordingly, in this study, a self-developed test method called "changes in underground environment due to waterproofing applications for underground structures" and the test evaluation method of "KCS 11 44 00: 2018 Joint District" were adapted and applied to determine the differences between the application of positive side waterproofing and negative side waterproofing in an underground structure [25]. The test verification plan is set as shown in Table 2 below.

Table 2. Verification plan for grading the performances of the waterproofing materials and methods used for the lowest level floor slab and positive-side walls of an underground structure.

Main Category	Middle Category	Subcategory	Verification Plan
Positive side waterproofing or negative side waterproofing	Positive side waterproofing	-	Evaluation of changes in underground environment due to waterproofing applications for underground structures, a self-development assessment
	Negative side waterproofing	-	
	Untreated	-	
Waterproofing material	Composite waterproofing material	-	KCS 11 44 00: 2018 evaluation of performance for waterproofing materials and methods for underground structures
	Single waterproofing material	Sheet	
		Membrane	

3.2. Test Method

3.2.1. The Changes in Environment Due to Waterproofing Applications for Underground Structures Test

The proposed "changes in underground environment due to waterproofing applications for underground structures" test, for verifying the waterproofing performance rating of underground structures in multi-unit housing, aims to measure and compare the differences in moisture penetration and humidity increase caused by positive side waterproofing, negative side waterproofing, and non-treatment at different temperatures. This test is intended to provide data for the performance rating of waterproofing materials. In this regard, test specimens were prepared as follows: Ø100 × 30 mm mortar specimens (Refer to Figure 1) with various positive side waterproofing methods, negative side waterproofing methods, and untreated specimens were each placed on the base surface. A cylindrical acrylic test chamber (Ø100 × 100 mm, thickness = 5 mm) was used that was capable of simulating underground conditions and facilitating data acquisition. The specimens were categorized into positive side waterproofing, negative side waterproofing, and untreated specimens. Water was filled in the lower part of the chamber, and on the upper part, temperature and humidity sensors were installed.

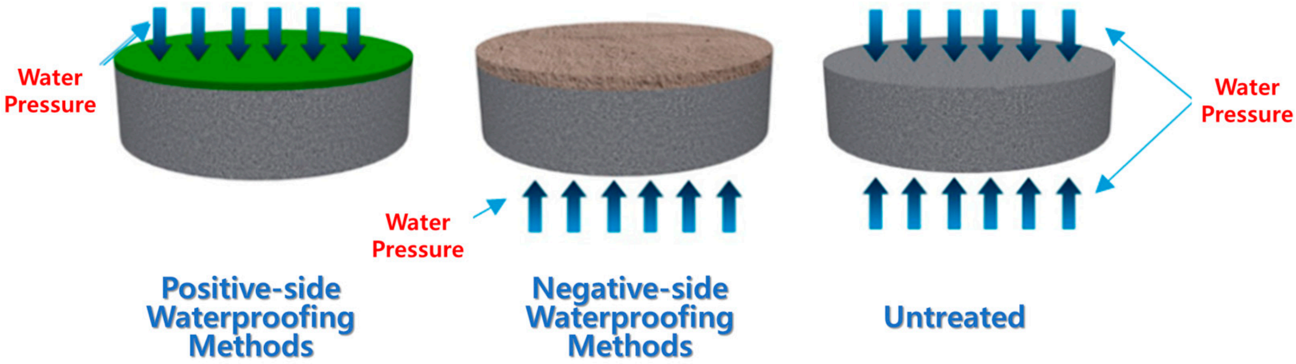


Figure 1. Test specimens based on changes in underground environment due to waterproofing applications for underground structures.

Subsequently, during the testing process, the waterproofing performance was evaluated by measuring permeation or absorption in a static water state where no hydraulic pressure was applied. The test preparation was carried out as illustrated in Figure 2.

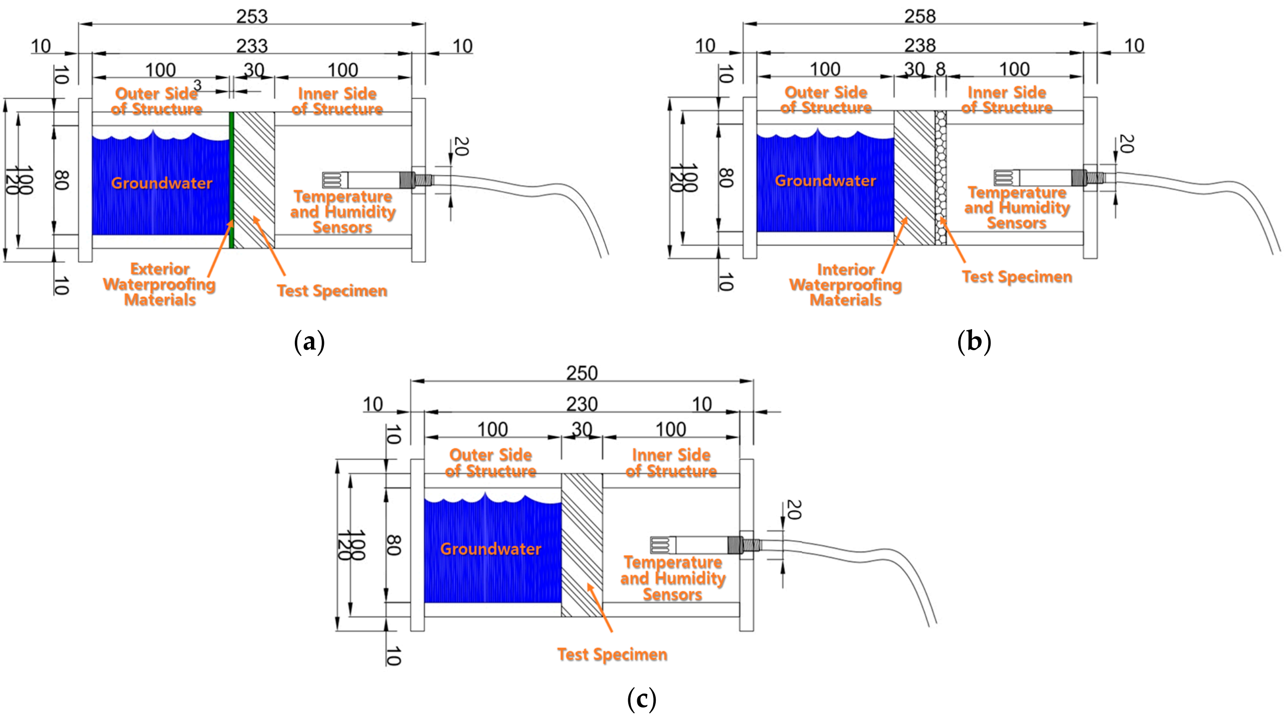


Figure 2. Test diagram for evaluating changes in underground environment due waterproofing applications for underground structures: (**a**) Positive side waterproofing test specimen; (**b**) negative side waterproofing test specimen; (**c**) untreated test specimen.

The connected test specimens were tested under different temperature conditions as follows: winter temperature condition (4 °C), spring and autumn temperature condition (20 °C), and summer temperature condition (40 °C). The data logger collected and stored data at intervals of 5 data points per hour, which was equivalent to every 12 min. The data collection period was 168 h (1 week), resulting in a total of 840 data points. The observed data on leakage and humidity variations were analyzed based on these temperature conditions.

3.2.2. KCS 11 44 00: 2018 Joint District Performance Evaluation

Various waterproofing materials such as sheets, membranes, and concrete waterproofing can be applied to the lowest level floor slabs of residential underground structures. Evaluating these materials according to specific criteria is difficult due to the significant variations in properties and characteristics among different materials. Therefore, in Korea, the waterproofing performance evaluation method "KCS 11 44 00: 2018 Joint District" was selected as the evaluation method for underground structures. The tests were conducted on the lowest level floor slabs and outer walls to confirm the performance of each waterproofing method. In the case of the lowest level floor slabs, in consideration of issues like differential settlement, an additional test method called the "subgrade floor pad settlement stability" test was employed to assess the waterproofing material's performance in relation to settlement of the foundation mat.

Therefore, the test method for grading the underground outer walls was conducted using the joint test method KCS 11 44 00: 2018 Joint District. Additionally, for grading the lowest level floor slabs in underground structures, the test was conducted by adding the subgrade floor pad settlement stability test to the joint test method KCS 11 44 00: 2018 Joint District. The test method for KCS 11 44 00: 2018 Joint District conducted in this study is identical to the test methods from Item 1 to Item 8 in Table 3, as presented in *MDPI Buildings* 2023, 13, 2164. https://doi.org/10.3390/buildings13092164 (A Study on Verification of Waterproofing Method Properties for Performance Grading in Apartment Houses—Upper Slab of the Underground Structure) (access date: 26 August 2023). Additionally, the test method for the subgrade floor pad settlement stability test conducted for the lowest level floor slab in the underground structure is detailed in Table 3 [26].

Table 3. Testing methods for verification of performance of the lowest level floor slab and positive-side walls in an underground structure.

Item			Contents	Note
1	Chemical resistance test	Test specimen	Same test in Table 3 [26]	-
		Pretreatment		
		Test methods		
2	Structural behavior responsiveness	Test specimen	Same test in Table 3 [26]	Referring to Figure 3
		Pretreatment		
		Test methods		
3	Moisture adhesion performance test	Test specimen	Same test in Table 3 [26]	-
		Pretreatment		
		Test methods		
4	Water tightness	Test specimen	Same test in Table 3 [26]	-
		Pretreatment		
		Test methods		
5	Temperature dependency	Test specimen	Same test in Table 3 [26]	-
		Pretreatment		
		Test methods		
6	Crack resistance	Test specimen	Same test in Table 3 [26]	-
		Pretreatment		
		Test methods		
7	Durability	Test methods	Same test in Table 3 [26]	-
8	Low-temperature adhesion stability	Pretreatment	Same test in Table 3 [26]	-
		Test methods		

Table 3. *Cont.*

Item			Contents	Note
9	Subgrade floor pad settlement stability	Test specimen	• Adhering 100 × 100 mm forced attachment on the upper and lower parts of the test specimens • Conducting a bond strength test at a tensile speed of 10 mm/min	Testing limited to the lowest level floor slab, referring to Figure 4
		Test methods	• Adhering 100 × 100 mm forced attachment on the upper and lower parts of the test specimens • Conducting a bond strength test at a tensile speed of 10 mm/min	

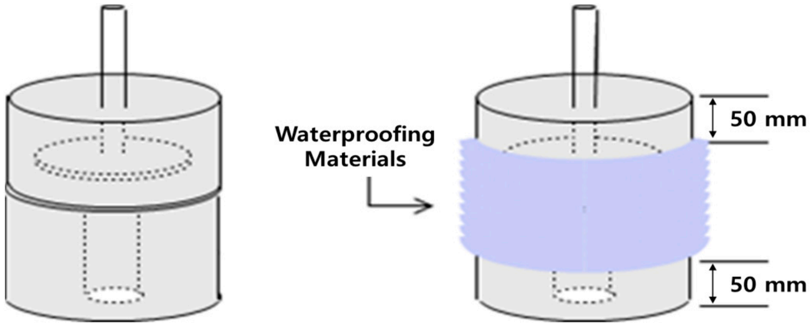


Figure 3. Performance of the structural response and adaptability test specimen.

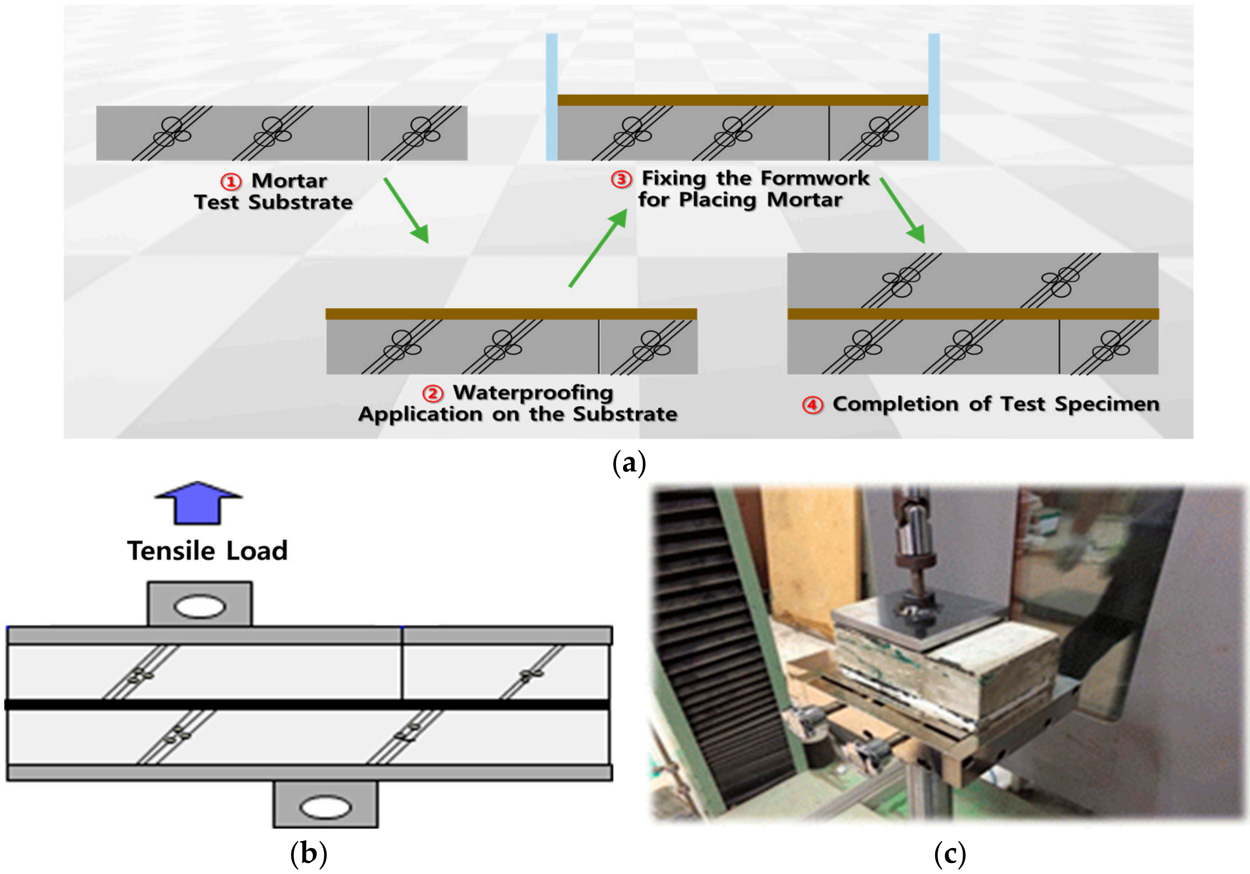
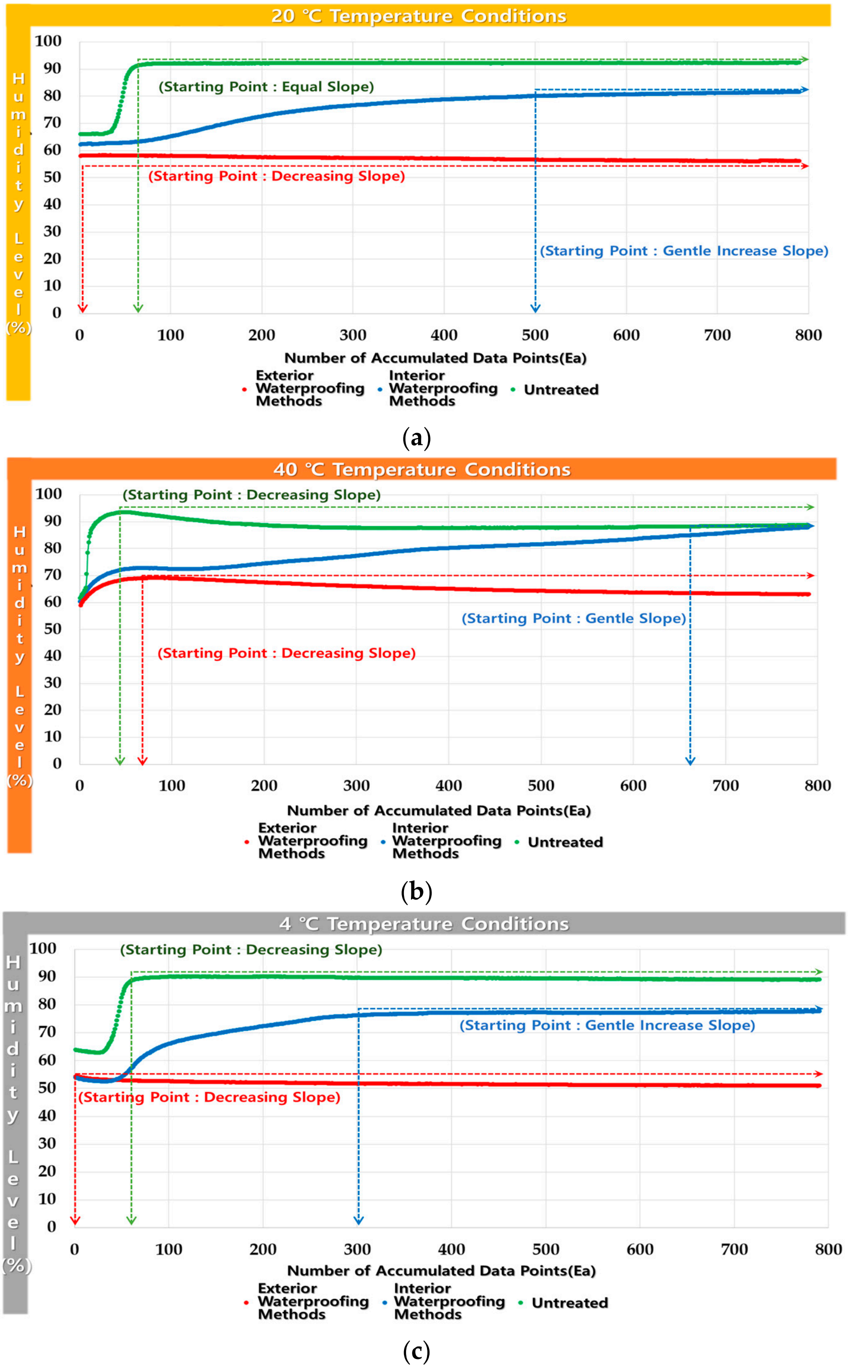


Figure 4. Methods for the subgrade floor pad settlement stability test: (**a**) Methods for fabrication of the subgrade floor pad settlement stability test specimens; (**b**) method for the subgrade floor pad settlement stability test; (**c**) status of the subgrade floor pad settlement stability test.

4. Results of Waterproofing Performance Rating for Underground Structures in Apartment Buildings

4.1. Test Results of the Changes in Underground Environment Due to the Waterproofing Applications for Underground Structures

As a result of the changes in the underground environment according to the application of waterproofing methods in the underground structure, a total of nine specimens were tested using data loggers, and each specimen acquired over 800 data points during a 168 h time period. The humidity changes for each specimen, where positive side waterproofing, negative side waterproofing, and untreated methods were applied to the underground structure under different temperature conditions, are shown in Figure 5 below.



(a) (b) (c)

Figure 5. Underground Environment Change Test Results, they should be listed as: (**a**) 20 °C Temperature Conditions; (**b**) 40 °C Temperature Conditions; (**c**) 4 °C Temperature Conditions.

When analyzing the humidity patterns at different temperature conditions, on the one hand, it was observed that at 20 °C, positive side waterproofing led to a gradual decrease in humidity over time. On the other hand, negative side waterproofing initially showed a gradual and mild change in humidity up to around the 70th data point (approximately 14 h), but after that point, the humidity started to increase gradually until the end of the test. As for the untreated specimens, there was a moderate change in humidity until around the 40th data point (approximately 8 h), but then the humidity increased rapidly from the 70th data point (approximately 14 h, 6 h later) and remained at an elevated level until the end of the test.

At 40 °C, the positive side waterproofing method resulted in an increase in humidity up to approximately the 70th data point (around 14 h), but later it gradually decreased, reaching a level similar to the initial humidity by the end of the test. Conversely, the negative side waterproofing method exhibited a continuous increase in humidity from the beginning to the end of the test, showing a humidity level similar to that of the untreated specimens by the test's conclusion.

At 4 °C, the positive side waterproofing method displayed a progressive decrease in humidity over time. Meanwhile, the negative side waterproofing method showed a gradual increase in humidity until approximately the 300th data point (around 60 h), and then it maintained the increased humidity level until the end of the test. In contrast, the untreated specimens experienced a rapid increase in humidity until around the 70th data point (approximately 14 h), followed by maintaining the elevated humidity level until the end of the test.

4.2. KCS 11 44 00: 2018 "Joint District" Performance Evaluation Test Results

4.2.1. KCS 11 44 00: 2018 "Joint District" Performance Evaluation Index Checked

The scoring for KCS 11 44 00: 2018 "Joint District" was distributed to allow for variations in scores based on the quantitative performance results compared to the original evaluation criteria. This was achieved by deducting points from the unsuccessful specimens relative to the total number of test specimens. For the lowest level floor slab, the scoring was based on the evaluation results for items 1 to 9 in Table 4, while for the positive-side walls, the scoring was based on the evaluation results for items 1 to 8 in Table 4 [26].

Table 4. Testing methods for verification of the performance of lowest level floor slabs and positive-side walls in underground structures.

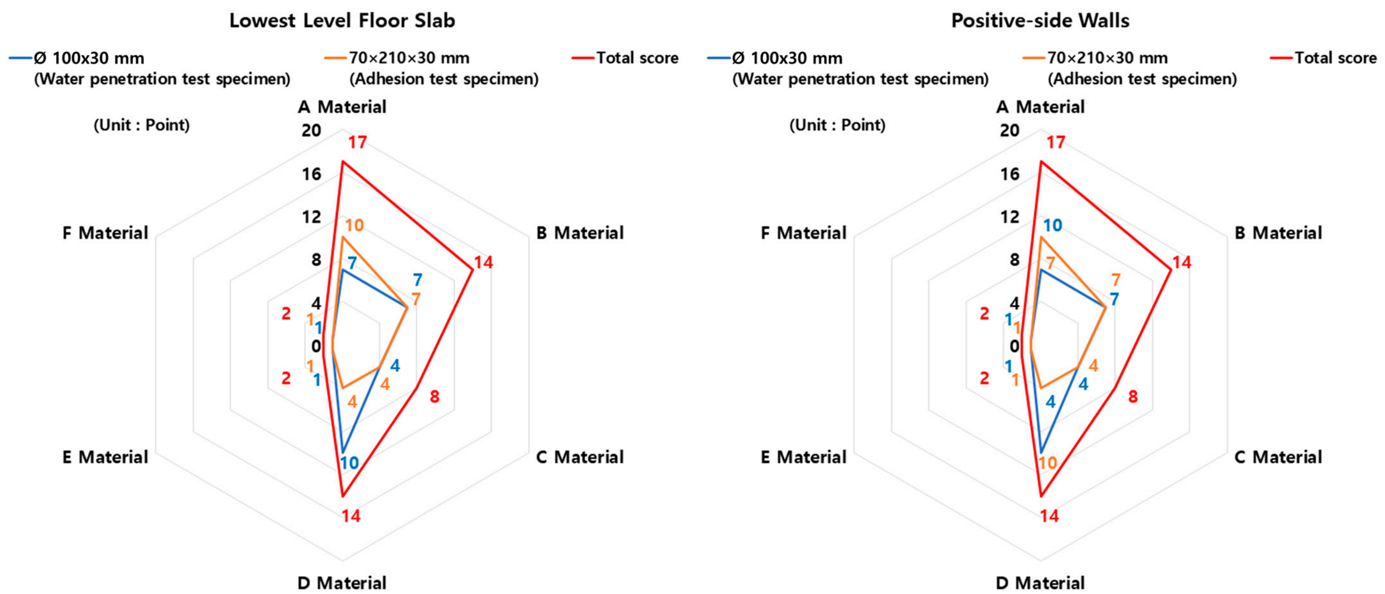
Sequence	Item	Number of Test Specimens	Evaluation Criteria	Score			
				Lowest Level Floor Slab		Positive-Side Wall	
				Max Score	Min Score	Max Score	Min Score
1	Chemical immersion stability	6	A deduction of three points will be applied for each test specimen showing performance degradation.	20 points	2 points	20 points	2 points
2	Structural behavior responsive-ness	6	A deduction of three points will be applied for each test specimen showing leakage.	20 points	2 points	20 points	2 points
3	Moisture adhesion stability	6	A deduction of one point will be applied for each test specimen showing displacement.	10 points	4 points	10 points	4 points
4	Water tightness	6	Each test specimen will incur a one-point deduction for permeability.	8 points	2 points	10 points	4 points

Table 4. *Cont.*

Sequence	Item	Number of Test Specimens	Evaluation Criteria	Score			
				Lowest Level Floor Slab		Positive-Side Wall	
				Max Score	Min Score	Max Score	Min Score
5	Temperature dependency	18	Each test specimen will receive a 0.5-point deduction for occurrences of locking, discoloration, displacement, cracking, delamination, and permeation.	8 points	0 points	10 points	1 point
6	Crack resistance	9	Each test specimen will incur a one-point deduction for the detachment of waterproofing material.	8 points	0 points	10 points	1 point
7	Durability	-	Two points will be deducted for each test specimen that does not meet the specific quality standards for the material.	8 points	0 points	10 points	0 points
8	Low-temperature adhesion stability	12	A deduction of half a point will be applied for each test specimen showing displacement.	10 points	4 points	10 points	4 points
9	Subgrade floor pad settlement stability	3	A deduction of two points will be made for each test specimen experiencing detachment of the waterproofing layer.	8 points	2 points	-	-
		Total Score		100 points	16 points	100 points	16 points

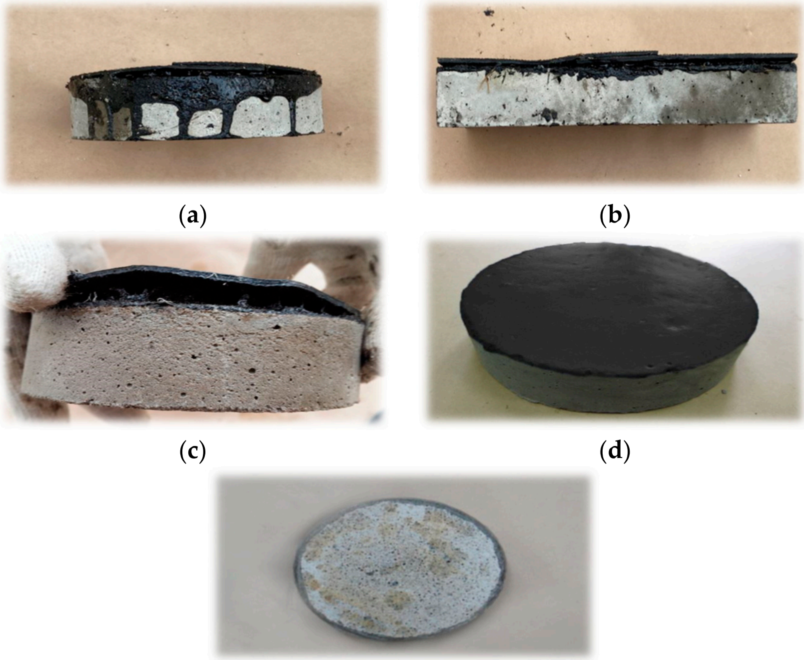
4.2.2. Chemical Immersion Stability

The test results for chemical immersion stability are shown in Figures 6 and 7 below.



(a) (b)

Figure 6. KCS 11 44 00: 2018 "Joint District" chemical immersion stability test results: (**a**) Lowest level floor slab; (**b**) positive-side walls.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 7. KCS 11 44 00: 2018 "Joint District" Chemical Immersion Stability Specimen Test results: (**a**) A Material; (**b**) B Material; (**c**) C Material; (**d**) D Material; (**e**) E Material.

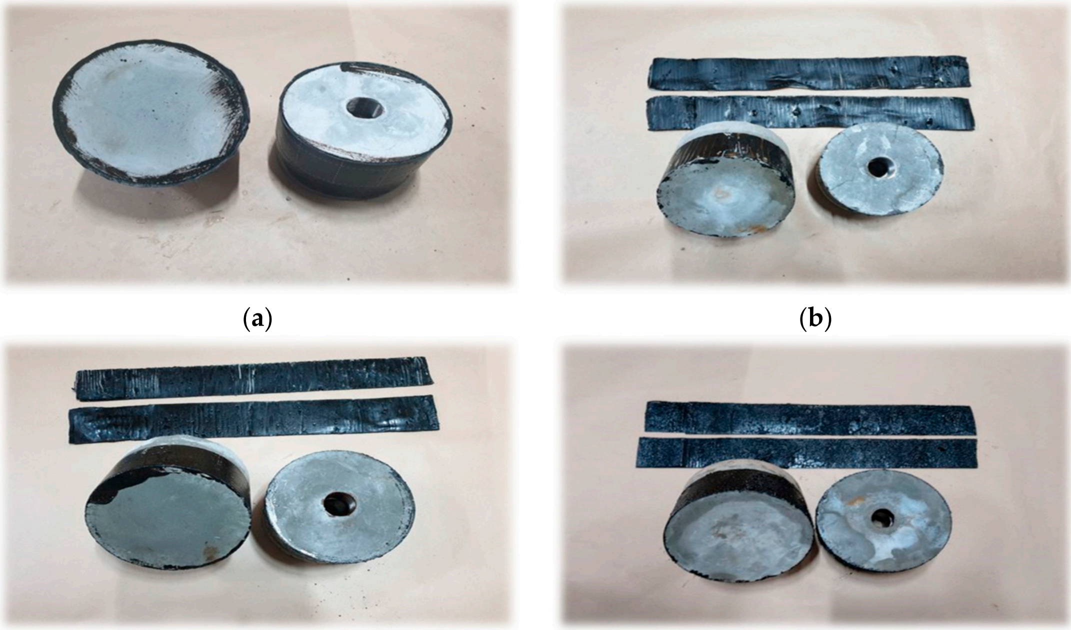
After subjecting the materials to a chemical immersion stability test, it was determined that material A scored 17 points for both the lowest level floor slab and the outer walls, while material B scored 14 points for both components. Additionally, material C received a score of 8 points for both the lowest level floor slab and the outer walls, attributed to joint excitation in four test specimens. Material D, on the other hand, garnered 14 points for both the lowest level floor slab and the outer walls. Finally, both material E and F were rated at two points for both the lowest level floor slab and the outer walls, owing to discoloration and non-testability across all test pieces.

4.2.3. Structural Behavior Responsiveness

The test results for structural behavior responsiveness are shown in Figures 8 and 9 below.

(**a**) (**b**)

Figure 8. KCS 11 44 00: 2018 "Joint District" structural behavior responsiveness test results: (**a**) Lowest level floor slab; (**b**) positive-side walls.



(**a**) (**b**) (**c**) (**d**)

Figure 9. KCS 11 44 00: 2018 "Joint District" structural behavior responsiveness specimen test results: (**a**) A Material; (**b**) B Material; (**c**) C Material; (**d**) D Material.

Following the structural behavior correspondence test, material A exhibited leakage on one moist surface. Meanwhile, material B showed leakage from one damp surface, resulting in a score of 17 points for both the lowest level floor slab and the outer walls. Additionally, material C experienced leakage on two wet surfaces and one dry surface, leading to an assessment of 11 points for both the lowest level floor slab and the outer walls. As for materials D, E, and F, they were rated at two points each.

4.2.4. Moisture Adhesion Stability

The test results for moisture adhesion stability are shown in Figure 10 below.

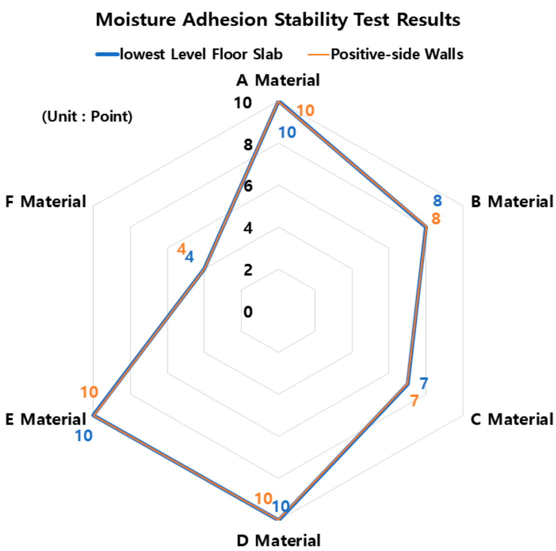


Figure 10. KCS 11 44 00: 2018 "Joint District" moisture adhesion stability test results.

Following the moisture adhesion stability test, on the one hand, material A received a score of 10 points for both the lowest level floor slab and the outer walls, as there were no abnormalities observed in the test piece under all conditions. Material B, on the other hand, attained a score of 8 points for both components. Moreover, material C garnered 7 points for both the lowest level floor slab and the outer walls due to exposure to moisture, freezing and melting cycles, and repeated exposure to cold temperatures. Materials D and E were both verified to have 10 points for both the lowest level floor slab and the outer walls. As for material F, it was not subjected to experimentation under all conditions, resulting in a confirmation of four points for both the lowest level floor slab and the outer walls.

4.2.5. Water Tightness

The test results for water tightness are shown in Figures 11 and 12 below.

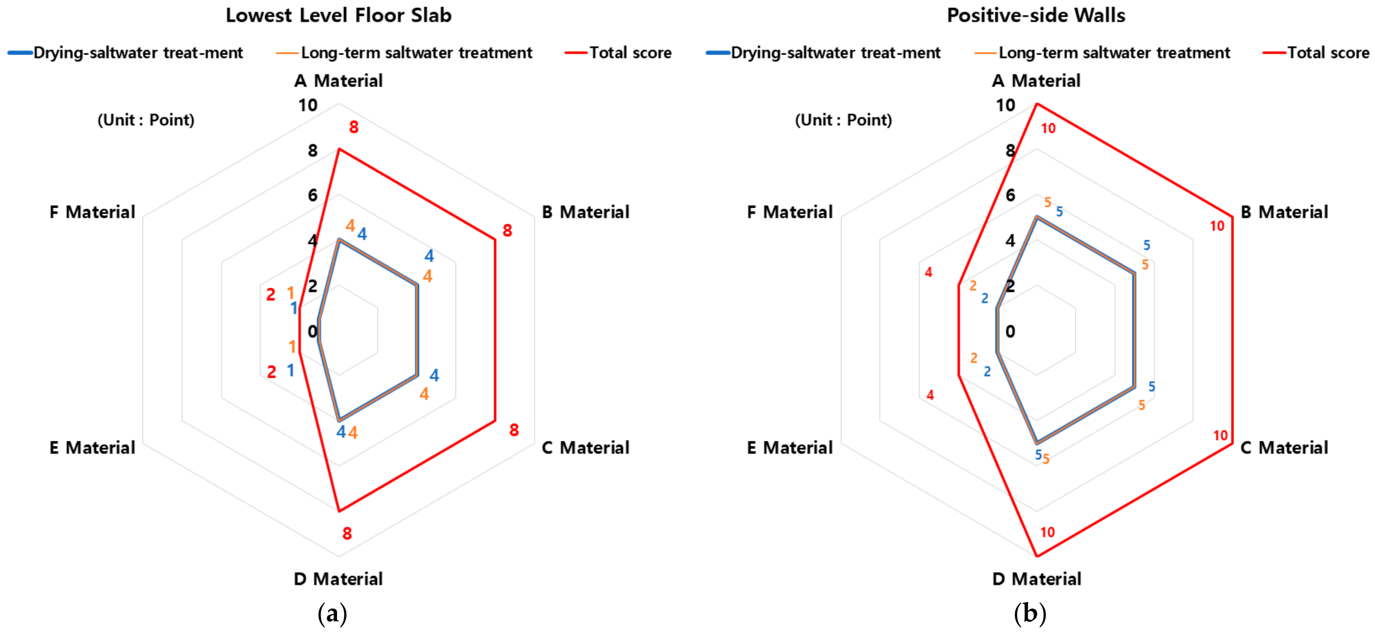


Figure 11. KCS 11 44 00: 2018 "Joint District" water tightness test results: (**a**) Lowest level floor slab; (**b**) positive-side walls.

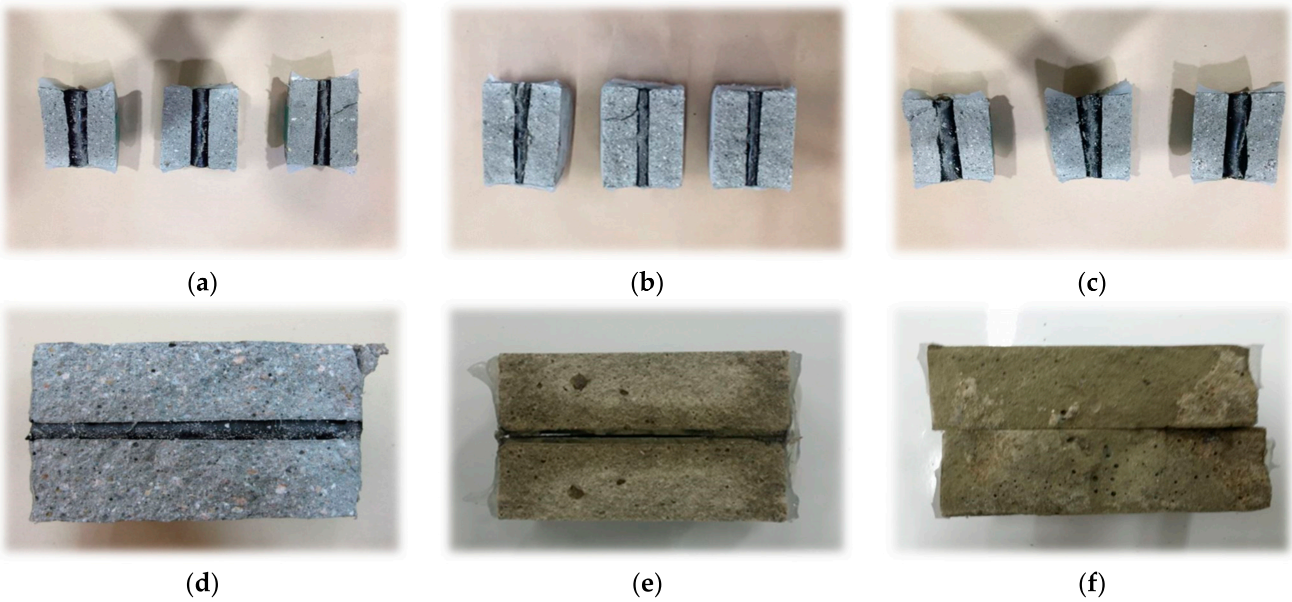


Figure 12. KCS 11 44 00: 2018 "Joint District" water tightness specimen test results: (**a**) A Material; (**b**) B Material; (**c**) C Material; (**d**) D Material; (**e**) E Material; (**f**) F Material.

Following the water-tightness test, the lowest level floor slab and the outer walls received scores of 8 points, while another set of lowest level floor slab and outer walls achieved 10 points. Additionally, a different combination of lowest level floor slab and outer walls obtained 2 points and 4 points, respectively.

4.2.6. Temperature Dependence

The test results for temperature dependence are shown in Figure 13 below.

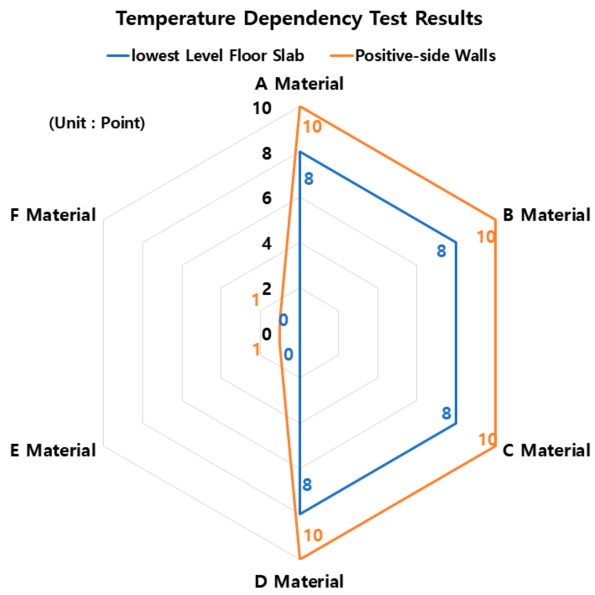


Figure 13. KCS 11 44 00: 2018 "Joint District" temperature dependence test results.

After conducting the temperature dependence test, on the one hand, it was observed that materials A, B, C, and D showed no permeation under all conditions. As a result, they were rated at 8 points for the lowest level floor slab and 10 points for the outer walls. On the other hand, both material E and material F exhibited permeation under all conditions.

4.2.7. Crack Resistance

The test results for crack resistance are shown in Figure 14 below.

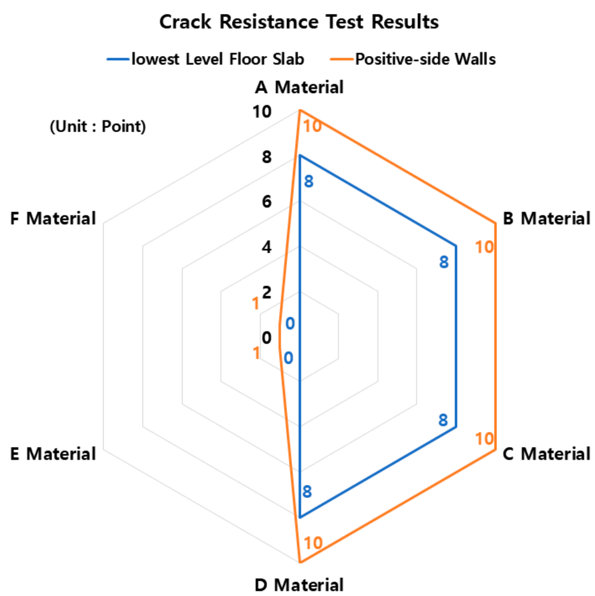


Figure 14. KCS 11 44 00: 2018 "Joint District" crack resistance test results.

Following the crack resistance test, materials A, B, C, and D exhibited no cracking or breakage in the test specimens under all conditions. Consequently, the lowest level floor slab was rated at 8 points, and the outer walls received a score of 10 points.

4.2.8. Durability

The test results for durability are shown in Table 5 and Figure 15 below.

As a result of the durability test, materials A, B, C, D, and E all met each quality standard item, and the lowest level floor slab and outer walls received scores of 8 points and 10 points, respectively.

Table 5. KCS 11 44 00: 2018 "Joint District" durability test results.

Item		Test Results	Note
A Material (composite waterproofing material (adhesive flexible sealant + modified asphalt sheet waterproofing))		(1) Korean Industrial Standard KS F 4917-16 "Modified Asphalt Waterproofing Sheet": Satisfied all quality criteria (2) Korean Industrial Standard KS F 4935-18 "Adhesive Flexible Rubber Asphalt-based Leakage Repair Injecting Sealant: Satisfied all quality criteria	-
Score	Lowest level floor slab	8 points	
	Positive-side walls	10 points	
B Material (self-adhesive waterproofing sheet (rubber asphalt-based or butyl rubber-based))		(1) Korean Industrial Standard KS F 4934-18 "Self-Adhesive Rubberized Asphalt Waterproofing Sheet": Satisfied all quality criteria	-
Score	Lowest level floor slab	8 points	
	Positive-side walls	10 points	
C Material (modified asphalt waterproofing sheet (rubber asphalt-based))		(1) Korean Industrial Standard KS F 4917-16 "Modified Asphalt Waterproofing Sheet": Satisfied all quality criteria	-
Score	Lowest level floor slab	8 points	
	Positive-side walls	10 points	
D Material (membrane waterproofing material (rubber asphalt-based or polyurethane rubber-based))		(1) Korean Industrial Standard KS F 3211-15 "Construction Waterproofing Membrane": Satisfied all quality criteria	-
Score	Lowest level floor slab	8 points	
	Positive-side walls	10 points	
E Material (silicate-based coating waterproofing material or liquid waterproofing material)		(1) Korean Industrial Standard KS F 4918-19 "Silicate-Based Powder Type Waterproof Coating Material": Satisfied all quality criteria	-
Score	Lowest level floor slab	8 points	
	Positive-side walls	10 points	
F Material (untreated)		-	-
Score	Lowest level floor slab	0 points	
	Positive-side walls	0 points	

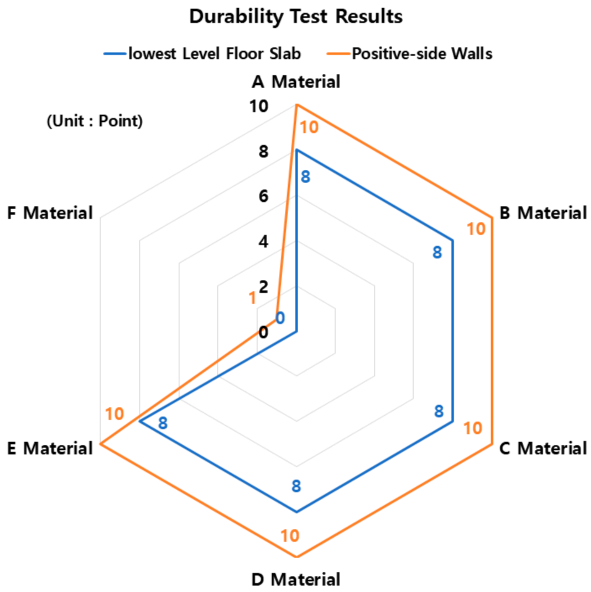


Figure 15. KCS 11 44 00: 2018 "Joint District" durability test results.

4.2.9. Low-Temperature Adhesion Stability

The test results for low-temperature adhesion stability are shown in Figure 16 below.

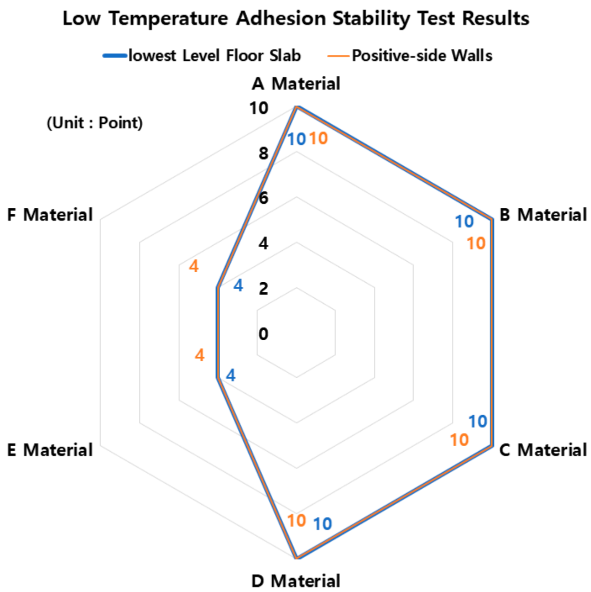


Figure 16. KCS 11 44 00: 2018 "Joint District" low-temperature adhesion stability test results.

As a result of the low-temperature adhesion stability test, materials A, B, C, and D scored 10 points for both the lowest level floor slab and the outer walls, and materials E and F received 4 points for all conditions.

4.2.10. Subgrade Floor Pad Settlement Stability

The test results for subgrade floor pad settlement stability are shown in Figure 17 below.

As a result of the subgrade floor pad subsidence stability test, all test pieces A maintained the structure body and waterproof layer, material B received 6 points because the structure body and waterproof layer were eliminated in one test piece, and material C received 4 points. In addition, materials D, E, and F each received two points because all test pieces were missing the structure body and the waterproof layer.

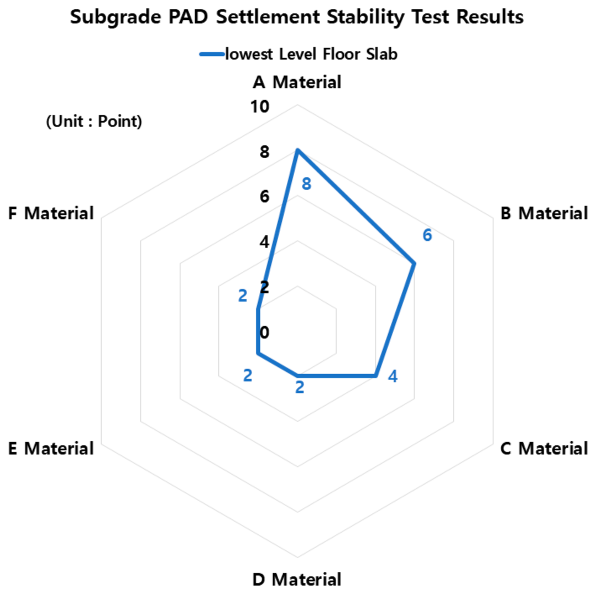


Figure 17. KCS 11 44 00: 2018 "Joint District" subgrade floor pad settlement stability test results.

4.2.11. KCS 11 44 00: 2018 "Joint District" Performance Evaluation Comprehensive

The comprehensive results of the performance evaluation for KCS 11 44 00: 2018 "Joint District" are shown in Table 6 and Figures 18–20.

Table 6. KCS 11 44 00: 2018 "Joint District" overall performance evaluation results.

No.	Item	Material													
		Lowest Level Floor Slab							Positive-Side Walls						
		Max Score	A	B	C	D	E	F	Max Score	A	B	C	D	E	F
1	Chemical resistance	20 points	17 points	14 points	8 points	14 points	2 points	2 points	20 points	17 points	14 points	8 points	14 points	2 points	2 points
2	Structural response and adaptability	20 points	17 points	17 points	11 points	2 points	2 points	2 points	20 points	17 points	17 points	11 points	2 points	2 points	2 points
3	Moisture adhesion stability	10 points	10 points	8 points	7 points	10 points	10 points	4 points	10 points	10 points	8 points	7 points	10 points	10 points	4 points
4	Water tightness	8 points	8 points	8 points	8 points	8 points	2 points	2 points	10 points	10 points	10 points	10 points	10 points	4 points	4 points
5	Temperature dependency	8 points	8 points	8 points	8 points	8 points	0 points	0 points	10 points	10 points	10 points	10 points	10 points	1 point	1 point
6	Crack resistance	8 points	8 points	8 points	8 points	8 points	0 points	0 points	10 points	10 points	10 points	10 points	10 points	1 point	1 point
7	Durability	8 points	8 points	8 points	8 points	8 points	8 points	0 points	10 points	10 points	10 points	10 points	10 points	10 points	0 points
8	Low-temperature adhesion stability	10 points	10 points	10 points	10 points	10 points	4 points	4 points	10 points	10 points	10 points	10 points	10 points	4 points	4 points
9	Subgrade floor pad settlement stability	8 points	8 points	6 points	4 points	2 points	2 points	2 points	-	-	-	-	-	-	-
	Total score	100 points	94 points	87 points	72 points	70 points	30 points	16 points	100 points	94 points	89 points	76 points	76 points	34 points	18 points

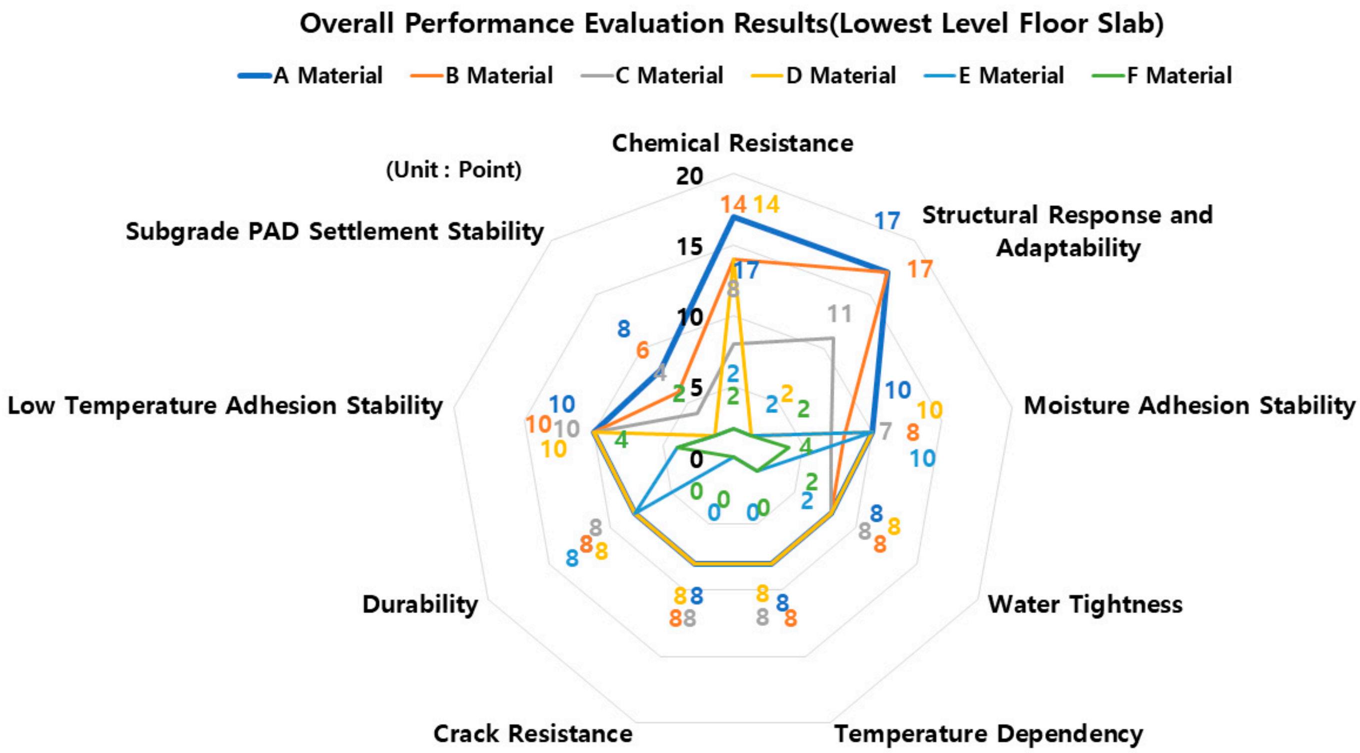


Figure 18. Lowest level floor slab overall performance evaluation results.

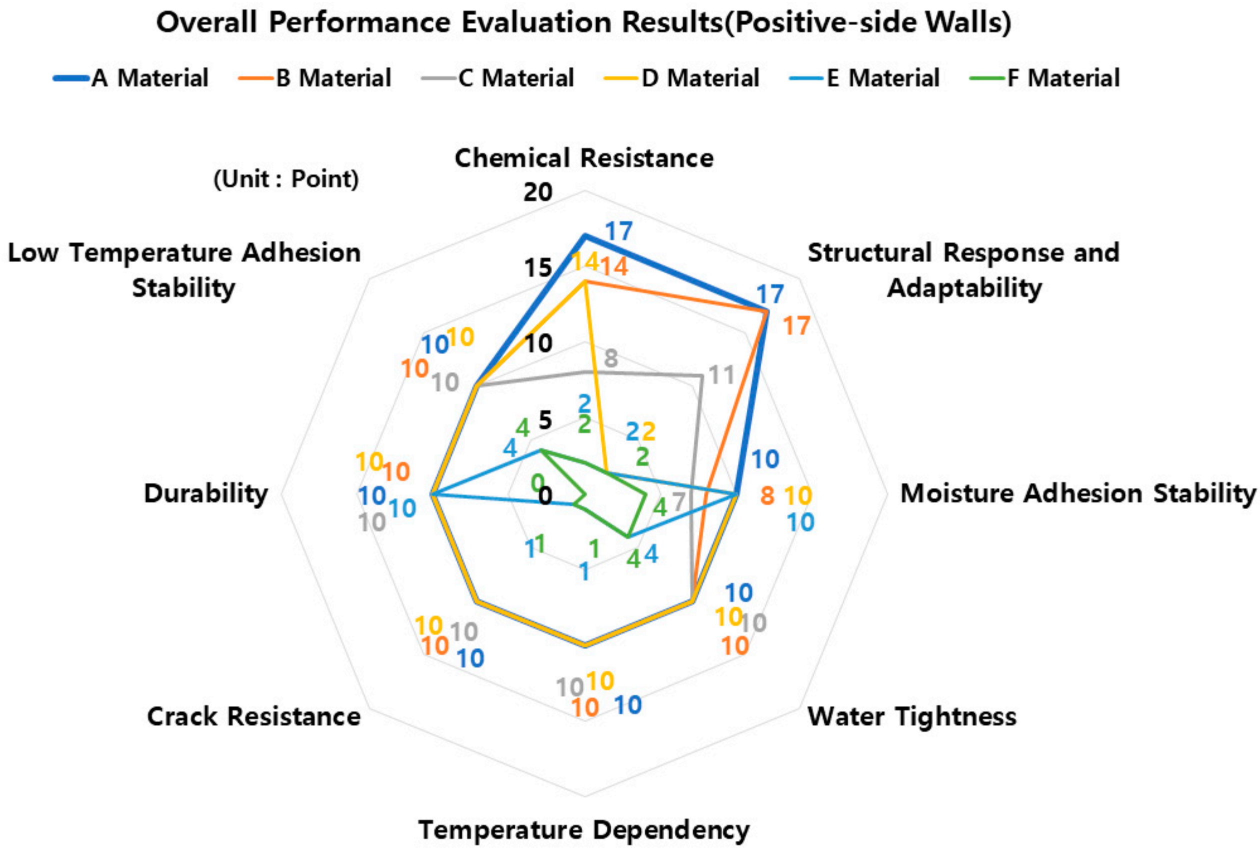


Figure 19. Positive-side walls overall performance evaluation results.

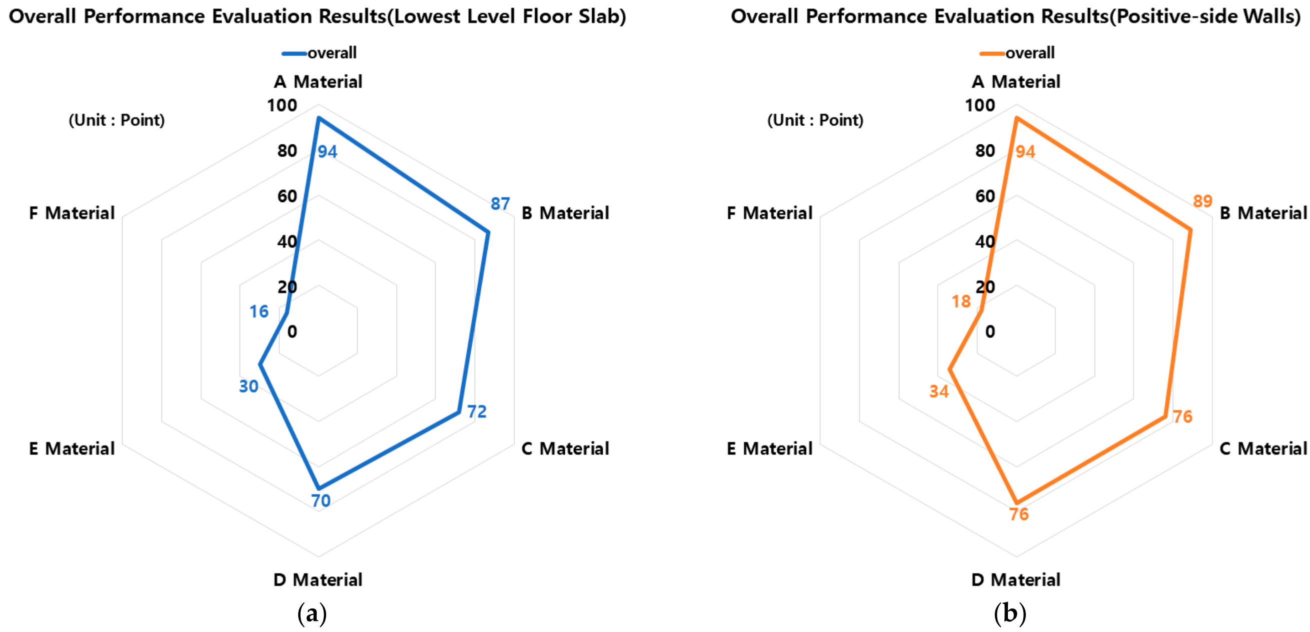


Figure 20. Overall performance evaluation total score results: (**a**) Lowest level floor slab; (**b**) positive-side walls.

According to the overall performance evaluation results, material A (composite flexible seal material + improved asphalt waterproof sheet) showed the best performance rating grade with both the lowest level floor slab and the outer walls scoring 94 points based on 100 points. For the lowest level floor slab and the outer walls, material B (rubber asphalt or butyl rubber) received 87 points and 89 points, Material C (improved asphalt waterproof sheet (rubber asphalt system) received 72 points and 76 points, material D (coating waterproofing material (rubber asphalt system or urethane rubber system) received 70 points and 76 points, material E (silicate-based coating waterproofing material) received 30 points and 34 points, and material F (untreated) received 16 points and 18 points, respectively.

4.3. Consideration

According to the test results of the change in underground environment due to waterproofing applications for underground structures, positive side waterproofing is ranked as a priority because it prevents moisture penetration or is excellent for humidity control compared to negative-side waterproofing or the untreated state. In addition, negative side waterproofing and non-treatment finally showed similar humidity, but negative side waterproofing with a gentle increase in humidity compared to non-treatment that reached the maximum humidity in the initial test environment is considered to have a relative waterproofing performance. Accordingly, regardless of the material group, the ranking of rating calculations for positive side waterproofing, negative side waterproofing, and non-treatment should be calculated in the order of positive side waterproofing, negative side waterproofing, and non-treatment.

If the material group is classified around materials that do not have large deviations, materials A and B form a group, and materials C and D can be grouped. In addition, materials E and F can each be classified into a group. These four groups can be classified from Grades 1 to 4 of the performance grade of apartment houses, but in the case of material D, even if the difference in performance scores between positive side and negative side waterproofing is the same, it is necessary to set a rating one step lower than material D's positive side waterproofing method.

Therefore, in consideration of the results of the waterproofing method by construction site, the types of waterproofing methods according to the materials used are classified as shown in Table 7 below.

Table 7. Overall performance rating determination results.

Item	Method	Ranking	Score		Grading	Note
			Lowest Level Floor Slab	Positive-Side Walls		
A Material (composite waterproofing material (adhesive flexible sealant + modified asphalt sheet waterproofing))	Positive side waterproofing	1	94	94	★★★★ (Grade 1)	-
B Material (self-adhesive waterproofing sheet (rubber asphalt based or butyl rubber based))	Positive side waterproofing	2	87	89		-
C Material (modified asphalt waterproofing sheet (rubber asphalt based))	Positive side waterproofing	3	72	76	★★★ (Grade 2)	-
D Material (membrane waterproofing material (rubber asphalt based or polyurethane rubber based))	Positive side waterproofing	4	70	76		-
D Material (membrane waterproofing material (rubber asphalt based or polyurethane rubber based))	Negative side waterproofing	5	70	76	★★ (Grade 3)	According to the negative side waterproofing method, a one-step lower performance rating is determined
E Material (silicate-based coating waterproofing material or liquid waterproofing material)	Negative side waterproofing	6	30	34		-
F Material (untreated)	-	7	16	18	★ (Grade 4)	-

5. Conclusions

The conclusions of this study are as follows:

1. Based on the results of scoring and displaying the performances of the waterproofing methods, the composite waterproofing method showed the best performance on the lowest level floor slab and outer walls of the underground structure, followed by the self-adhesive sheet waterproofing method. In particular, even with the same sheet waterproofing method, there was a difference in performance grade and score, which is believed to have caused a decrease in material properties in this process because the improved asphalt sheet waterproofing material is fused and attached by torch or heat.
2. Some sheet waterproofing materials showed similar performance scores to coating waterproofing materials, but in general, it is judged that sheet waterproofing materials have excellent performance. Coating waterproofing is believed to have a lower waterproofing performance rating than sheet waterproofing because of the construction

limitations of the coating waterproofing material, such as material flowability and wet surface construction failure, may occur at the actual construction site.

3. Due to the nature of inorganic materials, silicate-based coating waterproofing material, etc., which are applied only with waterproofing methods, absorb moisture in the long run, and when permeable pressure occurs during this process, the permeability of materials increases quickly.
4. In order to calculate the waterproofing performance rating for the lowest level floor slab and the outer walls of the underground structure of an apartment, it is necessary to differentiate the waterproofing performance rating depending on the method (positive side and negative side waterproofing).

In this study, we only investigated a waterproofing performance rating method for the lowest level floor slab and outer walls of an underground structure according to the performance rating method of apartment houses in Korea, and we suggested a performance rating limited to waterproofing materials and construction methods suitable for domestic conditions. Based on the results of this study, considering the physical property evaluation methods and evaluation standards presented by the International Standards Organization (ISO), it is expected that the results could be used as basic data for waterproofing performance rating applicable to all concrete building structures.

Author Contributions: Conceptualization, methodology, laboratory work, data curation, writing—original draft preparation, K.-w.A.; conceptualization, methodology, writing—reviewing and editing, B.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This study was financially supported by the Seoul National University of Science & Technology.

Conflicts of Interest: The authors declare no conflict of interest for the publication of the review paper.

References

1. An, K.W. Applicability of Grading System for Residential Building Waterproofing Performance. Ph.D. Thesis, Seoul National University of Science and Technology, Seoul, Republic of Korea, 2021; pp. 45–147.
2. An, K.W.; Cho, I.K.; Oh, S.K. Study on the Improvement of Waterproofing Performance Rating for the Introduction of Residential Apartment Complex Performance Grade Index. *J. Archit. Inst. Korea Struct. Constr.* **2018**, *34*, 41–49.
3. An, K.W.; Kang, H.J.; Cho, I.K.; Oh, S.K. Requirement of Performance Evaluation Criteria of Waterproofing Field for Residential Buildings—Professional Survey Based Data. *Archit. Inst. Korea* **2018**, *38*, 780–781.
4. An, K.W.; Kim, S.Y.; Oh, S.K. Development and Study on the Future Employment of Waterproofing Design Guideline for Leakage Prevention of Residential Underground Structure. *Archit. Inst. Korea* **2017**, *37*, 1073–1074.
5. An, K.W.; Lee, Y.S.; Lee, J.H.; Song, J.Y.; Oh, S.K. Humidity Change Rate Analysis for Various Waterproofing Method in Underground Structures During Winter Season. *J. Korea Inst. Struct. Maint. Insp.* **2016**, *20*, 118–125.
6. Jang, S.M.; Choi, S.M.; Lee, J.H.; An, K.W.; Oh, S.K. A Study on the Characteristics of Temperature-Hunidity by the Location of Waterproofing Layer with the Concrete Wall as the Center in the Basement. *Korea Concr. Inst.* **2013**, *10*, 31–32.
7. Choi, S.M.; Jang, S.M.; An, K.W.; Lee, J.H.; Song, J.Y.; Oh, S.K. A Study on the Characteristics of Temperature-Humidity by Applying the Waterproofing Layer on the Out of Concrete Wall in the Underground Parking Lot. *Archit. Inst. Korea* **2013**, *33*, 589–590.
8. An, K.W.; Kim, D.B.; Choi, S.Y.; He, X.Y.; Oh, S.K. Investigation on Products and Regulation of Flexible Adhesive Rubber Asphalt Type Sealant for the Development of Korea-China Joint Standard. *J. Korean Recycl. Constr. Resour. Inst.* **2019**, *7*, 323–332.
9. Lee, S.Y.; Cho, D.Y.; Park, C.Y.; Lee, S.H. Comparative Analysis of Evaluation Score Calculation Methods for Grading Certification of Overseas Green Building Certification Systems and Domestic Green Building Certification System. *J. Archit. Inst. Korea Plan. Des.* **2013**, *29*, 283–290.
10. Kim, M.S.; Hwang, J.W.; Chun, J.G.; Ha, D.W.; Park, K.S.; Son, W.T. A Study on the Improvement of Assessment Criteria for Housing Performance Indicator System and Green Building Certification Criteria. *J. Archit. Inst. Korea Plan. Des.* **2009**, *29*, 283–290.
11. Becker, R. A unified methodology for establishing minimum performance criteria and performance grading tools for buildings. *Build. Environ.* **1993**, *28*, 243. [CrossRef]
12. Bono, A.B.; Bono, S.T. Integrating Below-Grade Waterproofing into Structural Details for Successful Building Performance: A Case Study. *Concr. Int.* **2012**, *34*, 41–45.

13. Shi, J.; Wu, L.; Liu, J.; Liu, C.; Liu, B.; Song, J. Study on Combustion Performance of A Grade of Building Thermal Insulation Materials. *Guangdong Chem. Ind.* **2020**, *47*, 79–80.
14. Korea Land & Housing Corporation. *Establishment of Measures to Improve Quality of House Waterproofing*; Public Housing Project Office: Seoul, Republic of Korea, 2017.
15. *Methods for Zero Defects in Quality Management*; Public Housing Project Office: Gyeongnam, Republic of Korea, 2017; p. 3.
16. Korea Institute of Construction Technology. *Research on the Establishment of Standards for Installation and Maintenance of Ventilation Facilities*; Ministry of Land, Infrastructure and Transport: Seoul, Republic of Korea, 2016.
17. *KS F 4935-18*; Injectable Sealing Material for Leak Repair of Adhesive Flexible Rubber Asphalt-Based. Korean Standards Service Network: Seoul, Republic of Korea, 2018. Available online: https://www.kssn.net/search/stddetail.do?itemNo=K001010122364 (accessed on 31 July 2023).
18. *KS F 4934-18*; Self-Adhesive Rubberized Asphalt Waterproof Sheet. Korean Standards Service Network: Seoul, Republic of Korea, 2018. Available online: https://www.kssn.net/search/stddetail.do?itemNo=K001010120637 (accessed on 31 July 2023).
19. *KS F 3211-15*; Construction Waterproofing Membrane. Korean Standards Service Network: Seoul, Republic of Korea, 2015. Available online: https://www.kssn.net/ks/certicoldetail.do?itemNo=K001040001511 (accessed on 31 July 2023).
20. *KS F 4918-19*; Silicate-based Powder Type Waterproof Coating Material. Korean Standards Service Network: Seoul, Republic of Korea, 2019. Available online: https://www.kssn.net/search/stddetail.do?itemNo=K001010124883 (accessed on 31 July 2023).
21. *KS F 4917-16*; Modified Asphalt Waterproof Sheet. Korean Standards Service Network: Seoul, Republic of Korea, 2016. Available online: https://www.kssn.net/search/stddetail.do?itemNo=K001010139916 (accessed on 31 July 2023).
22. Seitllari, A.; Naser, M.Z. Leveraging artificial intelligence to assess explosive spalling in fire-exposed RC columns. *Comput. Concr.* **2019**, *24*, 271–282.
23. Zuzana, R.; Ryparová, P. The Dependence of Mold on the Relative Humidity in Different Types of Materials. In *Key Engineering Materials*; Trans Tech Publications, Ltd.: Zürich, Switzerland, 2017; Volume 731, pp. 98–102.
24. Shah, A.H.; Sharma, U.K. Fire resistance and spalling performance of confined concrete columns. *Constr. Build. Mater.* **2017**, *156*, 161–174. [CrossRef]
25. *KCS 11 44 00: 18*; Standard Specifications for Common Structures. The National Construction Standards Center: Goyang, Republic of Korea, 2018. Available online: https://www.kcsc.re.kr (accessed on 31 July 2023).
26. An, K.W.; Kim, B.I. A Study on Verification of Waterproofing Method Properties for Performance Grading in Apartment Houses-Upper Slab of the Underground Structure. *Buildings* **2023**, *13*, 2164. [CrossRef]