A study on fatigue durability of the top surface repair method using two types of adhesives for damaged RC slabs

Kiyoshi Ito [1] , Tadashi Abe [2] ,Manabu Fuchigami [3] ,Noriyuki Kozakai [4] and Takayoshi Kodama [5]

[1] Dep. of Civil Eng., Graduate School of Industrial Technology, Nihon University, Chiba, Japan
[2] Prof., Dep. of Civil Eng., College of Industrial Technology, Nihon University, Chiba, Japan, Dr. Eng.
[3] Engineering Manager, Kajima Road Co,. Ltd., Tokyo, Japan, Dr. Agr.
[4] Engineering Manager, Sumitomo Osaka Cement Co., Ltd., Tokyo, Japan.
[5] Vice-Technical Sales Manager,Kajima Road Co., Ltd., Tokyo, Japan, Dr. Eng.

ABSTRACT: In this repair method, the materials to be repaired were applied with two types of adhesives, such as a permeable adhesive and a high durability adhesive to the adhesion interface, and then cast. The repaired materials were then evaluated for fatigue resistance using wheel load running tests. This repair method was developed to ensure long-term integrity of the repair material and RC slabs. The results of the experiments confirmed that this repair method provides significantly better fatigue resistance than the conventional construction method. Moreover, this study proposes two wet repair cycles and one dry repair cycle with reinforcement measures to improve the load bearing performance.

1 INTRODUCTION

Most of Japanese road bridges were built between 1950 and 1970. By 2026, 46% of these bridges will be 50 years old or older, making the maintenance and management of aging bridges an important issue. Furthermore, implementation of waterproofing for the RC slabs was delayed. In fact, waterproofing in the design and during maintenance was required for expressways in 1988, but it was required for general national roads only after the road bridge specification was revised in 2002. For this reason, the upper surface of RC slabs covered with about 80 mm of asphalt pavement is wet from rainwater and being damaged by the traffic load. The damage has been left unrepaired due to cracks and potholes in the asphalt pavement. Japan is an elongated archipelago surrounded by water and has a varied climate with cold and temperate regions. As a result, bridges are affected by airborne salt near the coastline and damaged by salt attack and freezing effects from the snow-melting and anti-freezing agents that are used in snowy areas. Particularly in snowy cold regions, reinforcing bars become corroded, and the spraying of snow melting agents and anti-freezing agents causes daily freeze-thawing action. These factors accelerate damage to the concrete. As this damage progresses, the cement component of the concrete elutes and the concrete divides into coarse aggregate and sand with no bonding force. This separation into coarse aggregate and sand results in the aggregate eventually falling out of the RC slabs. Moreover, a repair site can be re-damaged and the damage can spread, resulting in the need to replace the RC slabs. In this study, we examined the soundness of the adhesion interface of the existing RC slabs, the adhesion strength between repair materials and existing RC slabs, and the measures to be taken with attention to the repair materials. A wheel load running test was conducted to evaluate the fatigue resistance of the repair material (ultrafast, hard, non-shrink mortar) used in the conventional repair method and in the repair method proposed in this research. The repair technique formed between repair material developed exclusively for repairing RC slabs (fiber reinforced ultrafast, hard, non-shrink, mortar) and the two kinds of adhesive (permeable primer and highly durable epoxy resin adhesive) Can reinforce the fine cracks in the RC slabs and integrating the repair material and the RC slabs, the repair technique ensures long-term durability and extends the repair cycle, thereby extending the service life of the bridge.

2 METHODS

2.1 Material properties of repair materials

2.1.1 Ultrafast, hard, non-shrink cement mortar

In Japan, road maintenance and repair work is restricted to about 8 hours. Rapid construction is required to demolish and remove road materials, repair the road, and release traffic from regulation within 8 hours. For this reason, ultrafast, hard, non-shrink mortar is used for the partial repair of conventional RC slabs. The curing characteristics of this repair material are as follows. Initial setting time: 17 minutes; initial strength development: 45.2 N/mm^2 after 3 hours of aging; static elastic modulus: 43.7 kN/mm^2 after 28 days of aging. Since this pot life is 30 minutes or less, prompt work is required. The compounding conditions and material characteristic values are listed in Table 1, respectively. Note that this repair material is described as UM-36 and is a conventional construction material.

2.1.2 Ultrafast, hard, fiber-reinforced cement mortar

Ultrafast, hard, fiber-reinforced cement mortar is a new repair material. This repair material was premixed with high strength vinylon fiber (fiber length: 12mm). By setting the elastic coefficient to about the same as that of the existing RC slabs, resistance to cracking was improved. The material properties are as follows. Curing: 45 minutes at setting completion time; compressive strength at 24 hours: 24.5 N/mm^2; static elastic modulus: 23.8 kN/mm^2. Therefore, compared with the ultrafast, hard, non-shrink mortar, adequate construction time is secured and cracking of thin-layer repairs is reduced. The compounding conditions and material characteristic values are listed in Tables 1, respectively. This repair material is called U-FM-45.

2.1.3 Permeable Adhesive

When repairing the RC slab, use a breaker to remove the damage and associated fragile areas. A permeable adhesive is applied to reinforce fine cracks generated by impact vibration of this breaker. The material properties of the permeable adhesive are listed in Table 3.

2.1.4 High Durability Epoxy Resin Adhesive

A highly durable epoxy resin adhesive (hereinafter referred to as “adhesive for adhesion”) is applied to a permeable adhesive that strengthens the adhering surface after damage. This firmly fixes the repairing material to the deck. This adhesive for adhesion was developed to help prevent fatigue in the steel deck. Kodama et al (2009) and Ito et al (2009). And as reinforcement of the RC floor slab, it has been evaluated as a reinforcing effect by the adhesive bonding technique. T. Abe et al (2013). Table 2 lists the material property values of the adhesive for joining.

2.2 Specification of floor slab specimen

A 3/5-scale model of the actual bridge has the following floor slab dimensions. Length: 1,600 mm; spacing: 1,400 mm; slab thickness: 150 mm. Japan Road Association (2002). D 13 double-reinforcing steel bars were arranged at 120 mm intervals perpendicular to the axis on the tensile side and in the axial direction. 1/2 of the tensile reinforcement bars were placed on the compression side. Figure 1 shows the dimensions of the floor slab, the rebar arrangement map, and the wheel-load running fatigue testing machine. The concrete consisted of ordinary Portland cement, crushed sand (5 mm or less), and crushed stone (5 mm to 20 mm). Compressive strength of concrete: 35 N/mm^2; yield strength of reinforcing bar: 377 N/mm^2; tensile strength: 511 N/mm^2.

2.3 Wheel load running test

2.3.1 Wheel load running tests method

In the wheel load running tests, a wheel load is repeatedly applied to the upper surface of the RC slabs and the repaired RC deck plate within the width of 300 mm, and 1,000 m in the axial direction. The wheel load starts traveling with an initial load of 100 kN. Loads are then added in increments of 20 kN every 20,000 runs. Deflection is measured every 5,000 run when wheel loading runs are once, 10 times, 100 times, 1,000 times, 5,000 times, and more. A frame 600 mm in width and 1200 mm in length was placed around the wheel's traveling position to be filled with water. Wheel loading is performed under wet conditions after the first and second repairs. Holes 9 mm in diameter are drilled in several repair interfaces in order to observe fluctuations in the water level and check for delamination. The specifications for the water filling is shown in Figure 1.

2.3.2 Repair method

Reproduce the state in which repair is required by applying an initial load to the floor slab. From the previous research, it was determined that repair is required when a deflection corresponding to 1/400 of the span length occurs and two-way cracking is developed on the lower surface of the deck. Abe et al (2011). The repair method was verified using a floor surface test specimen subjected to this initial loading. Using the repair material U-M-36 of the conventional construction method, break the repair area with a breaker, clean the surface, then apply the repair material U-M-36, and finish the surface. Next, apply several coats of a permeable adhesive to the prepared adhesion surface and pour repair material U-FM-45 onto the surface and finish the surface.

2.3.3 Repair cycle

The cycle of repair and running wheel load tests was conducted twice under wet conditions and once under dry conditions. In the two wet-condition cycles, repair was performed when the wheel load caused unevenness or scaling or when the deflection reached 1/400 of the slab span L. The dry-condition cycle was performed until the punching shear fracture occurred. Fatigue resistance is determined from the cumulative number of equivalent cycles obtained from these three tests.

2.3.4 Number of equivalent cycles in running fatigue test

The wheel load running fatigue test is a step-load that increases every 20 thousand runs, it calculated the equivalent running number and evaluated fatigue resistance. Assuming that the Minor's rule is applicable to the number of equivalent cycles, it is given by equation (1). Shigeyuki et al (2007). Reference load P in equation (1) is set at 72 kN, which takes into consideration a safety factor of 1.2 based on 3/5 of the design active load, to calculate the equivalent traveling number. The value of 12.7, as proposed by Matsui, is applied to the absolute value of the reciprocal m of the slope of the SN curve.

$$N_{eq} = \sum_{i=1}^{n} (P_i / P)^m \times n_i \tag{1}$$

The equation is expressed as follows: P_i: loaded load (kN), P: reference load (= 72 kN), n_i: number of experiment runs (times), m: reciprocal of slope of SN curve.

Table 1. Formulation and characteristic values of repair materials

Test items				U-M-36	U-FM-45
Compounding condition	unit content of water (kg/m³)	premix powder	Mixed material	938	618
			Other	912	1232
		fiber		-	5
		water		338	278
	Water bonding ratio（%）			36	45
Material properties	Setting time		initial setting	17 min	35 min
			final settung	25 min	45 min
	compressive strength		2 hours	25.1 N/mm^2	19.1 N/mm^2
			3 hours	45.2 N/mm^2	24.5 N/mm^2
			4 hours	52.3 N/mm^2	27.1 N/mm^2
			28th	62.3 N/mm^2	49.9 N/mm^2
	young's modulas		28th	43.7 kN/mm^2	23.8 kN/mm^2

Table 2 Specification of adhesive

Test items		Permeable adhesive	High durability adhesive
appearance	Base compound	Transparent liquid	White paste
	Curing agent	Transparent liquid	Blue liquid
Mixing ratio (main agent: curing agent)		10 :3	5 :1
Specific gravity of cured product Compression strength		1.2	1.42 N/mm^2
Compressive Strength		104.4 N/mm^2	102.9 N/mm^2
Compressive modulus of elasticity		3,172 N/mm^2	3,976 N/mm^2
Flexural strength		92.8 N/mm^2	41.6 N/mm^2
Tensile shear strength		58.2 N/mm^2	14.9 N/mm^2
Concrete adhesion strength		2.6 N/mm^2	3.7 N / mm 2 or more or destruction in the base material

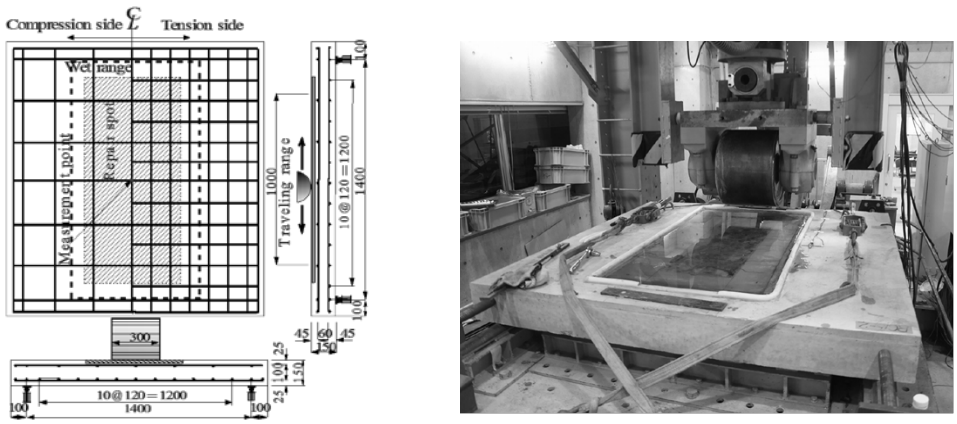


Figure 1. Dimensions of test specimen, plumbing diagram and appearance of running load fatigue testing machine.

3 RESULTS

3.1 Number of equivalent cycles.

Table 4 lists the number of equivalent cycles and the reinforced equivalent running number used in this study.

3.1.1 Specimen RC-U-36 using conventional repair material U-M-36

The number of equivalent cycles of the initial loading is 7.865 x 10^6. Repair material U-M-36 with wheel-loading under wet conditions in the first cycle: the number of equivalent cycles in the running wheel load running tests is 1.685 x 10^6. Similarly, the number of equivalent cycles of the 2nd repair cycle is 1.621 x 10^6. The number of equivalent cycles for the third repair performed under the dry conditions was 10.493 x 10 ^{6}, which resulted in punched shear failure. The cumulative number of equivalent cycles count from 1 repair cycle to 3 repair cycles was 21.665 x 10^6, which resulted in a repair effect of 1.57 for the unrepaired floor plate. Wheel Load Table 3 lists the number of equivalent cycles in the running wheel load running tests.

3.1.2 Test specimen RC-UM-45 using conventional repair material U-FM

The number of equivalent cycles of repairs using the proposed repair material U-FM and two kinds of adhesives was 3.685 x 10^6 in the first cycle of repair, 3.250 x 10^6 in the second cycle of repair, and 42.35 x 10 ^{6} in the third cycle. This is 2.19 times more in the first cycle under dry conditions than with the conventional repairing method, 2.01 times in the second cycle, and 11.49 times in the third cycle. Also, the cumulative number of equivalent cycles until destruction in the 3rd cycle was 57.152 x 10^6. A reinforcement effect of 2.64 times that of the conventional construction method was obtained.

3.2 Relation between deflection and number of equivalent cycles

3.2.1 Deck using traditional repair material U-M-36

The residual deflection under initial loading was 1.42 mm. For repairs with repair material U-M-36, in the first cycle, the cumulative number of equivalent cycles is 9.551 x 10^6, the cumulative deflection is 3.44 mm, and the residual deflection is 1.96 mm. The cumulative number of equivalent cycles in repair cycle 2 is 11.172 x 10^6, the cumulative deflection is 4.10 mm, and the residual deflection is 2.74 mm. In the third repair performed under dry conditions, damage on the repair surface was suppressed. Therefore, the cumulative number of equivalent cycles is 21.655 × 10^6 and the cumulative deflection is 6.65 mm. Figure 2 shows the relationship between deflection and the number of equivalent cycles. Figure 3 shows the condition of damage caused on the upper surface.

3.2.2 About the slab using the proposed repair material U-FM punching shear strength

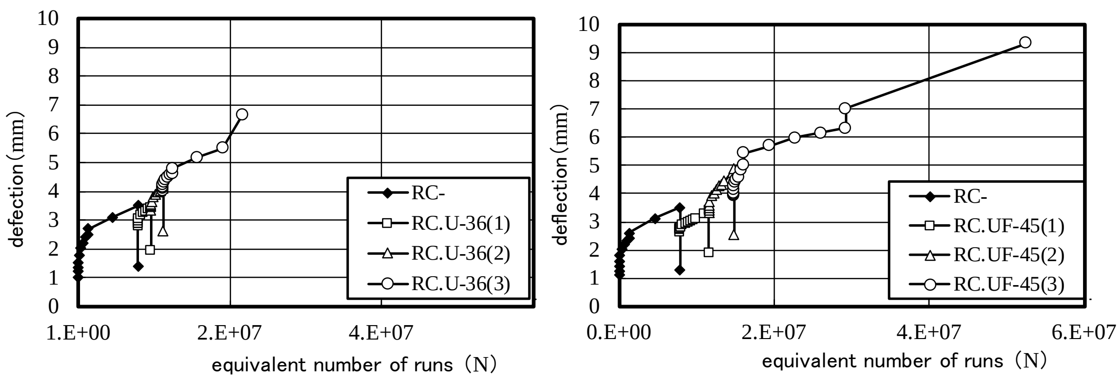
Residual deflection due to the initial loading of the proposed repair material U - FM - 45 and the test specimen to which two types of adhesives are applied is 1.31 mm. The cumulative number of equivalent cycles in the first cycle of repair is 11.551 x 10^6, the cumulative deflection is 3.39 mm, and the residual deflection is 1.90 mm. As shown in Fig. 3(2), the damaged upper surface of the specimen after the runs showed irregularities due to wear, but no cracks are observed. The cumulative number of equivalent cycles in the repair cycle 2 is 14.802 x 10^6, the cumulative deflection is 4.85 mm, and the residual deflection is 2.53 mm. The only damage is unevenness of the road surface. The cumulative number of equivalent cycles of repair cycle 3 under dry conditions is 57.152 x 10^6 and the cumulative deflection is 9.33 mm. Since the repair cycle 3 was conducted until the test specimen was destroyed by punching shear fracture, cracking occurred in the direction perpendicular to the axis on the upper surface of the test specimen. However, the number of equivalent cycles was four times that when using the conventional reinforcement method. These results confirm that the proposed repair method provides fatigue resistance and is practical for repairs using conventional reinforcement materials.

3.3 Penetration of permeable adhesive

After repair cycle 3 was completed for specimen RC-U-36, a permeable adhesive was applied to confirm its penetration performance. The sampling location on the core is shown in Figure 3(1). The infiltration state on the cut surface of the core is shown in Figure 4. In the diameter 60 mm core, the permeable adhesive penetrated the fine permeable cracks and horizontal cracks down to the depth of 50 mm. In the diameter 100 mm core, the permeable adhesive penetrated the horizontal cracks generated at the repair interface and the bond break at the position of the reinforcing bar. The permeable adhesive seemed to penetrate the fine cracks caused by running wheel load tests on the concrete surface. This shows that the attachment between the slab and the adhesive is strongly reinforced by the effect of the adhesion.

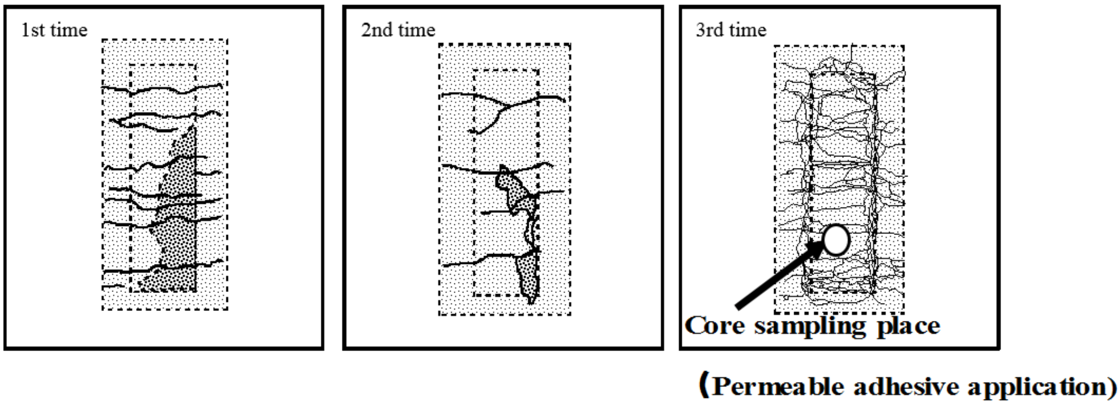
Table 3 The number of equivalent cycles and the reinforced equivalent running number

		RC.U-36	RC.UF-45
RC slab		7,865,598	7,865,598
Primary repair (wet state)	Equivalent runs number times	1,685,974	3,685,775
	Reinforcement effect	-	2.2
Secondary repair (wet state)	Equivalent runs number times	1,621,127	3,250,670
	Reinforcement effect	-	2.0
Tertiary repair (dry state)	Equivalent runs number times	10,493,077	42,350,384
	Reinforcement effect	-	4.0
Total until tertiary repair	Equivalent runs number times	21,665,776	57,152,427
	Reinforcement effect	-	2.64

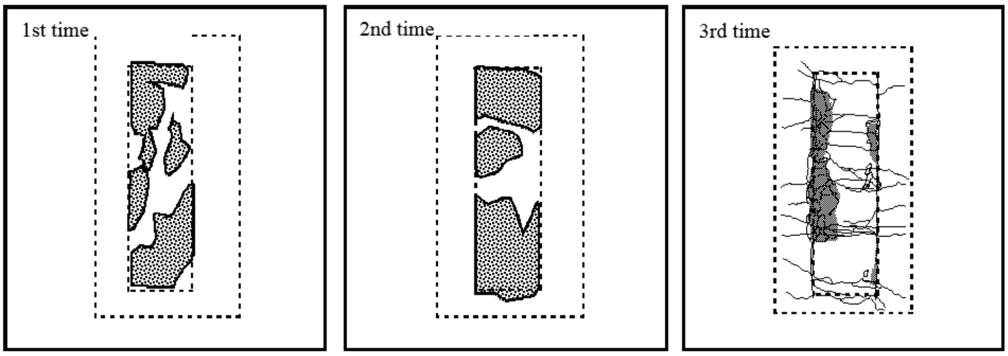


(1)RC.U-36 (2)RC.UF-45

Figure 2. Relationship between deflection and number of equivalent cycles

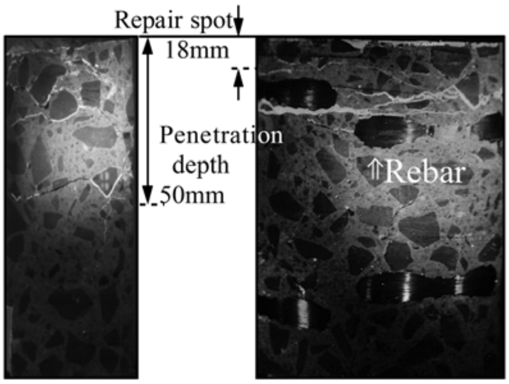


(1)RC.U-36



(2)RC.UF-36

Figure 3. Damage status after repair



(1) diameter 50mm (2) diameter 100mm

Figure 4. Result of permeation verification after specimen RC-U 36 destruction

4 DISCUSSION

4.1 Evaluation of fatigue resistance by number of equivalent cycles

Using repair material U-FM–45, after applying the two kinds of proposed adhesives is 2.2 times and 2.0 times that of the conventional construction method in repair cycle 1 and repair cycle 2, respectively. It was 4.0 times that of the conventional construction method in repair cycle 3 performed under dry conditions and the repair effect was 2.64 times greater at the time of breakdown.

4.2 Evaluation of crack resistance

Using the conventional construction method, after the wheel load running tests in repair cycle 3, many cracks appeared on the repaired surface. These cracks extended to the crack in the direction perpendicular to the bridge axis. However, although the surface repaired using the proposed two types of adhesives and repair material U-FM-45 showed damage due to wear, the amount of cracking in the direction perpendicular to the bridge axis was significantly smaller than was the case using repair material UM - 36, confirming that the fatigue resistance was improved.

5 CONCLUSIONS

In this study, we investigated countermeasure technologies presuming that re-damage is caused by delamination of the adhesion interface and cracking of the repair material, further supposing that rainwater, etc., intrudes and induces damage. The first countermeasure technology is a permeable adhesive for strengthening the adhesion interface. The second countermeasure technology is an adhesive for fresh concrete that firmly bonds the existing repair material with the new repair material. Finally, the third is the development and application of a repair material that has an elastic modulus equivalent to that of existing slabs and further improves resistance to cracking by using resin fibers to add toughness. In this research, we proposed a repair method that combines these technologies and confirmed that the method provides much greater fatigue resistance than the conventional construction method.

References

M. Shigeyuki, *Design and Construction of Road Bridge Slabs and Maintenance*: Mori Kita Publishing, Inc, 2007

Specifications and cmmentary for road bridges Ⅰ，Ⅱ, Ⅲ: Japan Road Association, 2002

T. Abe, T. Kida, M. Takano and Y. Kawai， EVALUATION OF THE PUNCHING SHEAR STRENGTH AND FATIGUE RESISTANCE OF ROAD BRIDGE RC SLABS. *Journal of Japan Society of Civil Engineers, Ser. A1 (Structural Engineering & Earthquake Engineering, Vol. 67 (2011) No. 1 P 39-54*

T. Abe, H. Suzuki, Y. Kishi, and K. Nomoto, Influence of Adhesive on Fatigue Resistance in SFRC Top Thickness Reinforcement Method of RC Deck Slab. *Proceedings of Structural Engineering, Vol. 59 A, pp. 1084-1091, 2013.3*

K. Ito, J. Takahagi, H. Chiba, and Y. Suzuki, 2009, Study on a Countermeasure for Improving the Fatigue Durability of Existing Orthotropic Steel Deck Plates Using SFRC Pavement. *Proceedings of 5th China-Japan Workshop on Pavement Technologies (CJWPT 2009*), *pp.221-226, 12th-13th September 2009*

T. Kodama, O. Kamada, M. Nishi, Y. Suzuki, and T. Fukute, 2009, A Study of bonded concrete overlays using epoxy adhesive in Japan. *International Conference on Maintenance and Rehabilition of Pavements and Technological Control(MAIREPAV6*)