# Applications of High Performance Concrete for Ultra-Thin Pavement Overlays (Whitetopping)

By J. T. Balbo

Synopsis: Employment of High Performance Concrete (HPC) for thin overlays construction for aged flexible pavements has become a reality during the 90's, specially in USA and some northwest European countries. While whitetopping old pavements was a technique employed from earlier decades of the twenty century, the construction of ultra-thin concrete overlays (by 100 mm) for rehabilitation of pavements has been enhanced by the availability of technology for manufacturing HPC and the possibility of fast tracking. Ultra-thin whitetopping is a technique requiring several field conditions to be met concerning the old asphalt pavement in order to perform well as an overlay. They are full bond condition at the interface of HPC and asphalt concrete (generally provided by milling), asphalt concrete without fatigue cracking and rational joint spacing. All these factors, by the other hand, must be taken into account on the basis of the peculiar resistance of the HPC are going to be used. Within this context, in this paper is presented a study with regard to the HPC strength to be achieved for UTW purposes, supported by a numerical analisys based on a finite element solution for slabs-on-grade and taking into account the elastic properties for both HPC and old asphalt, as well as slab dimensions and the load critical position. An international review of HPC applied on whitetoppings around the world is also presented that includes recent works in this field.

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# INTRODUCTION

Whitetopping is an expression used to refer to a portland cement concrete (PCC) layer built over an old distressed asphalt pavement as reinforcement for the pavement structure. Early employment of such layers has been referred to in the litterature as early as the twenties of this century (1).

The idea of using PCC as an overlay for old flexible pavements becomes very attractive considering the traditional employment of asphalt mixture overlay. The asphalt mixture has visco-plastic behaviour and its commom to experience rutting of asphalt surfaces due to creep, which can be considered as a functional distress, reducing step by step the comfort for the users.

Moreover, flexible pavements induces stress concentrations near the load position in opposition to the stresses being spread out under an stiff layer as the PCC, and, for sure the little stresses transmited by the concrete layer over the pavement bases and subgrades contribute to decrease or to avoid permanent deformation on such layers.

An ultra-thin concrete pavement overlay or simply ultra-thin whitetopping (UTW) could be defined as an structural reinforcement layer of a composite pavement; the UTW layer must have thickness from 50 to 100 mm (1,2,3). To employ thin PCC layers, at least two main conditions must be taken into account. Firstly, the joint spacing for PCC slabs must be less than the traditional one used for normal concrete slabs.

Secondly, it is essential to have a full bond condition to achieve composite behaviour of the pavement structure, i.e., both layers of PCC and old asphalt carpet (AC) should work togheter in terms of bending, and in such way that the neutral axis on concrete layer will approach the PCC-AC interface in order to decrease the flexural stresses on the upper layer of the UTW.

It seems to be clear at this point that the AC layer shall be in good condition, without fissuration once the cracks results not a composite pavement. Although full bond condition is taken during the design, shear stresses at the interface PCC-AC is another factor of paramount importance to be studied once loss of bonding might be possible in some conditions, and on this basis, UTW solutions should be avoided.

Despite achieving the essential conditions for the employment of UTW, the design of such pavements must take into account several factors regarding the resilient behaviour of the old pavement and its layers and the fatigue damage effects on concretes due to load repetition. Then, the concrete strength and fatigue properties must be considered as key parts of the design.

Another aspect to be considered for UTW tasks is that, to be competitive to overlay asphalt pavements it is necessary to reduce the delay for opening the lane to the traffic in order to avoid operational conflicts, thereby becoming more acceptable for the users and for the maintenance offices of transportation agencies. Due to these reasons, fast tracking concrete pavement are essential to successful UTW construction.

## CONCRETES MIXTURES FOR UTW

Considering both the questions of concrete strength and lane closure time for the UTW design, there are several experiences in the literature about the concrete design and a few completed field projects that could confirm the successful performance of these concretes as a pavement reinforcement layer.

High performance concretes, in a general sense, from years are applied to pavement construction around the world. Special cements were developed beside the introduction of organic and glass fibers; incorporating fly ash or silica fume as concrete admixtures to improve resistance is a very commom technique for concrete pavements; indeed, water reducers and setting accelerators are also employed. It must be remembered that pavement structures are subject to hard environmental conditions and in most cases the improvement of other properties besides strength are addressed.

The experiences on UTW construction around the world show a large range of concrete strengths and admixtures taken for specific projects. On Table 1 is presented a summary of such experiences referred to special concretes for UTW. From the presented data it can be inferred that, rarely, the concretes used for the UTW projects have required flexural strengths greater than 5.5 MPa at 28 days. Even so for UTW, there are several cases of concrete proportions that required strengths as typical as normal concretes for paving (flexural strength from 4 to 5 MPa). The compressive strengths for 24 hours ranged from 20 to 30 MPa, and for only one project has the value reached 35 MPa.

For one case, even for concrete proportions that reached more than 7 MPa for flexural strength during laboratory tests, the field cores did not showed similar results, generally little than an average of 4.6 MPa (8). Such kind of situation was also observed in the first Brazilian UTW project (10), when the concrete proportions were designed to reach a compressive strength of 60 MPa. However, the samples cored from the pavement two mounths after the construction resulted in an average of 41 MPa.

From the presented experiences, it is clear that for almost all cases the projects concerned urban and county roads with low traffic volume, what could justify the employment of concretes with not much higher compressive strength than conventional concretes for paving. By the other hand it is clear that for most cases higher earlier strengths was much more important as compared to the normal concretes.

From the Brazilian project when the performence was monitored in the short term, the experiment proved that the employment of normal concretes for UTW on high volume roads is not an acceptable solution. Less than one mounth after opened to traffic, development of distresses on the UTW had begun with corner cracks being the main damage found on every type of slab independently of joint spacings.

As a result of this experience a big question cross over the UTW suitability as a reinforcement for flexible pavements. Are the UTW suitable for all kinds of roads, i.e., for any situation of traffic volume ? The answer, if all the mentioned requirements for the old flexible pavement are sustainable, shall be dependent on the possibility of a HPC to reach, in the field conditions, the forecasted design strength.

## DESIGN OF UTW AND CONCRETE REQUIREMENTS

Slab geometry defined by joint spacing and the load position are basic aspects for the structural design of UTW. As a matter of fact, the surface dimensions of the slabs have important role for stresses on concrete, also due to the relative position of loads over the slabs. Former studies concerning joint spacings between 0.6 and 1.2 meters, for lane widths from 2.5 to 3.6 meters, has shown that, for design, the corner position must be considered as critical (12). Whatever will be the position of road axles for such geometry conditions, there will be a wheel over the corner of one slab.

In regard to the joint spacing, it is clear from a mechanical point of view that the flexural stresses decrease for short spacings; but this remark is supported by the road experiments. Field measurements in Mexico showed that deformations on concrete for square slabs 1.20 m width and 90 mm thick were 73 % higher than the measured values for 0.90 m width and 65 mm thick slabs (9).

In USA, an early experiment (5) with UTW carried out at Louisville, Kentucky, had shown the best performance of short joint spacings. After approximately 500,000 equivalent single axle loads, the slabs sawed each 1.80 m have developed corner cracks for almost all the cases; on the contrary, the slabs 0.60 width performed very well for such traffic volume (for both situations the thicknesses were 50 mm).

Another experiment in USA, at Leawood, Kansas, pointed out the better performance of short joints spacings. Slabs 0.90 m width presented less distresses in comparison to slabs 1.20 m width, for the same traffic volume, both of them 50 mm thick (7).

The better performance of shorter slabs, for the same concrete, is related to the smaller flexural stresses due to the load/pavement structure interaction. Obviously, the short spacing for joints has a tendency to create a “block pavement system” when the vertical displacements due to loads can take a relevant role in the design.

Based on the performance of former experiments, it is believable that UTW projects must limit the joint spacing to values not greater than 1.20 m; actually this empirical restriction could be enlarged by means of the use of suitable high resistant concretes to face the flexural stresses imposed on larger UTW slabs.

Studies developed at the Pavement Mechanics Laboratory of The University of São Paulo (13) have allowed to define theoretical-statistical equations to calculate the critical flexural stress due to corner loads of a dual tyre single axle for UTW, for 1.20 m joint spacing slabs. The finite element model employed for these studies was the program FEACONS 4.1SI, a modified version of the code developed by Tia at al. (14), where retangular elements are assumed in plane-stress state with one vertical displacement and two rotations for each node.

Bond at interface between UTW and AC and no load transfer across the joints are the basic boundary conditions. The load was placed at the corner of the UTW slabs and the mesh refinements were carried out in order to achieve no more than 10% difference between flexural stresses received from successive refinements (these differences resulted generally less than 4%) . The number of runs was 2,520 in order to cover the range assumed for each parameter. A intrinsically linear equation format was searched by employment of multi-linear regression technique. More details about the performed studies can be found in reference (15). The received models for computing the flexural stress for the UTW slabs have the following format:

$$\log_{10} \sigma_{tf,w} = a + b \cdot t_w + c \cdot \log_{10} Q$$

where $\sigma_{tf,w}$ is the critical flexural stress, $t_w$ is the UTW thickness, Q is the total load over the single axle and a, b and c are regression coeficients. The equations were developed by means of a finite element model which considered the UTW and the AC layer as a composite pavement, full bonded, without load transfers at transversal joints of slabs; elastic properties for both layers are typical of PCC and AC employed in pavement construction.

The coefficients of the above equation are taken as function of the thickness of AC and the modulus of subgrade reaction, namely k-value (Winkler model). On Table 2 are presented these coefficients for three AC thickness combined with two k-values.

As is well know, the design of concrete pavements requires the consideration of a concrete fatigue model to avoid cracks during the design period. Normally the maximal stress is computed caused by a critical load axle or a standard load axle; for the last case it is needed to convert all the anticipate axle loads into standard axle load by means of load equivalence factors.

Then, the stress level is related to the number of load cycles to fatigue by using an experimental or empirical relation known *a priori*. The fatigue relations generally consider the ratio between nominal stress and concrete strength (stress-strength relation, SSR) as a function of the number of load cycles to fatigue; once the number of load repetition is known, these relations make it possible to define the design flexural strength of the concrete if the nominal stress is also known; afterwards, the strength (or modulus of rupture in flexion) is converted into required average flexural strength by a numerical factor depending on the existing concrete manufacture control (safety factor).

In order to explore the requirements for a concrete to be used as UTW, it could be considered that for the concrete production it shall give excellent control of quality: the proportions are defined by weight, the aggregate moisture is fully controlled, the materials are homogeneous and an engineer expert on concrete technology is present. For such situation, the required average flexural strength could be found by adding the design flexural strength of 0.5 MPa (according the Brazilian standard for concrete pavements). For the fatigue verification a classical expression developed on the basis of three former concrete fatigue studies (16) could be used:

$$\log_{10} N = 16.61 - 17.61 (\sigma_{tf} / MR)$$

where N is the number of load repetitions to fatigue, $\sigma_{tf}$ is the flexural stress due to load aplication and MR is the concrete flexural strength.

In order to consider two differents design possibilities, it was taken both a low ($N=10^6$) and a high ($N=10^8$) number of load repetitions. Note that this choice is justified by the fact that it is difficult to define what is a low volume road or not on the basis of load repetition; it depends on the design period. Anyhow, it could be thought in terms of a short or a long-life period for the UTW in terms of development of fatigue cracking.

In Table 3 is presented the concrete design flexural strengths required based on the above discussed equations and conditions, taking a 100 kN single axle for the design. From the results it can be inferred that the choice of concrete strength is depending on several factors: the thickness of the remaining AC, the thickness of the UTW layer, the k-value and the number of load repetitions.

The analysis of the low volume road case ($N=10^6$) permits to verify the flexural strength required for the PCC; as it is not common in the milling operation to result AC layers thicker than 100 mm, from Table 3 it can be seen that it is needed for the concrete strength ranging from 3.5 to 7.3 MPa (in flexure). UTW slabs for high volume roads ($N=10^8$), within the same conditions, requires for concrete flexural strengths from 4.2 to 8.9 MPa.

For all the mentioned cases, both urban and rural pavements will be subjected to a defined number of load repetitions. It must be taken into account that $10^8$ repetitions of the standard axle can represent a long-life service for a county road and, on the contrary, a short endurance for an arterial metropolitan road. In order to ensure for several kinds of roads a long-lasting life $10^9$ load repetitions should be taken as a minimum for the design. In this case, concretes with 6.5 MPa of flexural strength are required for a 80 mm thick UTW layer over a minimum 70 mm thick AC layer when the k-value for the subgrade is 60 MPa/m.

The reason for changing the conventional AC overlay to the UTW overlay technology must be, firstly, the improvement of the pavement bearing capacity, and secondly the enhancement of the service life of the overlay.

## CONCLUDING REMARKS

The design and construction of UTW reinforcement of old AC pavements requires the consideration of several variables, such as the structural response of the old pavement to loads, the AC surface condition and the thickness of AC layer after milling. In regard to the UTW layer itself, joint spacing and concrete strength play a important role in determining performance.

The past experiments with UTW employed concretes with strentghs ranging from conventional values for concrete pavements up to concretes which could be classified as HPC; nevertheless, conventional concretes for paving were more commonly used for the low volume roads (county and secondary urban roads). Also fast-track concretes seem to be a prerequisit for UTW construction.

By referring to a numerical analysis of the composite pavement structure (UTW+AC) it was possible to determine the necessary flexural strength for some cases of low and high volume roads taking into account the number of load repetitions in the design. The analysis pointed out that, for high volume roads, flexural strengths ranging up to 9 MPa are required depending on some others design variables. The restriction for the employment of UTW for high volume roads, in spite of the control of several AC conditions, still be the feasibility to achieve high resistant concretes in field conditions.

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Table 1 - Concrete mixtures characteristics for several UTW projects

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1990 | Northampton County, Virginia, USA | Cement (type I, ASTM): 445 kg/cm<br>W/C: 0.42<br>coarse aggregate: 1113 kg/cm<br>fine aggregate: 620 kg/cm<br>max. aggregate size: 25 mm<br>water reducer: AASHTO M 194<br>air-entrained: 5.5% | 18 hours: 25<br>24 hours: 28.8<br>7 days: 39.3<br>28 days: 47.5 | 28 days: 5.6 | opened to traffic after 58 hours; traffic amount of 240 equivalent single axle load per day; | (1) |
| 1991 | Dallas County, Iowa, USA | Cement: 298 kg/cm<br>fly ash: 56 kg/m<br>coarse aggregate: 914 kg/cm<br>fine aggregate: 933 kg/cm<br>water reducer: 2.6 ml/kg<br>air-entrained: 0.56 ml/kg | 28 days: 27.5 | 28 days: 4.7 | - | (4) |

Table 1 - Concrete mixtures characteristics for several UTW projects (cont.)

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1991 | Louisville, Kentucky, USA | Cement (type I, ASTM): 475 kg/cm<br>W/C: 0.33<br>coarse aggregate: 1067 kg/cm<br>natural sand: 948 kg/cm<br>water reducer (ASTM C-494): 1.1 kg/ 100 kg<br>air-entrained: 4 to 6%<br>polypropylene fibers: 1.78 kg/cm | 18 hours: 27.6 | - | waste disposal facility;<br>90 trucks per day;<br>opened to traffic after 37 hours | (5) |
| 1994 | Georgetown, Kentucky, USA | Cement (type I): 475 kg/cm<br>W/C: 0.32<br>60%-40% ratio of coarse aggregate and natural sand<br>water reducer: 0.98 ml/ 100 kg<br>air-entrained: 5.5% | 24 hours: 24.6 | - | street intersection | (6) |
| 1994 | State Route 21, Iowa, USA | Cement: 340 kg/cm<br>W/C: 0.43<br>coarse aggregate: 986 kg/cm<br>fine aggregate: 809 kg/cm<br>air-entrained: 6%<br>synthetic fibers: 1.36 kg/cm | - | - | opening to traffic 5-7 days | (7) |

Table 1 - Concrete mixtures characteristics for several UTW projects (cont.)

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1995 | Leawood, Kansas, USA | Cement (type I): 363 kg/cm<br>W/C: 0.37<br>coarse aggregate: 1026 kg/cm<br>fine aggregate: 798 kg/cm<br>max. aggregate size: 25 mm<br>air-entrained: 6.5%<br>synthetic fibers: 1.36 kg/cm | 24 hours: 21.1 | - | opened to traffic after 24 hours; mixed traffic of 25,000 vehicles per day | (7) |
| 1995 | Tennessee & Dekalb Co., GA, USA | Cement: 474 kg/cm<br>W/C: 0.35<br>coarse aggregate: 1,008 kg/cm<br>fine aggregate: 730 kg/cm<br>synthetic fibers: 1.36 kg/cm | 24 hours: 34.5 (achieved) | - | - | (7) |
| 1995 | Lexington, Kentucky, USA | Cement (type I): 475 kg/cm<br>coarse aggregate: 1,067 kg/cm<br>natural sand: 948 kg/cm<br>max. aggregate size: 25 mm<br>air-entrained: 5%<br>water reducer (ASTM C-494, type F): 0.98 ml/100 kg<br>synthetic fibers: 1.36 kg/cm | 24 hours: 23.6<br>36 hours: 33.7<br>48 hours: 35.3<br>7 days: 44.5<br>28 days: 51.1 | 24 hours: 5.2<br>36 hours: 5.8<br>28 days: 7.1 | - | (5) |

Table 1 - Concrete mixtures characteristics for several UTW projects (cont.)

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1995 | Spirit of Saint Louis Airport, Missouri, USA | Cement (type I): 303 kg/cm<br>class C fly ash: 47 kg/cm<br>W/C: 0.36<br>coarse aggregate: 1115 kg/cm<br>natural sand: 749 kg/cm<br>max. aggregate size: 25 mm<br>low-range reducer: 362ml/ 100kg<br>air-entrained: 117 ml/ 100 kg<br>polypropylene fibers: 1.8 kg/cm | - | resulted, for 28 days, greater than 7 MPa during laboratory tests;<br>resulted 4.6 MPa for field cores | parking area | (8) |
| 1996 | Tijuana, BC, Mexico | max. aggregate size: 10 mm<br>polypropylene fibers: 0.9 kg/cm<br>water reducer used | - | 28 days: 5.1 | urban street; 2,100 vehicles for mixed traffic per hour (peak ?) | (9) |

Table 1 - Concrete mixtures characteristics for several UTW projects (cont.)

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1997 | São Paulo State Highway SP-280, Brazil | cement (CPV-ARI-RS): 440 kg/cm<br>silica fume: 44 kg /cm<br>natural sand: 493 kg/cm<br>coarse aggregate: 1.194 kg/cm<br>W/C: 0.40<br>polypropylene fibers: 0.9 kg/cm<br>air-entrained: 5% | 28 days design strength: 65<br>28 days achieved in laboratory: 56<br>28 days mesuared from field cores: 41 | - | - | (10) |
| 1991 | Suzukuisi-mati, Japan | cement content: 430 kg/cm | 24 hours: 30 | 24 hours: 3.5 | - | (11) |
| 1991 | Sin-jo-i, Japan | cement content: 430 kg/cm | 24 hours: 30 | 24 hours: 3.6 | - | (11) |
| 1992 | Aomori, Japan | cement content: 344 kg/cm | 24 hours: 30 | 24 hours: 3.5 | - | (11) |
| 1992 | Sin-jo-si, Japan | cement content: 430 kg/cm | 24 hours: 30 | 24 hours: 3.5 | - | (11) |
| 1992 | Suzukuisi-mati, Japan | cement content: 401 kg/cm | 24 hours: 30 | 24 hours: 3.5 | - | (11) |

Table 1 - Concrete mixtures characteristics for several UTW projects (cont.)

| Year | Place | Mixture Proportions | Compressive Strength (MPa) | Flexural Strength (MPa) | Notes | Ref |
|---|---|---|---|---|---|---|
| 1990 | Missouri R67, USA | cement content: 390 kg/cm | 18 hours: 24.1 | - | - | (11) |
| 1991 | Kansas City, USA | cement content: 420 kg/cm | 24 hours: 20.7 | - | - | (11) |
| 1990 | Virginia R13, USA | cement content: 445 kg/cm | 24 hours: 24.1 | - | - | (11) |

Table 2 - Regression coefficients for equation $\log_{10} \sigma_{tf,w} = a + b \cdot t_w + c \cdot \log_{10} Q$

| AC thickness (m) | k-value for the support (MPa/m) | a | b | c | $r^2$ |
|---|---|---|---|---|---|
| 0.07 | 120 | 0.023645 | -5.378814 | 0.412213 | 0.994 |
| | 60 | 0.008586 | -5.789584 | 0.446956 | 0.995 |
| 0.09 | 120 | -0.166944 | -4.360725 | 0.427317 | 0.991 |
| | 60 | -0.172026 | -4.790005 | 0.454847 | 0.994 |
| 0.12 | 120 | -0.391515 | -3.468629 | 0.443637 | 0.989 |
| | 60 | -0.418931 | -3.569332 | 0.467474 | 0.992 |

Table 3 - Example of search on concrete strength requirements (MR)

| AC thickness(m) | UTW thickness (m) | $\sigma_{tf,w}$ (MPa) for k=120 MPa/m | $\sigma_{tf,w}$ (MPa) for k=60 MPa/m | MR (MPa) for k=120 MPa/m | MR (MPa) for k=60 MPa/m | MR (MPa) for k=120 MPa/m | MR (MPa) for k=60 MPa/m |
|---|---|---|---|---|---|---|---|
| | | | | $N = 10^6$ | $N = 10^6$ | $N = 10^8$ | $N = 10^8$ |
| 0.07 | 0.05 | 3.79 | 4.10 | 6.8 | 7.3 | 8.3 | 8.9 |
| | 0.08 | 2.62 | 2.75 | 4.9 | 5.1 | 5.9 | 6.0 |
| | 0.10 | 2.04 | 2.11 | 3.9 | 4.0 | 4.7 | 4.8 |
| 0.09 | 0.05 | 2.95 | 3.15 | 5.4 | 5.7 | 6.5 | 7.0 |
| | 0.08 | 2.18 | 2.26 | 4.1 | 4.3 | 5.0 | 5.1 |
| | 0.10 | 1.79 | 1.81 | 3.5 | 3.5 | 4.2 | 4.2 |
| 0.12 | 0.05 | 2.10 | 2.18 | 4.0 | 4.1 | 4.8 | 4.8 |
| | 0.08 | 1.65 | 1.70 | 3.3 | 3.3 | 3.9 | 4.0 |
| | 0.10 | 1.41 | 1.44 | 2.9 | 2.9 | 3.4 | 3.5 |

# List of Tables

Keywords: pavement; concrete overlay; whitetopping.