A new technique to increase the safety of stone pavements through controlled evolution of unevenness

Crispino M.
Professor, DIIAR - Road Infrastructures, Polytechnics of Milan (IT)

Da Rios G.
Professor, DIIAR - Road Infrastructures, Polytechnics of Milan (IT)

Fiori F.
PhD Student, DIIAR - Road Infrastructures, Polytechnics of Milan (IT)

Papetti M.
Chief of Road Maintenance Division, Municipality of Milan (IT)

SYNOPSIS

Stone element pavements constitute a typical feature for many artistically valuable urban environments in Italy and Europe. Unfortunately, their deterioration under traffic loads may generate discontinuities in road surfaces compromising ride safety especially for two-wheeled vehicles. Along tramways, due to pumping phenomena, such discontinuities may become remarkable, with local very severe elevation and rotation of the blocks. Besides a loss of safety for two-wheeled vehicles, other consequences are higher noise and derailment of trams.

A complex multibody simulation allowed to set up a method able to quantify the danger level according to the actual road condition.

Classical maintenance of this type of distresses along tramways was shown to be not effective at all, needing continuous repair with high costs and without being able to assure safety for users.

In order to improve road safety a new rehabilitation technique of the pavement was developed. Such technique is based on the use of a polyurethane resin (set up in collaboration with chemical partners) able to seal the joints creating a structural continuity between the stone blocks. As consequence, the blocks are not allowed to locally displace as high stability is reached whereas, in case of permanent deformation of the pavement due to subgrade or foundation, the structural continuity supplied by the resin allows generation of only very long wavelength unevenness, less dangerous for riders respect to local discontinuities. In this way the evolution of unevenness is totally controlled.

Since 1999 many laboratory and in situ tests (run in very important and trafficked Milan roads - still under control), enabled to set up and validate the right formulation for the resin and the whole technique. Such technique is now becoming a practice in Milan rehabilitation works of stone pavements. All the experience became also of interest for an international workgroup aimed at studying methods to increase safety of urban roads when tramways are embedded into the pavement.

The present paper describes the research and the main results obtained with the aim to transfer acquired experience and knowledge to other Municipalities with face similar safety problems.

A new technique to increase the safety of stone pavements through controlled evolution of unevenness

INTRODUCTION

In most countries, aesthetical criteria lead many municipalities to preserve stone element pavements in artistically and historically valuable areas, whereas concrete or brick element pavements are a widespread strategy to upgrade urban environments, often in connection with policies of traffic limitation.
Many Italian cities have broad networks of stone paved roads in downtown; even if most of them are not so ancient, dating back only to the first decades of the twentieth century, they have become a well known feature of their urban environment; therefore, Artistic Superintendences often declare them to be preserved. The typical stone pavement the authors analyzed is made up of large granite or porphyry blocks, of different sizes. The stone elements, mostly rectangular, are not parallel to the alignment of the road, thus avoiding vehicular trajectories along joints. Pentagonal elements are used to complete the pattern by the curb and where longitudinal elements have to be inserted (e.g. tramway tracks). The natural rocks and the pleasant pattern give an high aesthetical value to the road. On the other hand, when these stone pavements deteriorate, they become dangerous, particularly for two-wheeled traffic. Inadequacies in the lower layers cause single elements to displace and rotate, thus generating steps in the road surface, which interrupt abruptly the overall smoothness. Pavements with embedded tramway tracks are particularly dangerous, since their deterioration rate has shown to be remarkably higher with tramway traffic; furthermore, the grooved rails themselves behave as discontinuities able to divert bicycle tires.
Within this framework, a broad research program was carried out by the Road Research Laboratory of Polytechnic of Milan to investigate stone element pavements, also supported by Municipality of Milan and by ATM (Milan Transport Company). The program has been ongoing for a number of years and includes a number of different activities:

- An overall model for the rider-bike-pavement system was developed, calibrated and tested. It was applied to many different situations, analyzing different combinations of parameters. The resulting data were examined according to the defined safety criteria and then summary tables of practical use were drawn in order to create reasonable thresholds for road managers, to decide if maintenance on a location can be postponed or not, considering the safety of two-wheeled users [1].
- Extended test sampling of broken up pavement, together with experimental testing to understand the processes responsible for the deterioration of the pavement [2].
- Following this phase, lab tests were carried out and followed by full-scale applications to establish new and effective design and maintenance methods [3].

The final aim is to prevent the dangerous deterioration of roads due to the dislocation of one or more stone element and, where this cannot be prevented, the transformation of the type of deterioration into one without dangerous unevenness and with a form of unevenness which is not dangerous to cycles or other traffic.
After about five years since first laboratory and in situ tests continuously monitored, the present paper describes the different research steps and particularly the final innovative technique chosen, which is now a commonly used technique for the rehabilitation of stone element pavements adjacent to tramways.

1 STONE ELEMENT PAVEMENT DANGEROUSNESS

This phase of the research program was carried out to identify the danger factors due to the deterioration of the stone element pavement [1]. The statistical approach, comparing accident rate and pavement condition, could not be applied, since the absolute numbers of accidents to two-wheeled users on stone pavements reported to the police is too low to have a reliable consistence. The problem is however real and perceived, since riding on uneven stone pavements is objectively uncomfortable and unstable, and complaints from users are very common. Besides, the statistical approach allows to state that a pavement is dangerous only after accidents have occurred. A different, preventive, approach was needed, but very limited aids were found in the technical literature. Therefore an utterly new method was developed and applied by Road Research Group at Politechnic of Milan [1]. It is deterministic in its formulation and it is based on simulations of two-wheeled vehicles impacting on a pavement discontinuity. They enable to verify the ride safety for any combination of vehicle speed and unevenness level. The fundamental parts of the study are discussed in the following.

1.1 The perceived danger according to riders

The first stage of the research was the detection of the most common unsafe conditions to be simulated and analyzed. In fact, while a generic danger associated with stone pavements is broadly perceived by riders, the actual deterioration features leading to dangerous situations were not known, and the dangerous situations were not clearly defined themselves. The data from the police database on accidents were not useful. Besides, police archives contain mainly cases resulting in serious injuries, which are a small portion of the whole set of bicycle accidents.

Therefore, the authors chose to make an inquiry into the upper classes of high schools to collect the needed information. Late teenage was considered a representative age range for Italian two-wheeled mobility, both for the relative numbers and the broad rate of unsafe behaviors.

A questionnaire was distributed only to the students who had declared to have risked a fall when riding two-wheeled vehicles on stone paved roads. The students were asked to focus only on the dangerous situation in which the pavement unevenness had played a major role. 237 valid interviews formed the survey sample.

The data show that the encountered dangerous situation, due to pavement conditions, led to a fall for 38% of the sample, whereas the other users were able to limit the consequences of the event. Only 19% of the sample had fallen also on asphalt pavements, thus confirming a greater unsafeness for stone element pavements.

Referring to pavement conditions, for which multiple answers were accepted, 63% of the interviewed students pointed out the surface unevenness as a cause of loss of balance, 62% of the sample accused the presence of grooved rails, while 33% pointed out adherence problems on wet stones (but 75% of the sample declared that the problem they were referring to happened during rainfalls or with wet pavement). Direct observation, confirming the survey results, shows that two-wheels users carefully avoid to ride on tramway rails, both because of the low adherence coefficient and the geometrical shape of the groove, able to divert bicycle tires. Hence, the information provided by questionnaires was interpreted considering the surface unevenness as the trigger for the ride perturbation that creates the dangerous situation, while the rail becomes a severe worsening factor after the bicycle ride has been perturbed.

Analyzing the specific kind of unevenness perceived as responsible, 40% of riders pointed at the overall unevenness, 40% at a single raised element, the remaining 20% at a single lowered element.

The effect of pavement discontinuities on the ride of two-wheeled vehicles was evaluated by a parametric multibody model. Several pavement discontinuity features were varied, as well as ride parameters such as vehicle speed and trajectory radius, reproducing a broad spectrum of realistic situations [1].

1.2 The 3D rider-bike-pavement model

The model [1] (fig. 1) that was implemented for the road-tire contact, was regarded to be an extension of the LRISM model (Linear Radial and Interradial Spring Model).

Preliminary simulations showed that the level of detail adopted to describe the rider's body plays a major role for the overall reliability of the simulation because the rider's weight is relevant in comparison to the bicycle weight and it can noticeably affect the global behavior of the system, especially during jumps.

The Drillis and Contini's scheme was regarded as a sufficient approximation for the geometrical definition of the human body. It considers the main joints of the human skeleton, which separate 13 rigid elements [1].

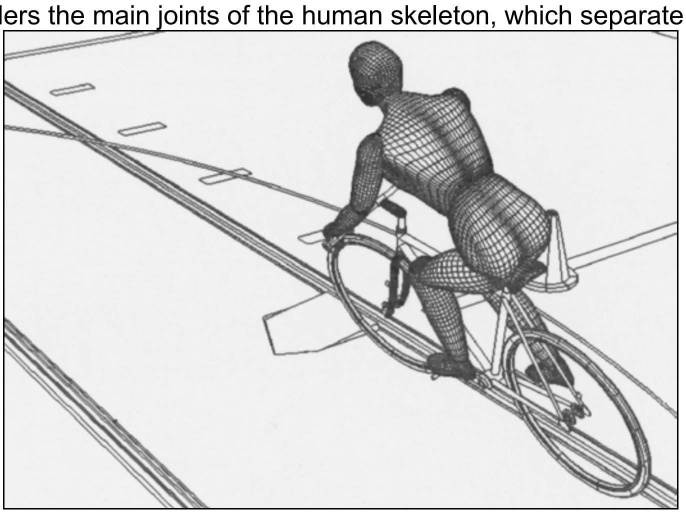


Figure 1. 3D rider-bike-pavement model [1]

Mechanical properties of joints were calculated by a pre-simulation, setting the rider on the saddle, his hands on the handles and his feet on the pedals, and determining the least control able to maintain the body in a steady position notwithstanding the gravity force.
After pre-simulations, it was decided to adopt a city-bike model because of safety considerations.
The profile of the tire was scrupulously measured and reproduced, the load-yielding relation, and hence the spring stiffness, was experimentally determined. The load-yielding relation for the rider-saddle contact was also measured.
The adherence and friction coefficients at tire-stone and tire-rail contacts were obtained through direct measurement under a known load, with the real tire on the real surfaces. Different surface conditions were tested on wet stones and on just wet rails (railway experience confirms that higher adherence coefficients can be measured during heavy rainfalls, when the steel is wet but clean, than during moist weather, when a slime can lubricate the rail).
To verify the overall model, experimental tests were carried out. On an even pavement, a step was artificially created by nailing a plane panel of known thickness. A rider of known weight and height rode the reproduced city-bike at different speeds to a normal impact on the discontinuity. The comparison was done on the jump length after the step.
Several impacts were reproduced and in every case the difference among simulation results and experimental measures was negligible [1].

1.3 The model applied to stone element pavements

Two main ride situations were examined with the aim of assessing safety thresholds for stone pavements: bicycle in straight motion close to tramway rail, and curve case, with the impact happening while the rider has a curve trajectory. All simulations assume wet pavement, for which the adherence condition leads to more severe risks [1].
The straight ride case assumes as initial condition a cyclist proceeding perfectly vertical and parallel to the tramway track, on a trajectory 100 mm shifted from the edge of the rail. The pavement pattern thus implies an orthogonal impact with the discontinuity. The behavior of the cyclist-bicycle system was studied by 45 simulations: five different speeds (10, 20, 30, 40, 50 km/h) were considered, for each of nine stone element tilts (generating a discontinuity height at the wheel impact point of +40, +30, +20, +10, 0, -10, -20, -30, -40 mm). The modeled road comprises also the RI60 rail surface and 499 other stone elements defining the regular pavement nearby.
In sections where rectilinear ride is assumed, pavement elements raised or lowered more than 30 mm from the road surface should never be tolerated, while the threshold should be lowered to 20 mm, at least for raised elements, if speeds among 40 and 50 km/h are expected. Discontinuities between 20 and 30 mm could be accepted only with a severe speed limit (20 km/h, or better 15 km/h introducing a safety factor) [1].
Thirty-six cases, differing for vehicle speed and discontinuity height, were analyzed to verify if cyclists riding on curve are able to maintain a stable attitude after having impacted on uneven elements.
As done for the straight ride case, the uneven element is assumed to be next to the rail and rotated around its longitudinal axis. It generates a discontinuity in the trajectory varying from –40 mm to +40 mm. The bicycle is expected to impact on the discontinuity at a right angle, with the front wheel at 100 mm from the rail edge (the rear wheel generally follows a different trajectory).
Each combinations of discontinuity size and speed was analyzed with two simulations, one without any intervention from the user on the handle-bar (the rider is not able to act on the handle-bar during the 1000 ms following the impact, e.g. for not having seen the obstacle), the other one assuming the rider makes limited suitable corrections, which, if possible, are able to get a stable attitude by the end of the simulation (1000 ms).
Element tilt has shown to have a great importance. It can be concordant or opposite to the banking angle, thus improving or worsening the motion conditions. Hence, each combination of discontinuity size and speed had to be split in two sub-cases, left-hand curve and right-hand curve, as shown in fig. 2, to consider the two different banking angles the rider can have in approaching the discontinuity. Eventually, a total number of 144 simulations were carried out.
The results can be summarized as follows:
As a rule, a general speed limit of 40 km/h for bicycles on stone pavements is recommended.
To enable speeds up to 40 km/h guaranteeing a level of risk labeled as acceptable, a very smooth road surface has to be assured, by eliminating any pavement discontinuity greater than 10 mm.
By limiting bicycle speed to 20 km/h, the acceptable level of risk can be obtained also with discontinuities in the 10-20 mm range.
Allowing a medium level of risk, elements lowered as much as 30 mm can be accepted, while elements raised over the smooth surface in the 20-30 mm range require a 20 km/h speed limit [1].

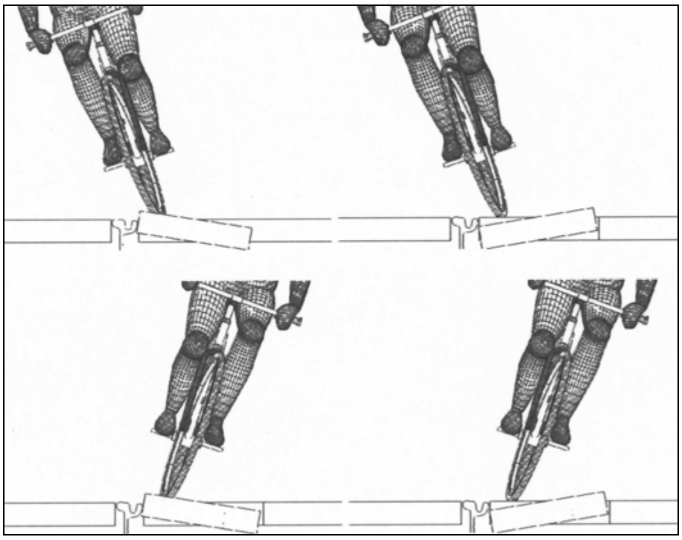


Figure 2. Model applied to curve cases [1]

1.4 Criteria for safety-oriented maintenance

The performed analyses produced some criteria of practical use to set some safety-oriented maintenance and speed thresholds. Different values could be suggested for the rectilinear case and the curve case [1].
Wet pavements were always considered, being this a critical adherence condition, but aquaplaning, mud or rotting leaves can create even worse conditions.
It should be remarked that the presented method does not require either specific instruments or specifically trained workers to determine the degree of risk for riders on a location. The vertical discontinuities to be detected in stone paved areas are quite evident and a quick overview is usually enough to spot the worst of them. Then, very simple instruments as rulers can be used to measure their height. That means that also unskilled workers can determine weather a discontinuity is dangerous or not.
After identifying the deterioration as a high-danger factor for the safety of cyclists, a maintenance technique was required to reduce the effects of the degradation of the pavement. On site inspections and lab tests were preliminary carried out to establish the causes of the degradation.

2 PRELIMINARY INVESTIGATIONS: THE SEARCH FOR CAUSES AND CONTRIBUTING FACTORS IN THE DETERIORATION OF STONE PAVEMENT

Stone pavement diagnostics was carried out to establishing the best maintenance techniques. For this purpose, visual inspection, in site measurements (including innovative types) and analysis of materials taken from the deteriorated site were carried out. The effect of rainfall was also evaluated, along with a number of other factors, such as traffic, age, etc.

2.1 Visual inspection

Visual inspection was carried out with the aid of the catalogue of stone pavements specifically set up for the task [4]. It was found that stone pavements when used for tramways are subject to high degrees of deterioration, negatively affecting the track and the safety of the most vulnerable road users. Stone elements were found to have lifted or dropped after sideways or frontal rotation (compared to the rails), up to different centimetres. The joints were found to be affected by excessive spanning, excessive depth, partial or total lack of seal, binder spread over the stone element. Visual inspection showed the correlation between the degree and extent of deterioration and the deflection of the rails [5], which in many cases was so high to be clearly visible.

2.2 Analysis of the materials under the stone

The displacement of the stone elements was found to be in great part due to the movement (pumping effect) of very fine parts of the bedding and joints sand and of the subgrade. In order to establish the percentage of fines in the sand bed, grading curves were determined from samples taken from the bedding layers of stone elements with different surface appearances. The percentage of fines in the materials examined was very high, in the region of 14% of the overall weight (with a peak of 22%).
This grading is unlikely to reflect the original composition of the sand, which was tested and shown to have between 2-4% of fines. The material is likely to come from below (subgrade) or from the bedding layer, accumulating in certain areas, particularly where the tramway sleepers displace under the passing loads.

2.3 The impact of other factors

In order to assess the impact of other factors such as traffic, the age of the pavement, moisture content, etc. data collected on site and on the premises of the relevant authorities (ATM and Milan Municipality) were analyzed.

The factors examined included:

- tram traffic;
- road traffic;
- the age of the tramway;
- the state of the pavement (width of joints, presence of sealing material, etc).

The presence of traffic, particularly heavy traffic, has been shown to aggravate the deterioration of pavement but it is the movement of trams that is specially damaging since roads with tram rails that are no longer used by the trams do not have the same degree of problems.

A study of individual displaced stone elements has shown that irregular joints and a lack of sealing material are not sufficient to lead to deterioration, because they also occurred in roads that were not deteriorated; clearly they are able to accelerate deterioration due to other factors. Narrow (under 1 cm) sealed joints showed a slower evolution rate of deterioration, by keeping out water and other materials.

It was not possible to find one single factor responsible for deterioration. A number of factors always contribute.

The most important factor, however, seems to be rainwater. Due to the large quantity of fines under the stone, the rainwater does not drain off but accumulates at the bottom, forcing materials out. This action generally follows the cyclical movement of the sleepers caused by the trams. Bibliographical research and site inspections showed that the deterioration of stone pavement (fig. 6) seems to be caused, particularly close to the tracks, by the movement of sleepers causing pumping of the fine materials in the joints, in the sand bed and in the subgrade foundations [5].

2.4 In site tests for deflection measurement

Deflection of the rails were measured in order to establish the correlation with the deterioration of the pavement subgrade.

Three methods were used: a mechanical comparator, a Benkelmann beam and a falling weight deflectometer (FWD).

The FWD had to be used due to some preliminary studies carried out through a comparator and a Benkelmann beam to measure the deflection of the rails while trams moved over them. The tests revealed how hard it is to count on a constant load during measurements, since the trams are in transit and load is affected by variable such as speed, the number of passengers, the condition of the wheels and the track, the condition and features of the suspension system on the tram, and so on. FWD was used to measure both deformation and loads, the latter being in the regions of those actually encountered for trams.

The innovative application of the falling weight deflectometer produced significant results. In addition to removing the problem of unknown loads, the method also eliminates problems concerning the reference system.

Deflection measurements were carried out on rails in different conditions of stone pavement, both with conventional tramway systems (new or old) and with rigid tramways [5].

In order to assess the impact of the deflection of the rail (due to trams passing) on the deterioration of the stone pavement, and especially the quantitative relationship between the rigidity of the rail and the amount of deterioration, a large number of tests were carried out in different roads in the Milan tramway area, using the FWD (fig. 3 - 4). Specifically, about 150 measurements were carried out (each repeated 3 times) of the tram rail in good or deteriorated conditions for the adjacent stone pavement.

Figure 3. FWD test equipment [5]

Positioning of the instrument on the rail

Positioning of the plate on the rail

Figure 4. Positioning of the test equipment [5]

2.5 Results and conclusions

The tests were carried out on seven different city streets in different conditions of deterioration. After eliminating irregular values, data were analyzed for all test heights and the three different load levels: 22.5, 35 and 51 kN. This was possible because, within the range of analysis, there was practically a linear ratio between the force applied and the resulting displacement. The required comparison between groups (at various stages) was carried out for each load, establishing a correlation between displacement and deterioration.

The FWD measurements on rail confirmed the correlation between deflection of the rails (under the tram load) and degradation of the nearby pavement (fig. 5).

Specifically, in points where the rail deflected by less than 900 micron, at maximum load of 51 kN, no deterioration of the adjacent pavement was found. The conditions of the subgrade were good enough to bear the load without high deformation of the sleepers.

Where the rails deflected more than 1000 micron, adjacent stone pavement resulted already deteriorated (the subgrade bearing capacity was inadequate).

There is an intermediate range of deflection between 900 and 1000 micron, where it is more difficult to make predictions. These values were in fact measured both where the pavement had deteriorated and where it was still intact.

Vertical displacement is therefore a fundamental parameter to assess the suitability of an infrastructure with stone pavement and should therefore be used to plan maintenance operations.

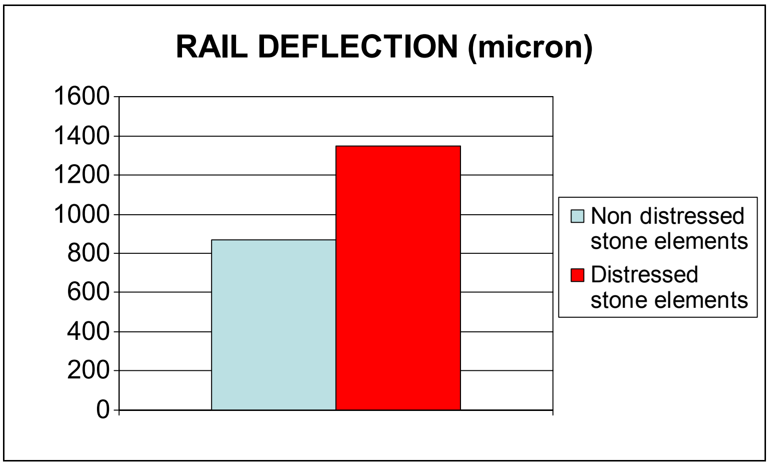


Figure 5. Average deflection of rails for deteriorated and non-deteriorated pavement surfaces [5]

3 DESIGN AND TECHNOLOGICAL DEVELOPMENT OF STONE PAVEMENT WITH CONTROL OF UNEVENNESS EVOLUTION

With reference to the problems encountered during the investigation of road surfaces along the tramlines in Milan, it became clear that new criteria were needed for the maintenance of the stone elements in order to improve their performance and load-bearing capacity and hence the safety and the comfort of road users.

The existing structure included joints filled with sand, enabling vertical interlocking (structural collaboration between adjacent elements) [6].
The aim of the research was to study a technique (through a "structural sealing") able to change the behaviour of the pavement, reinforcing it while achieving a sort of "hinge link" between adjacent blocks (fig. 6, 7). Due to the different behaviour so obtained (through the structural sealing between the blocks) the pavement would deteriorate without local displacements of the blocks but by "gently" deflecting, with a wavelength that would not constitute a danger to motorists or cyclists. This pavement is therefore characterized by a controlled evolution of the unevenness.

Stone elements with even surface | *Stone elements with uneven surface*

Figure 6. The surface of deteriorated stone pavements

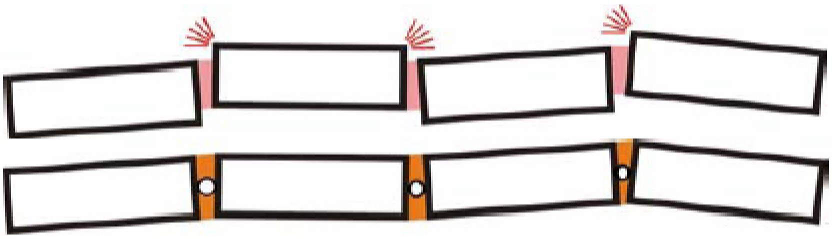


Figure 7. Existing structure (above) and "controlled unevenness" structure (below)

Once defined the basic theroretical idea, research was carried out to develop a technique to make it possible. Research was carried out in conjunction with ATM, the Milan Transport Company, and Milan Municipality.
The experimentation focussed on the features of the potential stabilizing and sealing material, never before used in this application: polyurethane resin.
Various forms of polyurethane are commonly used for industrial applications (machinery, tools, vehicles, etc.) for furnishings and in the building industry (insulation, sealing, etc.), and for clothing [7]; their use for stone pavement is entirely new and experimental.
A polyurethane resin with two components was used which can be applied cold. The basic component was a black amine (2/5 of the total) and a hardener, Polyisocyanate, which is dark yellow (3/5 of the total).
The resin was specifically designed to provide stability between adjacent stone elements (by interlocking), and to provide greater short- and long-term surface elasticity. Due to its chemical structure the material is not susceptible to heat.
In addition, a layer of geotextile was tested under the bed, laid in order to prevent or hinder the migration of fines (lime and clay) which are the cause of pumping [5, 8].
The first part of the experiment was carried out in laboratory and involved tests on joints (shear and bending test) of suitable sizes, specifically created for the purpose, and filled with polyurethane resin. Mechanical strength tests were then carried out in order to obtain the modulus of elasticity, tensile strength and characteristics of adhesion to stone and steel.
On the basis of these results, tests were then carried out on site: after a preliminary small-scale test, a larger-scale test was carried out in the center of Milan, using the innovative maintenance technique which was then applied over an extended stretch of road.

3.1 Laboratory tests

To test the strength of the polyurethane resin various blocks of stone were prepared on a reduced scale, cut from the real stone in order to ensure there were no differences due to the stone materials (fig. 8). The stones were laid exactly as they would be on the road surface. These samples were tested for shear and bending test.
Innovative tests were also carried out in order to assess the mechanical properties of the seal.
Tensile tests were carried out to assess the adhesion of the seal to various types of material including steel (for the rail) and stone used for the pavement. Tensile tests were also carried out directly on samples of sealing material only, after shaping.

3.2 Shear test for a polyurethane resin joint

The shear test was carried out on a group of three sealed elements in order to test the mechanical strength (adherence) of the resin and the elasticity of the joint subjected to a shear force.
The sample proved to have high deformation characteristics and the resin was elastic (after unloading the material went back into place as if no deformation had occurred).
The two side blocks of stone were placed directly on cubes of steel and stabilized by fixing to a frame. A load cell was used on the central block, via a very rigid steel element.
The test was carried out in controlled load conditions. The load leading to the first detachment of the resin was 11,124 kN. At this load the average displacement was 15 mm.
The joint finally got under rupture at 13,181 KN (fig. 8).

	
Specimen	*Deformation of the specimen during the load phase*

Figure 8. Shear test for a joint sealed with polyurethane resin

Tensile strength was σ_R= 4.51 MPa in line with the maximum tensile strength allowed for the resin according to the manufacturer's specifications (~ 4 MPa).
With reference to the upper part of the joint, the adhesion was calculated as 3.19 MPa [9].

3.3 Bending strength test for a joint in polyurethane resin

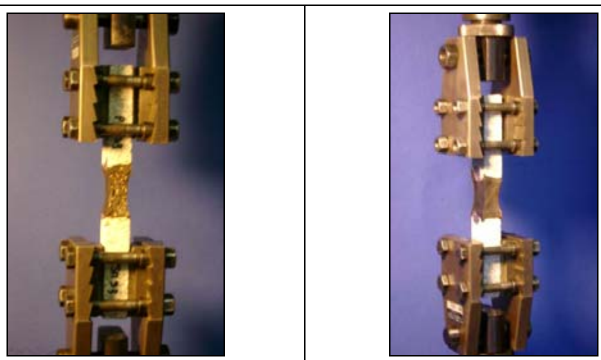
The bending strength test was carried out on two cubic stone elements, connected in the interface area by polyurethane resin.
The aim of the test was to measure the detachment strength of the resin (adherence) and the elasticity of the joint subjected to a bending force.
The test set-up is shown in fig. 9, with bending forces at 4 points.

Figure 9. Sample subjected to bending strength

During this test the maximum force reached was 17 kN. Tensile at the base of the sample generated a bending force just before rupture of 4.06 MPa [9]. Here too, the strength matches the manufacturer's specifications (about 4 MPa).

3.4 Adhesion test for the resin support

Some samples of polyurethane resin were prepared, used as cold sealing material: performance in fact depends on the environmental conditions in which the material is prepared. Therefore the samples were prepared with careful attention to the climatic conditions (18.5° C). Samples had a base of 20 mm x 30 mm
Some samples were prepared with pure resin whereas others mixed with 4% in weight (20% in volume) of cork acting as an inert in order to reduce the cost of the sealing material by reducing the amount of resin needed.
The sample surfaces (where the stone and resin adhered) were treated differently in order to observe different performances. In some cases the stone surfaces were left untreated, in others they were sandblasted or polished to improve the adherence of the resin and remove irregularities.
Steel samples were prepared by treating the surfaces of the prisms with a rough sandblaster, creating a rough surface able to increase the adhesion of the polyurethane resin.
Subsequently, for each sample, a solvent was used to eliminate impurities from the surface. Resin was applied to the contact faces with a brush, a film of base primer Methylethylchetone (a liquid adhesion agent) to improve the adhesion of the stone and sealing material.
An electromechanical dynamometer with a fixed upper part and mobile lower part (speed 20 mm/min.) was used to carry out the tests (fig. 10). Deformation grew constantly with time (set on the mobile crosspiece) and the load was measured continuously.
Tests were carried out at a constant temperature of 22°C and humidity of about 60% and samples were left to stand for about 24 hours before being tested.



Resin with 4% cork | *Pure resin*

Figure 10. Polished stone samples with polyurethane resin, with and without cork

The results, shown in table 1, show the following phenomena for most samples:

- fracture begins at the contact interface between the resin and steel or stone prism,
- subsequently the crack extends cohesively through the resin.

The fracture is practically cohesive (in the resin), whereas in adhesive fractures the primer and resin detach first.
In stone samples the fracture frequently begins with the detachment ("ripping") of small pieces of stone which break due to the tensile at the interface and stay glued to the resin.
The samples of stone and resin behaved the same irrespective of the surface treatment of the face between the stone and sealing material. The pure resin samples out-performed the samples with cork by about 20%.
The tests on stone samples treated at the surface were carried out in two different sessions three months apart; the second session tests had similar results but the polyurethane resin had a higher strength due to a better reticulation of the resin.

Table 1: Maximum tensile stress registered during Polyurethane adhesion tests

Specimen	Maximum Stress (MPa)	
	Pure Polyurethanic resin	**Resin with Granulated Cork**
Steel	1.49	1.18
Stone (10 days)	1.43	1.29
Stone (3 months)	1.76	1.59

3.5 Direct tensile strength test on resin samples

Tests were also carried out on samples of pure polyurethane resin (tensile strength) in order to assess its elastic properties (fig. 11). The samples were prepared in the form of "dog bones" by sticking the resin to a

silicone mould and allowing it to reticulate at a temperature of 19.5 °C; they were then left in a thermostatic chamber at 22° C. before testing.
The direct tensile strength tests were carried out using an electromechanical dynamometer, by creating a deformation of 10 mm/min.
The three samples behaved very similarly; nominal forces of about 2 MPa were found with a resistance force of about 8 MPa and deformation of about 300%, while the young modulus of elasticity was between 2.8 and 3 MPa.

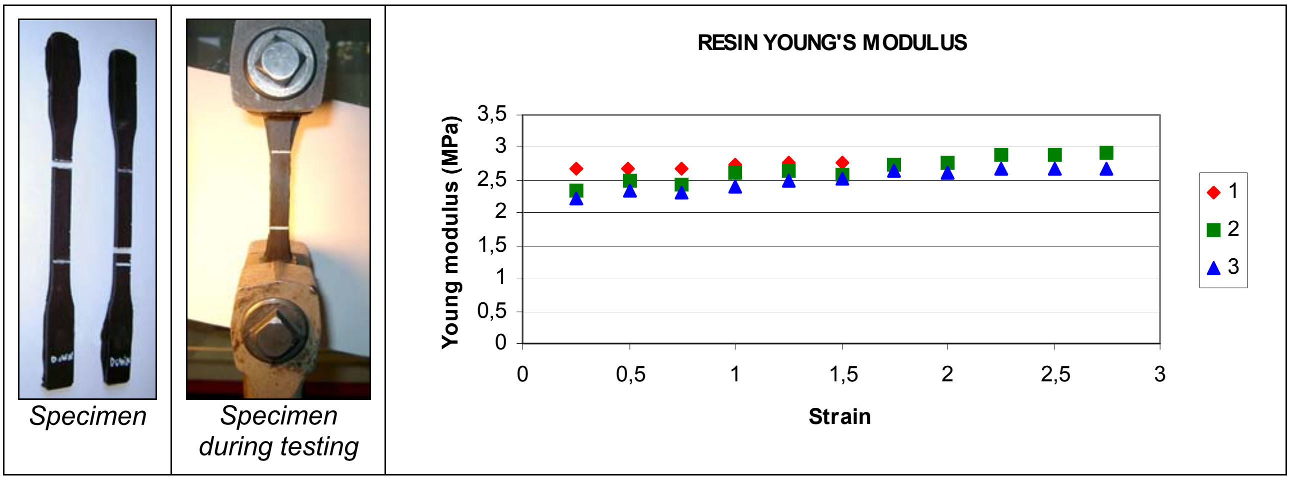


Figure 11. Direct tensile strength test carried out on 3 samples of polyurethane resin

The tests carried out on the polyurethane resin showed that the material is effective for sealing stone pavement next to tramway tracks. The resin was then tested on site.

3.6 Preliminary on-site experimentation

In order to compare the conventional method with the new method using polyurethane resin, a preliminary test was carried out in Piazza Leonardo da Vinci in Milan. This test involved comparing the performances of different techniques after a period of time.
Four disconnected stones in two areas were used for the test, all adjacent to the tramway (the area of maximum deterioration): two were repaired with the innovative method, using polyurethane resin to seal the joints, and two with traditional methods.
The streets were re-opened to traffic a few hours after ending of the work. After 15 days, visual inspection of the stone pavement showed that:
- the elements sealed with polyurethane resin were not displaced compared to adjacent elements of the pavement;
- one of the blocks conventionally repaired had already displaced.
Five months after re-opening to traffic, a second visual inspection was carried out on the site, confirming the good condition of the elements with polyurethane resin seal and the poor condition of the other two conventionally repaired blocks, which had been significantly displaced.

3.7 Full-scale experimentation

Following the positive results of the preliminary stage, the test moved to full-scale and to a badly deteriorated site in the center of Milan. This new phase involved designing the technique for laying the joints with polyurethane resin, with a layer of geotextile, if considered necessary, in order to prevent the migration of fines from the subgrade. In fact, if the problem of infiltration could be solved by an effective, long-lasting seal, to solve the problems of transporting the material from the lower layers, it was decided to use a layer of geotextile under the subgrade. In addition, it was decided to use materials only with a known grading curve and with less than 1% fines. The road involved was about 100 m long. To decide on the best maintenance procedure, a different technique, with a pre-preparation of a block of stone elements, was also experimented.

The main phases are set out below for the innovative technique, with some photos of the most important operations (fig. 12):
- removal of the stone from the site,
- removal of the subgrade,
- laying the geotextile,
- laying the new layer of sand subgrade, with fines of less than 1%,

- cleaning and polishing the faces of the removed stone elements,
- brushing a layer of primer onto al the surfaces for the seal,
- pouring the resin onto the subgrade, if this was required to reinforce the subgrade under the stone elements,
- installation of the stone elements and knocking into place,
- filling the joints with resin.

Polishing the stone elements

Laying the adhesive primer

Laying the geotextile

Laying the sand on the geotextile

Pouring the resin over the subgrade

Pouring the resin into the joints

Figure 12. Installation of the stone elements with the new technique

It takes rather longer to prepare the stone elements than in conventional methods, mainly due to the polishing and cleaning process. In order to get round this problem, some blocks were pre-prepared in the lab (fig. 13). This speeded up the procedure, because it was necessary to prepare only the surfaces of the elements which had not been removed.

Pre-prepared block

Installation of the pre-prepared block

Figure 13. Installing the prefabricated block

In all cases the road was re-opened to traffic a few hours after installation.
After three months, visual inspections were carried out on site, and the pavement proved to be in a good state of repair; the stone blocks were properly located respect to the road surface and the tramway.
The resin in the joints was perfectly adherent to the stone walls and was not aged.

Following this experiment on a full-scale, numerous other maintenance works were carried out with the innovative technique, testing other streets in Milan over a surface area of 3,000 m^2 to fine-tune the method and decide on the definitive procedure.

3.8 Results of full-scale experimental tests

The last applications showed that the maintenance technique is really effective. No more distresses of stone pavement took place whereas, before applying such technique, maintenance repairs were very frequently needed. Only in one case a macroscopic deterioration of the pavement next to the rail occurred, but a long wavelength (about 5-6 m) - not dangerous for cycles or other vehicles - was produced by the pavement instead of local steps and discontinuities. The full-scale experiments showed that the maintenance technique is therefore effective and is now being investigated by the relevant authorities in France for guidelines on the construction of pavement next to tramways (“Guide pour la conception des plates-formes tramway revêtues de matériaux modulaires” Rapport du groupe de travail).

4. CONCLUSIONS

The research was firstly aimed at simulating and analyzing the risks due to deteriorated stone pavement (particularly from local discontinuities); a simple method was developed to establish risks and dangers to cyclists [1]. The main causes of deterioration were then investigated. They often involve low rigidity values and/or loss in strength of the layers under the sleepers of the tramway, generating pumping. This mechanism causes the displacement of the stone elements [10].

The “weak” parts of the traditional stone pavement are the joints, so research was focussed on this element. Laboratory and site test were carried out replacing the sand filler with polyurethane resin which proved to have good elastic properties, with excellent binding properties to the stone surface.

The maintenance technique developed led to the elimination of local deterioration due to the local displacement of stone elements. Where it was not possible to eliminate the problem (due to the poor characteristics of the subgrade under the tramway) the developed technique created a controlled unevenness deterioration. In fact the resulting deformations had a wavelength of 5-6 m, not dangerous for cycles or other vehicles, whereas without such technique local and very dangerous discontinuities would have occurred.

To sum up, the maintenance technique described above has now become the customary practice of the Milan Municipality for the repair of deteriorated stone pavement road with tram rails. Great interest to the technique was also expressed by other countries such as France.

REFERENCES

[1] Crispino M., Tasora A., Vaghi E. (2004), A *new method to asses ride safety on uneven element pavement,* accepted for publication on Journal of Transportation Engineering (ASCE)

[2] Crispino M. (2000), *Analisi di caratteristiche funzionali e strutturali di pavimentazioni in pietra a masselli*, X Convegno nazionale SIIV, Acireale

[3] Crispino M., Venturini L. (2001), *Analisi sperimentale su resine poliuretaniche monocomponenti per la sigillatura delle pavimentazioni a masselli in pietra*, XI Convegno SIIV, Verona

[4] Crispino M. (2001), *Proposta di catalogo dei dissesti ed indice di stato per pavimentazioni in pietra a masselli*, Quaderno Scientifico della Sezione STM, Politecnico di Milano, n° 2.

[5] Crispino M., Da Rios G., (2002) *Misure deflettometriche per l’analisi del degrado di pavimentazioni a masselli con interposti binari tranviari*, XII Convegno SIIV, Parma

[6] Knapton J., Bullen F. (1998), *The role of bedding sands in segmental pavement instability*, Third International Workshop on Concrete Block Pavement, Colombia.

[7] Woods G. (1990), *The ICI polyurethans book*, ICI Polyurethanes and J. Wiley & Sons.

[8] Alobaidi, Hoare (1996), *The development of pore water pressure at the subgrade-subbase interface of a highway pavement and its effect on pumping of fines*, Geotextiles and geomembranes, vol.14.

[9] Crispino M., Venturini L. (2002), *Sistemi innovativi di sigillatura strutturale di pavimentazioni lapidee a masselli in presenza di binari tranviari,* XII Convegno SIIV., Parma