Development of New Semi-Rigid Joint System for Slabs (Part 2) ~ Verification Testing of Filler ~

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Abstract

Nippon Steel Engineering is developing a semi-rigid joint for connecting precast pre-stressed slabs using filler only in the axial direction of the bridge or overpass. The intended application is the replacement of slabs in highways. We conducted several tests to ascertain the workability, joint mechanical performance, and chemical durability required for the filler to maintain the specific usability and durability of the proposed joints over the service period. The test results demonstrated that epoxy resin mortar has sufficient durability, but lacks the hardening ability required for rapid installation. It was also concluded that the poorer fillability performance of epoxy resin mortar would require the same joint width as polymer cement mortar. Polymer cement mortar, meanwhile, provides both low static elasticity and adequate freeze-thaw durability given appropriate adjustment of the moisture and polymer content.

1 Introduction

Expressways in Japan are increasingly suffering from fatigue due to heavy traffic and other forms of environmental deterioration, with 40% having been in use for 30 years. Accordingly, the respective expressway operating companies for eastern, central, and western Japan (collectively referred to below as "NEXCO") have adopted plans for large-scale upgrading and refurbishment[1] that they are currently putting into practice.

The majority of the upgrade work involves the replacement of road slabs, with a total of 224km of such work being planned. Recognizing the need to perform slab replacement rapidly in order to keep the economic impact of the accompanying traffic delays to a minimum, the standard practice is to use precast prestressed concrete (PC) slabs that minimize the amount of on-site work required. Transportation constraints mean that these precast PC slabs are delivered in sections of up to 2.5m wide and joined on-site using loop joints or similar means of joining reinforcing bars. In response, we have developed and tested a new type of joint that uses fillers with a lower Young's modulus than the concrete used in the precast PC slabs and an adhesive strength and tensile strength equal to or better than those of concrete. Fig. 1 shows an overview.

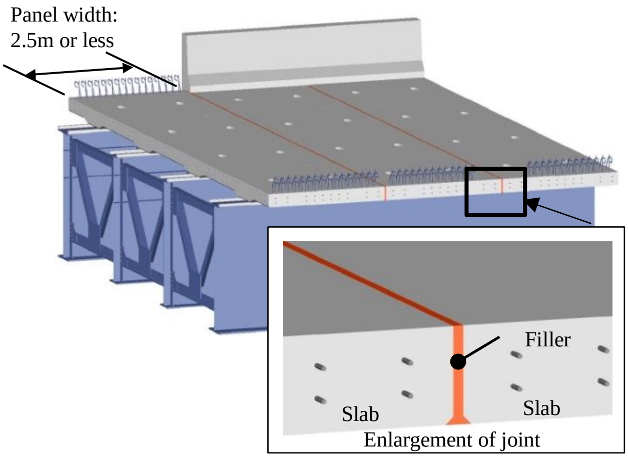


Fig. 1 Concept of Semi-rigid Joint

Analytical studies and structural testing conducted to date has demonstrated that semi-rigid joints exhibit adequate load-bearing performance and fatigue durability[2]. However, the tensile stresses that act on the joints between precast slabs are typically transmitted through the reinforcing bars and no previous joint designs have involved the stresses being transmitted through the filler alone. Moreover, because the filler contains organic compounds, degradation due to exposure to the environment is also a concern.

For these reasons, the requirements for the filler include not only mechanical performance, but also that it perform well during installation ("workability"), and in terms of joint mechanical performance and chemical durability to ensure that the semi-rigid joint will maintain the required usability and durability throughout its intended service period. Accordingly, testing also covered these factors. This paper describes the experimental methods and results.

2 Material Testing

2.1 Filler Materials Tested

Material testing was conducted on the polymer cement mortar (PCM) and epoxy resin mortar (ERM) used in past structural testing. PCM is an improved version of a compound used in slab repair and has a static modulus of elasticity of about one-third to one-fourth that of concrete. Likewise, ERM is an improved version of a compound used for repairing slab cracks and has a very low static modulus of elasticity of about one-tenth that of concrete. To enable comparison, concrete specimens with a nominal strength of 50N/mm^2, similar to a precast PC slab, were produced for use in some of the testing. Table 1 lists the properties of the materials used in testing.

Table 1 Properties of Materials (Age: 28 days)

Material	Ambient temperature	Static modulus of elasticity (kN/mm^2)	Compressive strength (N/mm^2)	Remarks
PCM	23°C	9.5	32.6	
ERM		3.8	52.4	
Concrete		31.1	58.8	Nominal strength 50 (for comparison)

2.2 Tests

Table 2 lists the tests used to assess filler performance. The tests used to assess installation performance, joint mechanical performance, and chemical durability complied with the rules for testing materials for section repairs to the top surface of slabs, which are published by NEXCO as the No. 439 requirements and test methods for structural engineering work (Requirements for Structural Engineering Work)[3]. Those tests, methods, or criteria that differ from the performance assessments in the Requirements for Structural Engineering Work are highlighted in yellow in Table 2. Details of these changes are given in section 3.

3 Test Summary and Results

3.1 Tests for Performance in Installation

3.1.1 Initial Setting Time

The time for hardening to start was measured for PCM based on the penetration resistance value as defined in JIS A 1147. As the setting of ERM is an exothermic reaction, the initial setting time cannot be determined from the concrete setting time. The temperature rise method specified in JIS A 6024[4] was used instead.

Table 2 List of Verification Tests on the Filler

Type	Test	Relevant standard	Criteria	Specimen dimensions
Installation performance	Initial setting time	Test method 439/JIS A 1147	(PCM): 30 minutes or longer	φ150× H150mm
		Temperature rise method/ JIS A 6024	(ERM): 30 minutes or longer	500mL plastic container
	Initial strength	Test method 439 JIS A 1108	(No time constraint) 24N/mm² or higher (With time constraint) 2 hours: 10N/mm² or higher 4 hours: 24N/mm² or higher	φ100×H200mm
	Fillability	Original	No voids or other indicators of inadequate filling	Original specimen no. 1
Joint mechanical performance	Crack resistance	Original	No cracking occurs when specimen tested while constrained between two surfaces	Original specimen no. 2
	Settling resistance	Original	No more than 1mm unevenness in filler	Original specimen no. 2
	Adhesion to concrete	JIS A 1106	No fracture in interface between concrete and filler, with test continuing until fracture in concrete only	Original specimen no. 3 □-100×100×400mm
Chemical durability	Hot and cold cycling load resistance	JIS A 1171/JIS A 1106	No fracture in interface between concrete and filler, with test continuing until fracture in concrete only	Original specimen no. 3 □-100×100×400mm
	Freeze-thaw durability	Test method 439/JIS A 1106	No fracture in interface between concrete and filler, with test continuing until fracture in concrete only	Original specimen no. 3 □-100×100×400mm
	Freeze-thaw durability	Test method 439/JIS A 1148	Relative dynamic modulus of elasticity after loading is 60% or more	□-100×100×400mm
	Neutralization resistance	Test method 439/JIS A 1153 JSCE-G574-2013	Equal or better than slab concrete	□-100×100×400mm
	Salt resistance	Test method 439/ JSCE G 572 JSCE-G574-2013	Equal or better than slab concrete	φ100×H200mm

* : Indicates items that differ from the performance assessments in the Requirements for Structural Engineering Work

Table 3 lists the results, with initial setting time of 30 minutes or more in both cases.

Table 3 Initial Setting Time

Material	Ambient temperature	Initial setting time
PCM	23°C	43 minutes
ERM		30 minutes

3.1.2 Initial Compressive Strength

A specimen with dimensions of $\varphi 100 \times$ H200mm was used to determine initial compressive strength. The test results are shown in Fig. 2. These show that both PCM and ERM reach a strength of 24N/mm^2 or more within 7 days. However, they do not meet the compressive strength thresholds (10N/mm^2 or more after 2 hours and 24N/mm^2 or more after 4 hours) when subject to a time constraint. In the case of PCM, this can be addressed by adjusting the quantity of retarder used to achieve strength more quickly. In the case of ERM, investigations are currently ongoing into how the material composition can be changed to improve setting performance.

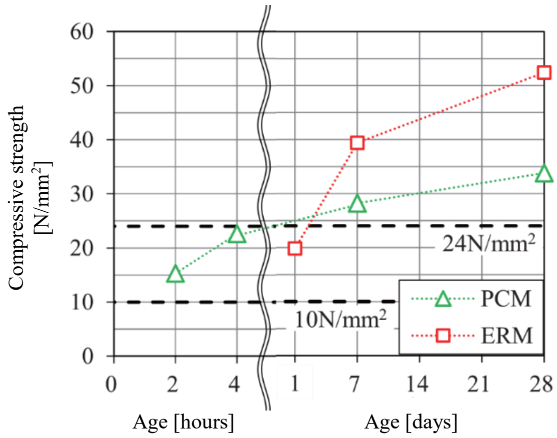


Fig. 2 History Curve of Initial Compressive Strength

3.1.3 Fillability

This test is not covered by the Requirements for Structural Engineering Work. As the required fatigue durability will not be achieved if voids or other instances of poor filling are present at the interface between the concrete and filler, fillability was verified using a specimen that simulates the proposed precast slab joint (original specimen no. 1 – see Fig. 3). Table 4 lists the design values for joint width, which take account of variability in installation as well as the fillability and cost of each material. To determine that filling will be adequate even when the joint width is at the lower bound of the design value, the fillability test used widths of 20mm for PCM and 10mm for ERM. Fig. 4 shows images that indicate filling performance along the side of the joint, with poor filling visible along most of the length of the ERM. As the poor filling is believed to be due to ERM having a large amount of filler compared to conventional crack repair material, this was addressed by adjusting the amount of filler and also by adopting a more accommodating design value of 30mm+/-10mm (the same as PCM).

Table 4 Joint Width Used in Fillability Test

Material	Design value	Joint width in test
PCM	30mm+/-10mm	20mm
ERM	20mm+/-10mm	10mm

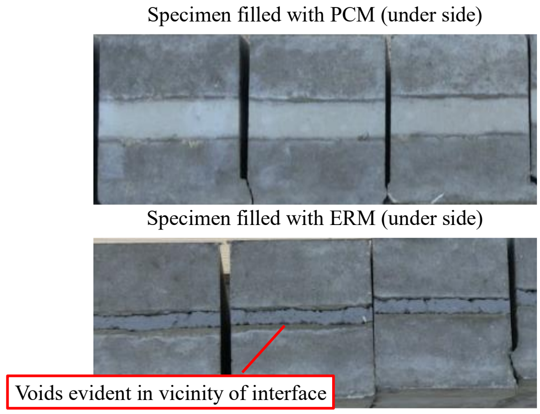


Fig. 4 Result of Fillability Test with Original Specimen No. 1

3.2 Testing of Joint Mechanical Performance

3.2.1 Crack Resistance

Although the test itself is specified in the Requirements for Structural Engineering Work, a different specimen shape was used. Unlike repair materials used for concrete sections, which are used in a variety of different ways and for different section shapes, the fillers being tested here are intended for use under predetermined conditions.


Fig. 3 Appearance of Original Specimen No. 1

Accordingly, a specimen that simulates the proposed precast slab joint (original specimen no. 2 – see Fig. 5) was used and testing was performed with the specimen constrained between two surfaces.

The test checked for cracking in the joint and surrounding concrete 28 days after the joint was filled with filler. To test the filler under worst-case conditions, the upper bound of the design value was chosen for the joint width (see Table 5). The check was performed visually using a water spray. No cracking in the joint or surrounding area was found in either specimen (see Table 6).

3.2.2 Settling Resistance

This test is not covered by the Requirements for Structural Engineering Work. It was added to test for settling (subsidence) in the joint due to autogenous shrinkage of the filler. This was measured using the depth gauge shown in Fig. 6, with the criterion specified in the slab waterproofing system[5] being adopted. The test used the same specimen as the crack resistance test.

Table 6 lists the results. Settling was less than 1mm for both specimens.

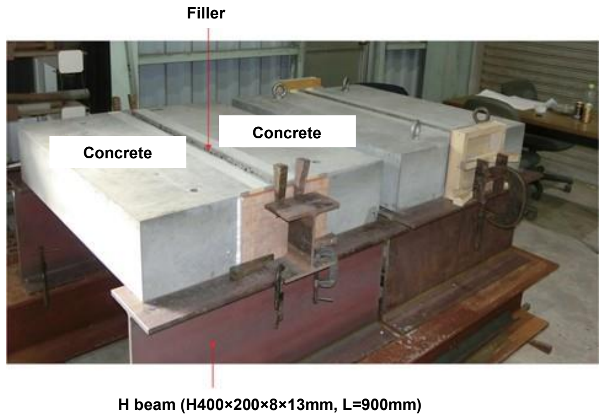


Fig.5 Original Specimen No. 2

Table 5 Applied Joint Width with Original Specimen No. 2

Material	Design value	Joint width in test
PCM	30mm+/-10mm	40mm
ERM	20mm+/-10mm	30mm

Table 6 Results of Crack Resistance Test and Joint Settlement Test

Material	Cracking?	Settlement
PCM	None	0.02mm (<1mm)
ERM	None	0.05mm (<1mm)

Fig. 6 Appearance of Measuring Settlement

3.2.3 Adhesion to Concrete

Although the test itself is specified in the Requirements for Structural Engineering Work, a different reference standard and specimen shape were used. A specimen that simulates the proposed precast slab joint (Original Specimen No. 3 – see Fig. 7) was used. The test assessed the adhesion between concrete and filler by means of a bending flexural test performed in accordance with JIS A 1106 using the apparatus shown in Fig. 8. The criterion for test success was that no fracture occur in the interface between concrete and filler, with fracturing of the concrete only.

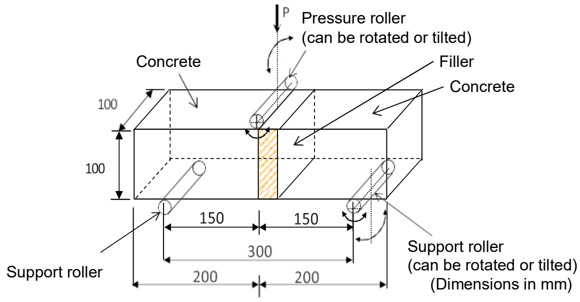
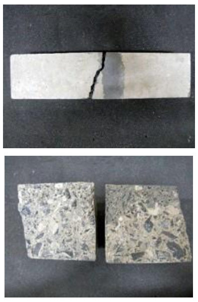


Fig. 7 Original Specimen No. 3

Fig. 8 Machinery for Three-Point Bending Flexural Test

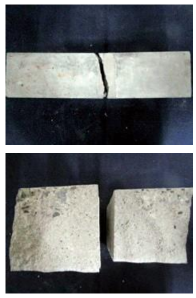
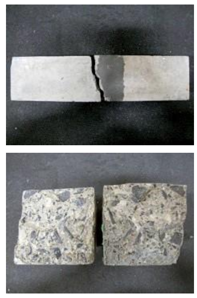
Adhesion was improved by roughening the concrete surface of the joint in the same way as an actual-size slab. The joint width used in the test was the mid-point of the design value. The test was conducted 7 days after the joint was filled with filler. Table 7 lists the test results. Both the PCM and ERM specimens had a flexural tensile strength (at the bottom of the joint) of 5.00N/mm^2 or more. For all PCM specimens, the fractures were located in the concrete, whereas some fractures in the ERM specimens occurred at the interface. One of the reasons for this is believed to be that ERM takes longer to strengthen.

Table 7 Results of Three-Point Flexural Test (No Environmental Load)

Material	PCM	ERM
Joint width (mm)	30	20
Mean flexural tensile strength (n=3) (N/mm^2)	6.75	5.28
Percentages of fractures in concrete and filler	A (100%)	A (72.5 to 75%) AB (25% to 27.5%)
Example fracture surfaces		

* A: Fracture occurred in concrete, B: Fracture occurred in filler, AB: Fracture occurred at interface

Table 8 Results of Three-Point Flexural Test (After Hot and Cold Cycling Load)

Material	PCM	ERM
Joint width (mm)	30	20
Mean flexural tensile strength after thermal cycling (n=3) (N/mm^2)	6.77	7.08
Percentages of fractures in concrete and filler	A (20% to 50%) B (50% to 80%)	A (90% to 95%) AB (5% to 10%)
Example fracture surfaces		

* A: Fracture occurred in concrete, B: Fracture occurred in filler, AB: Fracture occurred at interface

3.3 Chemical Durability

3.3.1 Adhesion after Hot and Cold Cycling Load

This test is not covered by the Requirements for Structural Engineering Work. The test verified that the joint adhesion between the concrete and filler does not deteriorate when exposed to the maximum and minimum temperatures experienced in actual use. The hot and cold cycling resistance test was conducted in accordance with JIS A 1171 (test methods for polymer-modified mortar). The specimen shape, adhesion test conducted after the hot and cold cycling resistance test, and criteria were the same as for “Adhesion to Concrete”. The test cycle involved soaking in water at 20℃ for 18 hours followed by 3 hours each of cooling at -20℃ and heating at 50℃ in a constant-temperature chamber. This cycle was repeated 10 times (a test duration of 10 days). This was followed by flexural testing to assess strength and inspection for fractures.

Table 8 lists the test results. For PCM, a comparison with Table 7 indicates that, while there is no loss of flexural tensile strength, a larger percentage of fractures occurred in the filler. This can be interpreted as indicating that thermal cycling causes changes in PCM and that this risks degrading its strength.

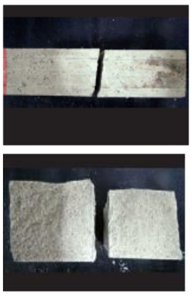
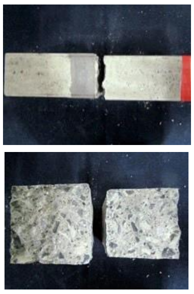
For ERM, the results indicate that flexural tensile strength is somewhat higher after thermal cycling. This is believed to be because ERM continues to strengthen beyond 7 days. Similarly, the percentage of fractures that occurred in the filler is lower than in Table 7. These results indicate that the ERM in the joint has sufficient flexural tensile strength even after thermal cycling.

3.3.2 Adhesion after Freezing and Thawing Cycling Load

This test is intended to determine whether joint mechanical performance is diminished by cracking or degradation due to repeated freezing and thawing of the moisture in the concrete and filler. Although the test itself is specified in the Requirements for Structural Engineering Work, a different specimen shape was used and the test method and criteria for adhesion after freezing and thawing cycling load were also different. The specimen shape, method, and criteria were the same as for “Adhesion to Concrete”. For the freezing and thawing cycling load test, the temperature at the center of the specimen was lowered and raised from 5℃ to -18℃ and back to 5℃, with each cycle taking 3 to 4 hours and the test being continued for 300 cycles (a test duration of 50 days). This was followed by flexural testing to assess strength and inspection for fractures.

Table 9 lists the test results. For PCM, a comparison with Table 7 indicates that there was a loss of flexural tensile strength and that a larger percentage of fractures occurred in the filler. This can be interpreted as indicating that freezing and thawing cycling load causes changes in PCM and that this degrades its strength.

Table 9 Results of Three-Point Flexural Test (After Freezing and Thawing Cycling Load)

Material	PCM	ERM
Joint width (mm)	30	20
Mean flexural tensile strength after freezing and thawing (n=3) (N/mm²)	4.05	5.48
Percentages of fractures in concrete and filler	A (0%～40%) B (60%～100%)	A (100%)
Example fracture surfaces		

* A: Fracture occurred in concrete, B: Fracture occurred in filler, AB: Fracture occurred at interface

For ERM, a comparison with Table 7 indicates that flexural tensile strength remains roughly the same and that no fractures occurred in the filler. These results indicate that the ERM in the joint has sufficient flexural tensile strength even after freezing and thawing cycling load.

3.3.3 Freeze-Thaw Durability (Relative Dynamic Modulus of Elasticity)

Measurements were performed on a rectangular column specimen made of a uniform material with dimensions of □-100×100×400mm to determine how the relative dynamic modulus of elasticity (an indicator of freeze-thaw durability) and weight change varied over time. Fig. 9 shows the relative dynamic modulus of elasticity and weight change for each specimen. For both specimens, the dynamic modulus of elasticity remained over 60%.

On the other hand, the weight of PCM after freezing and thawing cycling load was approximately 100.7% of the initial weight, indicating that freezing and thawing had slightly increased its weight due to the adsorption of water, with some surface scaling also evident. The ERM weight of approximately 100.1% means that its weight changed by less than PCM, with no scaling observed.

These results indicate that PCM is affected by freezing and thawing cycling load, and that its freeze-thaw durability is not equal or better than that of concrete.

3.3.4 Neutralization Resistance

Neutralization resistance indicates the extent to which a specimen resists penetration by the carbon dioxide in the air.

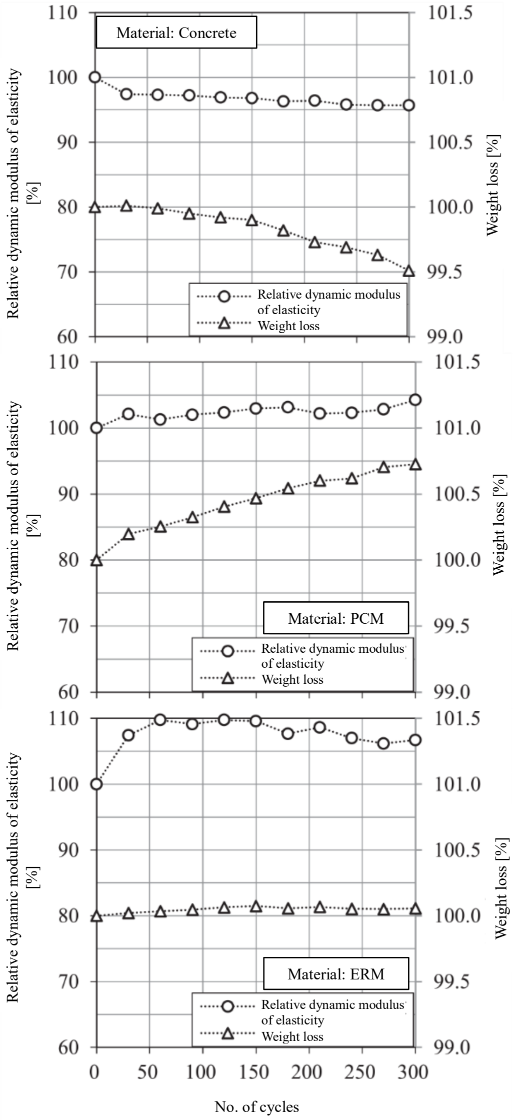


Fig. 9 History Curve of Relative Dynamic Modulus of Elasticity and Weight Loss

As test method 439 assumes an alkaline material, its default method is to use a phenolphthalein solution to measure the depth of neutralization. However, because ERM is neutral, meaning that the standard test cannot be used, whether or not penetration by carbon dioxide has occurred is determined by performing a surface analysis to map the carbon concentration using an electron probe micro-analyzer (EPMA) as specified in JSCE-G574-2013. An accelerated test was performed by producing a rectangular column specimen with dimensions of □-100×100×400mm and placing it in an environment with a temperature of 20°C, relative humidity of 60%, and carbon dioxide concentration of 5%.

The test results are listed in Table 10 and show that both PCM and ERM performance were equal or better than concrete.

Table 10 Results of Neutralization Resistance Test

Material	Concrete	PCM	ERM
Accelerated time	26 cycles		
Neutralization depth/Depth of penetration by carbon dioxide(mm)	0.5	0.5	0
Neutralization rate coefficient (mm/√cycle)	0.1	0.1	No penetration after 26 cycles

3.3.5 Salt Resistance

Although the test itself is specified in the Requirements for Structural Engineering Work, a different specimen measurement method was used. Instead of the potentiometric titration specified in test method 439, the apparent diffusion coefficient was determined by performing a surface analysis using an electron probe micro-analyzer (EPMA), which is more accurate and easier to judge visually. A rectangular column specimen with dimensions of □-100×100×400mm was produced and immersed for three months in a brine bath with a temperature of 20±2°C and a sodium chloride concentration of 10%. The apparent diffusion coefficient and chloride ion penetration depth were then calculated.

Fig. 10 shows the results of the EPMA surface analysis and Table 11 lists the diffusion coefficients and penetration depths. These indicate that both PCM and ERM have better salt resistance than concrete.

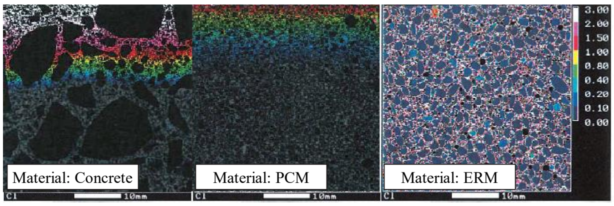


Fig. 10 Results of Salt Resistance Test with EPMA

Table11 Results of Chloride Diffusion Coefficient and Chloride Depth Analyzed with EPMA

Type	Apparent diffusion coefficient Dap(cm²/y)	Depth of chloride penetration (mm)
Concrete	1.50	18
PCM	0.372	13
ERM	Unable to calculate because no penetration	0

4 PCM Improvement and Retesting

The composition of PCM was modified to give it a lower static modulus of elasticity than conventional repair materials. It is believed that the higher moisture content resulting from these changes was a factor in PCM's lower durability with respect to hot and cold cycling load and freezing and thawing cycling load.

Accordingly, the composition was reformulated to increase the amount of polymer and thereby reduce moisture content. The durability of the new composition with respect to freezing and thawing cycling load was then retested. Table 12 lists the material properties of the improved PCM mixture. Note that, because the higher polymer content was not expected to affect other performance factors, the other tests were not repeated.

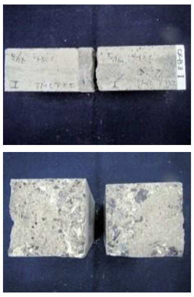
Table 12 Properties of Improved PCM Mix (Age: 28days)

Material	Ambient temperature	Static modulus of elasticity (kN/mm²)	Compressive strength (N/mm²)	Remarks
PCM	23°C	9.5	32.6	Initial formulation
		9.6	31.1	Improved formulation

4.1 Adhesion after Freezing and Thawing Cycling Load (Retesting)

Table 13 lists the test results. The flexural tensile strength was approximately 1.6 times higher than for the previous composition. The percentage area of fractures in the filler was also improved.

Table 13 Results of Three-Point Flexural Test with Improved PCM Mix (After Freezing and Thawing Cycling Load)

Material	PCM
Joint width (mm)	30
Mean flexural tensile strength after freezing and thawing (N/mm^2)	6.40
Percentages of fractures in concrete and filler	A (60% to 100%) B (40% to 0%)
Example fracture surfaces	

* A: Fracture occurred in concrete, B: Fracture occurred in filler, AB: Fracture occurred at interface

4.2 Freeze-Thaw Durability (Relative Dynamic Modulus of Elasticity) (Retesting)

The test results are shown in Fig. 11. These show that the relative dynamic modulus of elasticity after loading remains above 60%, as for the previous composition. Also, the weight after freezing and thaw cycling load of approximately 100.4% is lower than before and there was no scaling visible. These retest results indicate that the new PCM composition has improved freeze-thaw durability and is able to satisfy the material durability requirements.

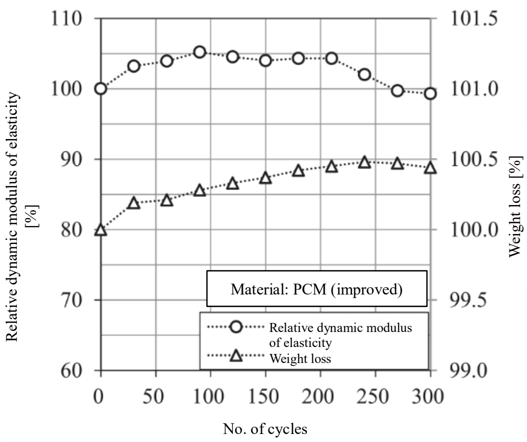


Fig. 11 History Curve of Relative Dynamic Modulus of Elasticity and Weight Loss with Improved PCM Mix

5 Conclusions

The filler material was reformulated to facilitate its use in the semi-rigid joint and material testing redone. Furthermore, because the way the filler is used differs from the materials used for section repair or injected into cracks, additional quality management practices specific to this application, such as settling resistance, were determined and tested. The conclusions from this work are as follows.

[1] While the composition of epoxy resin mortar needs to be reformulated for some slab replacements because of the need for installation to be completed quickly so that traffic disruption can be avoided, the practicality and durability of the material are adequate for purpose.

[2] The large amount of filler in the epoxy resin mortar intended for use in the semi-rigid joint means it has poorer fillability performance than conventional materials for injection into cracks. For this reason, a design value of 30mm+/-10mm was set for joint width, making it the same as for polymer-modified mortar.

[3] When the static modulus of elasticity is made lower than that of conventional polymer-modified mortar, the moisture content needs to be controlled to increase the amount of polymer in order to maintain freeze-thaw durability.

Acknowledgements

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