ACHIEVING AND MAINTAINING THE EVENNESS OF CONCRETE PAVEMENTS

CONTENTS

INTRODUCTION

Whereas concrete pavements have well-known advantages over flexible pavements (long life, resistance to permanent deformation, virtually no maintenance required), the main disadvantages often mentioned are a certain lack of comfort as a result of an unsatisfactory surface evenness, and a high level of rolling noise.

This publication starts with a brief review of the measuring methods for evenness. Afterwards it aims at analysing in an objective way the parameters that have an influence on concrete pavement evenness both during construction and afterwards. It has been also endeavoured to present the state of the art of techniques used to restore evenness.

When such good practices are applied, the perceived disadvantages of concrete pavements are easily overcome.

This publication has been prepared by the Technical and Promotion Committee and Best Practices Working Group of EUPAVE (European Concrete Paving Association).

It is an updated version of the Technical Report "Achieving and maintaining the evenness of concrete pavements" of the World Road Association (PIARC), which was prepared by the PIARC Technical Committee on Concrete Roads and published in 1991.

Members of EUPAVE who have contributed to this publication:

Özlem Aslan, EUPAVE, Belgium;

André Burger, Cement&BetonCentrum, The Netherlands - Chairman of EUPAVE's Technical and Promotion Committee;

Romain Buys, Robuco, Belgium;

Jeroen De Vrieze, KWS, The Netherlands;

Jesus Diaz Minguela, IECA, Spain;

Carlos Jofré, Spain - Principal author of this publication;

Rory Keogh, Gomaco, U.K. - Chairman of EUPAVE's Best Practices Working Group;

Wim Kramer, Cement&BetonCentrum, The Netherlands;

Stéphane Nicoud, LafargeHolcim, France - President of EUPAVE;

Luc Rens, FEBELCEM, Belgium - Managing Director of EUPAVE and Coordinator of the revision of this publication;

Sergio Tortelli, HeidelbergCementGroup, Italy.

The text of this publication has been reviewed by:

Anne Beeldens, AB-Roads, Belgium;

Margo Briessinck, Flemish Agency for Roads and Traffic, Belgium (chapter 1);

Karl Downey, EUPAVE, Belgium;

John Gibbs, ERMCO, Belgium;

George Jurriaans, ECCRA, The Netherlands.

EXECUTIVE SUMMARY

Among the surface characteristics of a road pavement, evenness is probably the factor to which road users are most sensitive when it comes to gauging the quality of that pavement. Therefore, it is of great importance for designers and builders to know how good evenness of a road can be achieved, maintained and, if necessary, restored.

Different measurement systems are available to assess the level of evenness of a finished road and to link it with the user requirements. High-speed profilers are mainly used, and the results are indicators such as IRI (International Roughness Index), PrI (Profilograph Index) or WLP (Weighted Longitudinal Profile).

Not only after but also during construction, the evenness can be measured in real time. The aim of such checks is to appraise the quality of work and to detect faults inherent in the construction equipment or methods.

For a concrete pavement, several parameters can affect the evenness at the time of construction. First of all adequate materials must be used in order to obtain a workable and constant concrete mix. A good batch-to-batch consistency also depends on the quality of the concrete mixing plant. Stockpile management and moisture controls are crucial in the production process.

If the rules of good practice are applied, smooth concrete pavements can be obtained with slipform paving machines as well as by paving between fixed formworks. Obviously, the position of the forms for manual paving or of the stringlines that guide the slipform paver is extremely important to achieve an even concrete surface. Problems with stringlines can be eliminated with stringless paving, using a total station or GPS survey instruments. This offers other advantages such as shorter construction time, increased work access to the paver and decreased overall width. Another important aspect in the case of slipform paving is the need for a stable, clean and even rolling path for the paver tracks.

The concrete supply rate should match the progress of the laying machines, in order to avoid stoppage. Therefore, an adequate number of delivery trucks is necessary. There are several ways of discharging concrete: directly in front of the paver, through a belt placer or into an open box placed at the side and afterwards spread in front of the paver by means of an excavator. An appropriate amount of concrete must be placed in front of the slipform paver. The front split auger and the spreader plow serve to distribute the concrete uniformly to a predetermined width. The series of vibrators consolidate the concrete; a tamper bar system evenly tamps it down and a finishing pan serves to level the concrete. The key to a smooth paving job is to maintain uniform head pressure at the nose of the finishing pan.

Concreting on horizontal curves or on vertical grades requires extra attention and adjustments to the paver in order to avoid irregularities and undulations in the surface.

Including steel reinforcement or dowels in a concrete pavement should not lead to uneven surfaces. Today's design and construction techniques should avoid any of the problems that occurred in the past such as lack of consolidation or reinforcement ripples. Modern slipform pavers are equipped with dowel bar insertion units which have been shown to properly insert dowels in the fresh concrete to a level of accuracy as good as or better than with baskets. Embedded items may also affect the pavement surface and require particular attention during construction. Construction joints also require special care since they often contribute to the unevenness of concrete roads. For jointed plain concrete pavements (JPCP), a solution is to pave through and cut off the last part of the pavement.

Immediately after paving, the surface needs to be finished, textured and cured. Care should be taken to achieve good evenness before carrying out the surface finishing. Tearing of the concrete surface can be avoided by using the right concrete mix and choosing the adequate vibrator elevation and paver speed. The wavelengths of irregularities caused by the surface treatment (brooming, tining, grooving, exposed aggregate, etc.) should in principle have no adverse effect on riding comfort.

Finally, the surface needs to be cured by applying a curing compound or with a plastic sheet. Improper curing can affect surface evenness by causing differential or increasing irreversible shrinkage. Differences in shrinkage strains between the top and the bottom of the slab cause it to curl or warp.

Regardless of the process or practices to improve pavement evenness, an educated, trained and motivated crew is needed to do the job. Only skilled personnel can achieve excellent results at the end of the concrete paving project.

Parameters that may affect the evenness of concrete pavements in service are often related to either the structural design of the pavement or the presence of water in the structure. Several preventive measures against the detrimental effects of water can be adopted: sealing of the joints, installing appropriate draining systems, using selected materials in the subbase and the hard shoulders or the use of an asphalt interlayer between the subbase and the concrete pavement. The modern design of jointed plain concrete pavements with narrow doweled contraction joints, reduced slab lengths and non-erodible subbase materials has eliminated the problem of pumping and faulting of the joints. In addition, the effect of curling and warping, due to a temperature and/or moisture gradient throughout the slab is reduced. The use of continuously reinforced concrete pavements (CRCP) also solves potential problems with transverse joints.

Local problems of unevenness immediately after construction, or more generalised problems after several years of service of the road, can be solved by diamond grinding, fine milling and slab lifting. Diamond grinding is a cutting process using diamond blades, mounted on a rotating drum. It creates longitudinal parallel fine grooves, resulting in a very comfortable, skid resistant and low-noise surface. In the case of micro-milling or fine milling the upward rotating drum is equipped with hard tools, arranged in a grid pattern. This removes the material at the concrete surface and eliminates irregularities. Finally, injection with cement grout is a technique to stabilise or lift concrete slabs, or restore the evenness of a CRCP.

1. ASSESSING THE EVENNESS OF CONCRETE PAVEMENTS

1.1 WHY DO WE NEED TO MEASURE EVENNESS?

Among the surface characteristics of a road pavement, evenness is probably the factor to which road users are most sensitive when it comes to assigning a level of quality to that pavement. The following depend on evenness:

- user comfort and safety: the impact of longitudinal unevenness on these two parameters is a function of the lengths and amplitudes of the waves in the road profile and of the frequency of the irregularities in relation to vehicle speed;
- vehicle operating costs (repairs and fuel consumption);
- pavement deterioration due to the dynamic effects of surface irregularities.

The aim of measuring evenness and setting acceptability thresholds is to link user requirements with technological capabilities to achieve well-defined levels of evenness on the various types of road networks. The results of evenness measurements are mainly used to appraise the quality of road works against specified criteria. Moreover, they constitute an important input in management maintenance systems for roads in service.

1.2 METHODS OF MEASURING EVENNESS

1.2.1 EQUIPMENT FOR MEASURING EVENNESS OF PAVEMENTS

Evenness measurements [18] started with straightedge devices in the early 1900s, and have evolved to vehicles that can measure the road profile while traveling at normal traffic speed.

Equipment used to measure evenness of pavements can be divided into the following five categories

1. response type road roughness measuring systems: they measure the response of the pavement on the vehicle or on a special trailer using a transducer. Automobiles or standardized trailers have been used to house response type devices. The vehicle-mounted systems measure and accumulate the vertical movement of the rear axle of the automobile with respect to the frame of the vehicle, while the trailer mounted systems measure and accumulate the movement of the trailer with respect to the frame of the trailer.

2. high-speed inertial profilers: the principal components are height sensors, accelerometers, a distance measuring system, and computer hardware and software for computation of the road profile. The height sensors record the height to the pavement surface from the vehicle. The accelerometers that are located on top of the height sensors record the vertical acceleration of the vehicle. Data from the accelerometers are used to determine the height of the vehicle relative to an inertial reference frame. The distance measuring system keeps track of the distance with respect to a reference starting point. Using the data recorded by the distance measuring system, height sensor and the accelerometer, a computer program calculates the profile of the pavement surface. The non-contact height sensor types can be either laser, ultrasonic, optical or infrared. Currently laser sensors are the most commonly used height sensors in profilers.

   A different approach is that of the APL equipment, where an inertial pendulum is used to define a reference plane in order to compute vertical displacements. The system can include one or two single-wheel trailers towed by a car.

3. profilographs: a profilograph consists of a rigid beam or frame with a system of support wheels at either end, and a centre wheel. The support wheels at the ends establish a datum from which the deviations of the centre wheel can be evaluated.

4. light-weight profilers: they are devices in which a profiling system has been installed in a light vehicle, such as a golf cart. The profiling system in a light-weight profiler is similar to the profiling system of an inertial high-speed profiler and consists of height sensor(s), accelerometer(s), and a distance measuring system. They were primarily developed to record the profile of newly placed concrete pavements, since the light weight of these devices makes it possible to ride on concrete at early ages as soon as the pavement is able to support the weight of the profiler.

5. manual devices: several manually operated methods and devices are available that can be used to obtain the profile of a pavement. Some examples are static straightedge, rolling straightedge, rod and level, stringline and inclinometer-based devices (pivoting and walking dipsticks, walking profilers).

Measurement devices for longitudinal evenness: the APL profiler ("Analyseur de Profil en Long") and a light profiler for bicycle paths

(Photos : Belgian Road Research Centre)

1.2.2 EVENNESS SPECIFICATIONS

1.2.2.1 Introduction

There are two basic types of evenness specifications: those that consider measured evenness, and those that consider actual ride quality [30].

Measured evenness

Specifications that consider measured evenness use devices such as rolling straightedges and profilographs to develop roughness profile traces of the pavement surface (normally measured in the wheelpaths) to calculate overall pavement evenness indices. These indices are then related back to established thresholds of what drivers consider "acceptable" and "objectionable" in terms of evenness. Some administrations set pay adjustments based on these thresholds. To determine "must correct" or "must grind" areas, some administrations make use of a bump template which identifies unacceptable local deviations from a reference plane.

Ride quality

Evenness specifications that measure ride quality better account for actual user perception, or what drivers really feel. Devices which are able to best measure ride quality include "response-type" devices and inertial profilers. Response-type devices measure characteristics such as vehicle suspension travel, which can be related back to established thresholds for acceptable and objectionable ride quality. Inertial profilers, on the other hand, are able to produce profile traces showing the actual shape of the pavement surface, which can be then used to determine ride quality. Using established guidelines for what most drivers consider acceptable and objectionable in terms of ride quality, pay adjustments schedules and localized roughness criteria are developed by each owner-agency.

The type of specification used depends on the involved administration or stakeholder. More and more stakeholders are realizing the importance of measuring actual ride quality, and not just raw evenness. Ride quality better relates to user perception, and ride quality measurement devices are less susceptible to certain measurement biases. However, ride quality specifications generally require more sophisticated equipment and intensive training in measurement and interpretation of results.

1.2.2.2 Components of evenness specifications

The first component of any evenness specifications is the evenness index system that will be used. This system will drive the specifications in terms of how to select and certify measurement equipment, how to specify evenness measurement for projects, how to evaluate collected data, and how to determine pay adjustments based on the evenness data collected.

Two commonly used evenness indices are the International Roughness Index (IRI) and the Profilograph Index (PrI).

The International Roughness Index (IRI) is a profile-based statistic that was initially established in a study by the World Bank [25] [26].

The IRI has been developed mathematically to represent the reaction of a single tire on a vehicle suspension (quarter-car) to roughness in the pavement surface, traveling at 80 km/h. The IRI's algorithm models one corner (a quarter) of an automobile. The model includes one tire, represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and a damper, and the mass of the body supported by the suspension for that tire.

IRI can be determined using measurements from any valid profiler (inertial profiler, inclinometer-based device, rod-and-level, etc.) which generates a profile trace showing the "true" shape of the pavement surface. IRI can also be crudely measured by response-type systems using correlation to a reference profiler.

The Profilograph Index (PrI) is generally measured with a profilograph (e.g. California-type), although some software programs can compute PrI from a profile trace produced by an inertial profiler. PrI is sometimes called Profile Index (PI) but the former is more specific.

Both IRI and PrI are reported in units of meters/kilometer or millimeters/kilometer. However, these measurements are not directly correlated and cannot be directly interchanged. In general, profile traces are collected in either one or both of the wheelpaths within a pavement lane.

Two indices that are also commonly used and are derivatives of the IRI are the Mean Roughness Index (MRI) and Half-car Roughness Index (HRI). The MRI is simply the average of the wheelpath IRI values reported for a given section of road or lot. The HRI is calculated by applying the IRI algorithm to the average of the wheelpath profiles.

In Germany and Austria the Weighted Longitudinal Profile (WLP) is used. This is a longitudinal profile which has been weighted by a weighting function in the frequency domain.

There are software applications available which can analyze the data provided by several types of profilometers [29] to obtain evenness related information such as:

- ride statistics: ride indices such as International Roughness Index (IRI), Half-car Roughness Index (HRI), and Mean Roughness Index (MRI);

- power spectral density: wavelength or frequency contents of profiles;

- profilograph simulation: profilograph traces, profilograph indices, etc.;

- rolling straightedge simulation: rolling straightedge traces;

- automated fault measurement: identification of joint locations and estimation of joint faulting from profile data.

1.2.2.3 Evenness specifications for airfield pavements

There are some differences between highway and airfield pavements concerning evenness [9]. The evolution of the straightedge criteria has roots in highway construction. As the criteria evolved, so did the correlation between evenness measurement and ride quality experienced in the passenger car. But a car or truck has a suspension system that dampens the experienced roughness. The primary purpose of an aircraft suspension system is not to absorb pavement roughness. Its main func-

In airfield pavements evenness criteria are commonly based on straightedge measurements, e.g. a vertical limit of 6.5 mm measured anywhere along a straightedge 5 m long. However, use of a physical straightedge is a manpower intensive process. Moreover, the number of measurements necessary to assure 100% compliance is beyond reasonable expectations. Consequently, practice has evolved to where it is common to see the use of a profilograph specified for airfield pavement evaluation.

tion is to absorb the energy of landing impact, which means that most of the available strut stroke is already used up when the aircraft is on the ground. Therefore, some indices developed to characterize evenness in highways, such as the International Roughness Index (IRI), are not used in airfields. In addition, the pavement used by an aircraft is significant in two dimensions, meaning that the width is just as important as the length of a pavement feature. The surface irregularities that cause undesirable aircraft response or poor drainage characteristics must be identified by measurement prior to opening to traffic.

1.2.3 EVENNESS MEASUREMENTS DURING CONSTRUCTION

1.2.3.1 On plastic concrete

The aim of such controls is to appraise the quality of work during construction and to detect any faults inherent in the construction equipment or methods. A pavement profile is affected by numerous design and construction factors. Understanding the relationship that exists between these factors and the as-constructed pavement profile is beneficial. Knowing what that profile is in real time, during construction, adds that much more value. With it, paving operations can be adjusted "on the fly" to maintain or improve smoothness. Real-time measurements can allow paving crews to adopt better practices, leading to improved smoothness.

The most widespread technique for evenness control on the plastic concrete is the use of a straightedge, generally 3 m long, which is placed lengthwise or crosswise on the surface of the concrete. The usual specification or desired criterion is that differences in level should not exceed 3 mm, this value being determined by measurement or visual observation.

In addition, there are some real-time evenness measuring systems, that can be attached to the paving equipment, the texturing machine or a bridge work; these are towed behind the paving equipment on the fresh concrete or can stand alone [23]. They can be adapted to take simultaneous readings for several traces. Currently however, neither technology is capable of measurements suitable for quality control.

Real time smoothness measurement equipment on self-propelled work bridge (Gomaco) including a computer assembly, real-time graphic display, media storage card, two sonic sensors, slope sensor and distance counter wheel assembly.

They should be used instead for process monitoring and improvement. Because these profilers provide real-time feedback of process modifications, overall paving quality can be improved in short order. As such, it can be of significant value to both the contractor and the stakeholder, particularly when they are working under a stringent ride quality specification. Indeed, based upon the immediate graphic display of smoothness of the surface, localised irregularities in the slab can be corrected as the concrete surface is still in plastic state.

1.2.3.2 On hardened concrete at early ages

There are several devices which can be used on hardened concrete at early ages for quality control during construction: static straightedge, rolling straightedge, rod and level, profilographs, inclinometer based profilometers, lightweight inertial profilers… They are low output devices, which cannot be used for high-speed pavement evenness data collection, but they make possible to measure the profile just a few hours after each section is paved. Then results of the profile analysis are available to the crew before starting work on the next day.

1.2.4 EVENNESS MEASUREMENTS FOR QUALITY ACCEPTANCE AFTER CONSTRUCTION

Most instruments mentioned above for evenness controls on the hardened concrete at early ages are also used for the acceptance of works. However, there is a trend towards the use of high-speed inertial profilers.

Such devices allow rapid measurement of longitudinal road profile, and data processing by using different reference bases selected in accordance with preset criteria. It should be noted that using such measuring techniques and setting stricter criteria for evenness has in several cases resulted in a markedly higher quality of evenness of the concrete pavement.

1.2.5 EVENNESS MEASUREMENTS IN SERVICE

For the systematic survey of the evenness of their road networks, many stakeholders are using high-speed methods, such as those described above, which do not disturb traffic. Generally they are mounted in multi-function vehicles with other features to be used for distress evaluation, road geometric characteristics, GPS location or measurement of rolling noise.

1.2.6 THE PARTICULAR CASE OF STEPPING AT JOINTS

Stepping or faulting at joints is one of the main causes of deterioration of the evenness of undowelled jointed concrete pavements. It marks a change in the support of the slabs, thus constituting an indicator of pavement deterioration. Generally there is no specific intervention criterion based on difference in level across joints, this parameter being actually integrated in the overall assessment of pavement evenness.

Stepping is most often measured by means of a straight edge and a rule. Specific equipment has been developed for higher accuracy and speed of measurement. Differences in level across joints can also be measured with inertial profilers. Some countries have adopted intervention criteria based on slab rocking under a heavy axle load passing over the joints, or on deflection measured with a falling weight deflectometer.

Finally, it should be mentioned that the problem of step faulting between slabs has been largely solved by the general application of dowels in the joints, the use of continuously reinforced concrete in some countries, or the provision of non-erodible subbases and pavement drainage.

1.2.7 TRANSVERSE EVENNESS

The primary reason for conducting transverse measurements is for drainage and not specifically evenness. To evaluate drainage, the measured profile must be based upon mean sea level elevations. The devices that measure relative profile, i.e., high or low speed inertial profilers, profilographs or the physical straightedge, will not detect areas where water may collect on the pavement (birdbaths). The straightedge will detect vertical misalignment at longitudinal joints where runoff water will be trapped unless there is a longitudinal slope.

In order to detect birdbaths, the device used to measure evenness must be able to measure the slope. The process includes measuring the transverse and longitudinal profiles to determine if the area has sufficient slope for the water to run off the pavement surface.

Devices such as inclinometers or paver-mounted profilers can conduct these measurements. Some multi-function vehicles are provided with scanning lasers to accurately measure transverse profiles.

ARAN (Automatic Road Analyzer) equipped with a laser system to measure transverse profiles

(photo: AWV- Flemish Agency for Roads and Traffic)

2. ANALYSIS OF THE PARAMETERS AFFECTING EVENNESS AT THE TIME OF CONSTRUCTION

2.1 PLANNING CONSTRUCTION LOGISTICS

The achievement of good evenness of a newly placed pavement depends mainly on the following factors

- uniform consistency concrete with suitable workability for the laying machines;
- the guidance of the laying machines, including the setting up of forms or stringlines (guide wires), the evenness of rolling paths, the adjustment of sensors, etc.;
- steady supply of concrete and even distribution before the paver;
- regular progress of the paver without stoppage, at a speed adapted to the consistency of the concrete and conditions on the site;
- the use of specific equipment to smooth out small irregularities behind the paver: correcting beams, longitudinal mechanical floats, etc.

Good job organization, efficient quality control of concrete manufacture and laying, the use of reliable and well-maintained equipment, the commitment of a qualified team of personnel, and observing the rules of good practice are probably the best guarantees of obtaining good evenness at the time of construction.

2.2 CHARACTERISTICS OF THE MATERIALS AND THE CONCRETE

Manufacturing concrete with constant composition and characteristics is a prerequisite for constructing a high quality concrete pavement. The main parameters involved in achieving good surface regularity are uniformity in production and constant workability adapted to the construction method (slipform paving, compaction between fixed forms, etc). The nature and characteristics of the constituents of the concrete can, therefore, affect the evenness of the pavement mainly by acting on workability. Hence the use of particles with a high flakiness index should be avoided or limited, as they tend to reduce workability. A general requirement for the flakiness index is not to exceed 20 (FI20 according to European Standard EN 12620) for aggregates with a maximum size D ≥ 16 mm.

Sand is an important component in the composition of a concrete, because of its influence on mortar quality and on workability. The use of natural rounded sand is recommended, as it benefits workability and generally contains less fines (≤ 63μm) than crushed sand. On the other hand, a certain amount of fines is required for the cohesiveness of the mortar, to allow the laying and finishing of the concrete.

Appropriate types of stones and sand are needed for a good pavement quality concrete mixture

Precautions should be adopted when the fine aggregate used includes crushed limestone sand with a high percentage of material passing the 500 μm, 250 μm, and 125 μm sieves. In these cases, the concrete can become sticky and in addition, on some occasions an excessive swelling of concrete immediately behind the paving machine has been observed, resulting in an inadequate evenness.

Moreover, a certain proportion of siliceous sand (over 30 %) is needed when vehicles circulate directly on top of the concrete mortar (i. e., when coarse aggregates are not exposed) to obtain a surface resistant to abrasion.

The concrete mixture should be proportioned to assure proper compaction without excessive vibration. This is achieved through optimization techniques that develop mixtures containing well-graded aggregates. These mixtures are not harsh and unworkable, flow easily when vibrated and consolidate well around embedded fixtures and reinforcement.

If an exposed aggregate finish is selected, mainly for reasons of noise reduction, it is frequent to prescribe a gap-graded concrete mix in order to facilitate aggregate exposure. In this regard, it should be mentioned that in Austria and Germany, two – layer construction is compulsory for concrete pavements in motorways and expressways. Maximum aggregate size in the upper layer (with a thickness usually between 5 and 8 cm) is limited to 8 or 11 mm.

Fine particles (< 125µ) are divided into the fractions of the sand (0/1 mm – 0/2 mm) and the fine stones (e.g. 4/8 mm). Coarse, gap-graded mixtures typically require more vibration to consolidate, whereas fine mixtures require high cement contents to achieve specified strength. Over-vibration may cause vibrator trails, which are weakened longitudinal strips within the pavement caused by segregation during vibration. See also § 2.4.6.

Upper layer with an exposed aggregate concrete surface

The concrete mixture may affect the degree of smoothness. A harsh and unworkable mixture can override other attempts by a contractor to attain a smooth surface. In some cases, a harsh and unworkable mixture is known to have decreased the smoothness achieved despite a stabilized paving platform and generally favorable paving conditions.

The nature or quality of the cement has, in principle, no influence on evenness, except when the cement may cause flash set or stiffening (for example if the cement used is too hot). Also to be avoided is the use of rapid hardening cement in hot weather concreting.

The water-cement ratio and any admixtures used play a part insofar as they have a direct influence on the consistency of the wet concrete. Care should therefore be taken to keep up a constant moisture content of the mix, by making allowance for the random variations in moisture contents of the constituents. As for admixtures, it will be obvious that their proportioning and introduction in the mix require the greatest possible accuracy to ensure uniform production and constant workability.

Some concretes exhibit undesirable characteristics because of incompatibility among different materials. Examples of them are:

- early loss of workability (early stiffening), e g a slump loss of 25 mm in 15 minutes. False setting is another possible cause;

Slump test on site to check constancy of workability

- delayed set (retardation);
- early-age cracking due to excessive autogenous and drying shrinkage of concrete;
- lack of proper air-void system when air entrainers are used.

These may be caused by incompatibilities among the constituents. In most cases, surface evenness can be impaired as a result of incompatibilities.

Steps to minimize incompatibility problems include the following:

- all admixtures used on the project need to be from the same manufacturer to ensure compatibility among them. Recommended dosages should not be exceeded;
- if Portland cement is blended at the mixing plant with other cementitious materials, e g fly ash, all of them should meet the requirements of appropriate standards.

Some incompatibility problems can be exacerbated with increasing temperatures. Therefore, testing the mixture at the expected temperature at the job site is strongly recommended.

It is also advisable to have hot and cool weather mixture designs in locations where seasonal differences in temperature are significant.

2.3 CONCRETE MANUFACTURING AND LAYING PLANT

2.3.1 CONCRETE MIXING PLANT

The production capacity of the mixing plant should be adequate to ensure continuous feeding of the paving equipment and to avoid stoppage of concreting work due to delivery delays. It is recommended that the output of the mixer should be one third greater than the requirement of the paving train moving at normal rate. This is because any stoppage of the paving train

Mobile concrete batching plant
(Photo: AWV, P. De Winne)

can result in faults that may affect the evenness of the pavement.

The mixing plant should also be capable of producing a uniform concrete with constant consistence. It is therefore recommended to use plants with devices which allow continuous control of the parameters of concrete manufacture, for instance torque meters to assess the consistence. It is essential to rapidly detect and correct any deviations in production.-

Good batch-to-batch consistency of the concrete mixture improves the quality of the finished pavement because it directly affects how paving equipment performs. Stationary (ready mix) plants, on-site batching and mixing plants and truck mixing operations can produce concrete with consistent fresh properties. However, control of the mixture consistence is not limited to the mixing process. It is important that quality control continues during all phases of the paving process: transport, placing, and finishing.

The following list provides important considerations for controlling batch-to-batch consistency:

- aggregate stockpile management, i.e. the coordination of delivery, storage, and transfer of the aggregates into the mixing plant, is a vital aspect of consistent quality concrete production. A consistent and clean operation of the equipment that move raw materials at the batch plant should be assured, not least to prevent contamination. Removing aggregate consistently from the stockpiles will control the aggregate moisture content to within reasonable levels;

- some coarse aggregates are highly absorptive, and often dry, requiring a significant quantity of water to create the saturated surface dry condition assumed in the mixture design. Watering the stockpiles may be necessary for these coarse aggregates;

- moisture tests must be performed on the fine and coarse aggregate on a periodic basis (at least twice per day) and any changes taken account of in the batching;

- truck drivers must remove any water or release compounds from drums or trucks after washing or rainfall.

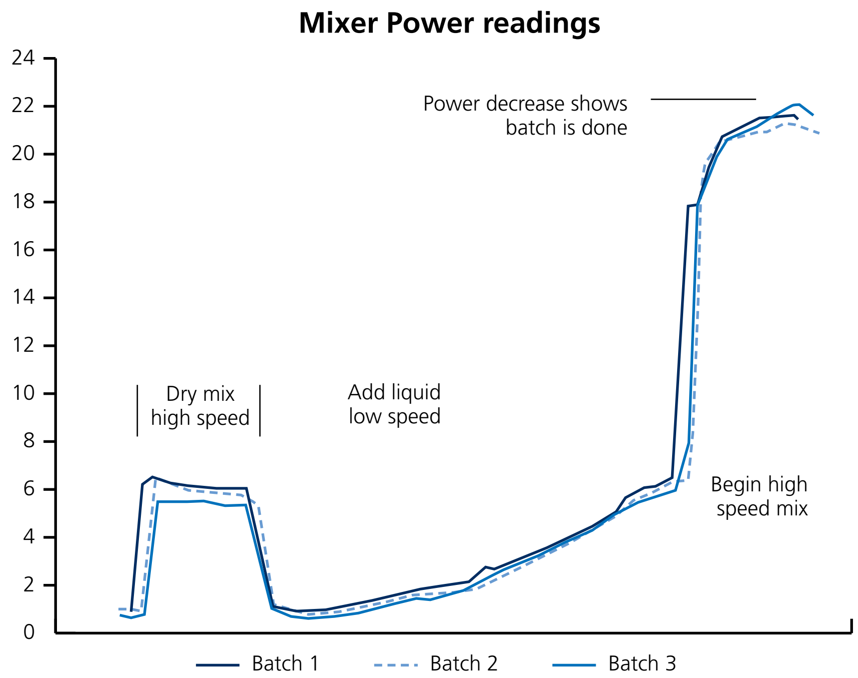
Stockpile management is crucial to produce concrete with consistent properties

Understanding moisture management in concrete production is an essential element in assuring that consistent material is delivered to the job site. Any mix is sensitive to increases in moisture, especially from free moisture in the fine aggregate. Normally, the moisture content of the fine aggregate affects the concrete more than that of the coarse aggregate.

Devices such as ammeters (sometimes called slump meters), wattmeters or power sensors are often used to provide an indication of concrete mix consistence. Care must be taken when using them, since their reading is an indirect indicator of the consistence, which is derived from its correlation with the current needed to rotate the mixer. An interesting possibility offered by some of them is to send a signal of the power used in mixing to computers, recorders or data-collection systems. Graphs can then be produced providing an indication of the uniformity of the different batches. They may also be used on truck mixers. Management of water content in aggregates in concrete production is an essential element in assuring that consistent material is delivered to the job site. Any mixture is sensitive to increases in moisture, especially from free moisture in the fine aggregate.

An adjustment in the mixture to account for the free water in the aggregate is required to maintain the water-cement ratio and workability. It may be necessary to alter both the fine aggregate content and water content or the mixture proportions will be incorrect and result in yield loss. If free moisture in aggregates is ignored, the mixture’s workability will vary dramatically, which can be detected in widely varying slump measurements. Readymix concrete producers are accustomed to managing this issue.

Difficulties in concrete mixing at the design water-cement ratio, non-uniform concrete during discharge, and excessive loss in slump may indicate the following possible problems:



Power consumption graphs of a concrete mixer during different batches

- materials not sequenced properly into the mixer;
- too large a batch size relative to mixer capacity;
- inadequate mixing times;
- admixture incompatibility with cement or supplementary cementitious materials;
- initial concrete temperature;
- moisture content changes in aggregates.

If difficulties in mixing or concrete uniformity are encountered, changes to the plant, changes in the mixing process, changes to the concrete mixture designs, and/or additional plant uniformity testing should be considered.

Mixing time should be long enough to ensure the uniformity of batches. In particular when an air-entraining agent is used, this time should be kept constant so as to avoid fluctuating air contents with possible consequent variations in workability of the fresh concrete.

The distance to the work site should be limited to avoid stiffening of the concrete during transport, which has been found to affect mainly short-range (2.5 m) pavement evenness. This means that the location of the mixing plant with respect to the job site is of prime importance. Transport time with dump trucks should not exceed 45 minutes, or even 30 minutes in hot weather, if no retarders are used.

It has also been noted that slow rates of concrete delivery are detrimental to medium-range evenness (15 m). Therefore both mixing plant output and the number of dump trucks should be in accordance with a reasonable speed of the paver.

2.3.2 TRANSPORT EQUIPMENT

Regardless of placing equipment, the rate of paving impacts the finished pavement smoothness and quality. Consistent delivery of concrete to the paving project site is probably the most important element in keeping a steady paving operation. This is usually less challenging in rural areas than in urban areas because haul roads are wider and haul trucks may travel freely. However, densely populated urban areas

Consistent delivery of concrete requires a sufficient number of lorries or mixing trucks

require careful evaluation to predetermine whether traffic delays will hamper concrete delivery. Consideration of the concrete mixture's strength development properties is also necessary, with normal mixtures allowing longer travel times than rapid hardening mixtures.

More details on the influence of the concrete supply can be found in §2.4.5.

2.3.3 PAVING EQUIPMENT

The type of equipment used (concreting paving train running on fixed formwork or slipform paving train) does not seem to have an overriding influence on the evenness of the pavement. Slipform concreting has become general in most countries, although paving machines with steel wheels to ride on paving forms are still being used sometimes. The two systems are essentially different with respect to paver guidance and concrete placing, but in both cases achieving good evenness is dependent upon the application of rules of good practice that will be discussed in detail in the next sections:

- supply of uniform and suitably consistent concrete; slipform pavers generally require lower water- cement ratio than fixed formwork pavers; this is necessary to ensure the edges are stable, and maintain a 90° profile;
- even distribution of the concrete in front of the paving machines;
- for fixed form trains, correct setting and height adjustment of the formwork;
- for slipform pavers correct setting out of stringlines;
- regular supply of the concrete to ensure the paving train does not stop;
- well-trained and motivated personnel;
- good job organization.

It should be noted however that the use of stringline guiding systems on slipform pavers is one of the critical operations in obtaining good evenness compared to guiding systems using fixed formwork as a stable datum.

A fixed form train can be reversed to resurface what had been paved, providing the concrete is still workable enough to correct evenness if necessary. On the other hand,

Slipform (left) and fixed form (right) paving operations

with a slipform paver, the concrete expands when it is released from the mold, making it difficult to reverse a slipform paver to try to improve the evenness. This is bad practice and should not be done.

Slipform pavers can be used to pave over fixed forms by extending the paver width track line beyond the fixed forms. The electronic sensors can be set up to take reference from the fixed forms. This technique is mainly used in airports to minimize possible problems caused by edge slump.

Slipform pavers can incorporate devices such as a transverse finishing beam or a longitudinal or oblique oscillating finishing beam ("supersmoother") aimed to improve evenness. In addition, they have a sealing effect on the surface.

Lighter machines can also be used for fixed form construction, as for instance bridge deck pavers, vibratory truss screeds or tube rollers. However, they are not suited to producing a very even surface and are unlikely to be seen on a work with stringent ride specifications. Productivity is also relatively low.

Labor-intensive manual paving is typically carried out for small areas such as fillets at the angles formed by the junction of two pavements, or for low volume roads.

Use of a roller finisher for the construction of a concrete roundabout (Photo: Cement&BetonCentrum)

Manual vibration of a fillet at the junction of an access road and a roundabout

2.4 PARAMETERS RELATED TO CONCRETE PAVEMENT CONSTRUCTION

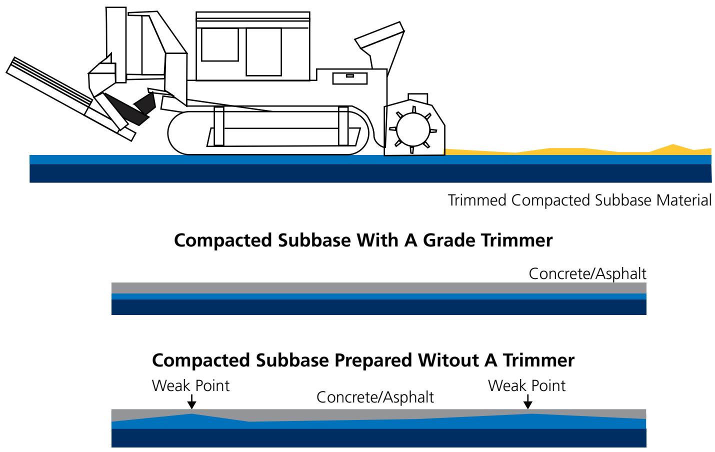
2.4.1 SUBBASES

Although at first sight the nature and characteristics of the subbase do not seem to have an overriding influence on evenness attained in construction, it cannot be denied that the provision of stable and properly finished subbase layers greatly contributes to achieving good surface regularity of the concrete slab. Indeed a subbase with a high quality bearing capacity and evenness (specifications generally allow differences in level up to 10 mm) make it possible to lay a consistent thickness of slab and provides a firm bedding for the concrete laying machines.

Cement bound subbase

Unlike asphalt pavements, in which the asphalt is placed in successive layers, concrete pavements are usually built in one layer. Therefore, it is critical that the subbase surface be as true to grade and as even as possible before placing the concrete. With asphalt paving, each layer allows the averaging out or reduction of bumps and dips created in the previous layer. In concrete paving there is usually only one opportunity to average out any unevenness in the subbase.

Slight variations in concrete slab thickness do not, in principle, affect evenness as long as the tolerance in thickness is not exceeded. A two-layer construction of the pavement, with the bottom layer serving as a



Automated fine-grading equipment

(Photo: Gomaco)

support for the wearing course, makes this issue less critical. Finally, it may be mentioned that the nature of the subbase layer is probably one of the essential parameters of concrete pavement design for the durability of evenness in service.

Automated fine-grading equipment, either guided by a stringline or 3D controlled, generally creates the most accurate granular subbase surface possible compared to other grading methods for granular materials. Fine-grading equipment is capable of meeting specifications within a tolerance of ±5 mm, when controlled by a stringline.

Stabilized subbases, such as cement-treated, asphalt-treated or lean concrete, also require close control to facilitate pavement surface smoothness. Cement-treated and asphalt-treated subbases are typically placed to an approximate depth on the grade and compacted with rollers for density. Precision control of the grade using these methods is difficult. Operator skill and experience will often contribute significantly to meeting surface tolerances for these subbase materials.

Vibrated lean concrete subbases essentially require the same manner of construction and the same equipment as concrete pavements. The only differences are: (1) jointing requirements, and (2) treatment of the surface. It is not difficult to meet a surface tolerance of ±5 mm in 3 m, particularly if the lean concrete subbase is placed using a stringline for grade control.

Extending the subbase layer, e.g. by 1m, on each side beyond the edge of the pavement benefits surface evenness. This also contributes to edge support, which reduces stresses in the pavement and prevents settlement of shoulders. The same is true when an asphalt sandwich layer is placed between the subbase and the concrete pavement. In addition this sandwich layer produces a very even platform and is very convenient for the positioning of dowels, tie bars or steel reinforcement.

2.4.2 ROLLING PATHS FOR PAVER TRACKS

The quality of the rolling paths provided for the tracks of the paver is undoubtedly one of the parameters that may contribute to achieving good surface regularity. The following should be aimed at:

- adequate bearing capacity to carry the laying machines without deforming;
- sufficient skid resistance to prevent the paver tracks from slipping, especially when concreting uphill;
- good evenness to reduce the amplitude of corrections to be made by the guiding systems of the machine during the work; this evenness criterion is, of course, more critical in the absence of vertical guidance, when the paver is operated

Rolling path for slipform machine; left picture: on an asphalt interlayer; right picture: on a widened subbase layer

with locked jacks; in any case, the rolling paths should be permanently cleared before the tracks.

2.4.3 DESIGN OF THE CONCRETE PAVEMENT

The type of pavement (dowelled or undowelled jointed pavement, continuously reinforced concrete) should, in principle, have no effect on evenness, except perhaps through incorrect methods of placing dowels or reinforcement. See further in §2.4.10.

The influence of variations in thickness of the concrete slab on evenness was already referred to in § 2.4.1 above. The importance of concrete consistence with slab thickness has also been reported, mainly with regard to avoiding edge slump of the concrete slab – see also §2.4.9.

In the past, some countries have constructed jointed concrete pavements trapezoidal in section, with a greater thickness in the slow lane. No effect of this particular design on evenness has been mentioned.

2.4.4 POSITION OF FORMS AND STRINGLINES

It will be obvious that forms or stringlines must be set up accurately if good surface regularity is to be achieved.

2.4.4.1 Fixed forms

In most cases fixed forms are used for manual working. With manual spreading, compacting and levelling of the concrete, it is more difficult to obtain smooth surfaces compared to machine work.

When the concrete is spread and compacted by machines, forms should be placed on a stable bedding, in order not to move at the passage of the paving equipment. The quality of the support beneath the form depends upon the uniformity of the subgrade or subbase surface. The base of the form should be completely supported by the subbase or subgrade surface and not lie on any soft areas or large stones.

Straight sections require standard steel forms that are attached to the subbase or the subgrade with at least three pins or stakes. They are also acceptable for forming compound-radius curves (or transition curves) and curve radii exceeding 30 m, but smaller radii require curved steel or flexible wooden or plastic forms. Short, 1.5 m, straight forms also produce acceptable results on curves with radii less than 30 m.

Each straight metal form must be clean, and in acceptable condition to produce a smooth pavement. Contractors should examine forms with a straightedge or stringline before using the forms on a project. Straight form sections that deviate by more than 3 mm along the top, or 6 mm along

Examples of steel and plastic side forms

the inside edge should be repaired or replaced.

A stringline set to the top elevation of the pavement can be used to determine the location and height for the forms. Curved sections require a tighter staking interval for the stringline than straight sections. To ensure the forms meet the design location and surface elevation, a stringline staking interval of 1.5 m is ideal for curve radii less than 15 m.

Tolerances in level should be minimal because of their direct impact on the evenness of the pavement.

After setting the forms, the form crew should visually check to ensure they are aligned and fully supported, and also to be sure their ends are locked together securely. Adequately securing forms also is crucial when they must support the paving equipment. Forms that are not secured and fully supported will deflect under the weight of the machines and create bumps in the pavement surface. In addition, the forms must remain in place until the concrete has hardened.

Standard steel forms must be fastened to the subbase or the subgrade with at least three pins or stakes Additional bracing is also sometimes necessary to secure forms around smaller curves; where necessary a bracing interval of 0.6 m is usually sufficient.

2.4.4.2 Stringlines

The stringline is the primary guidance system for a slipform paver. The paver's elevation sensor rides beneath the string, and the alignment sensor rides against the inside of the string. Neither of them should deflect the line a measurable amount.

Setting up the stringline takes careful planning. A typical stringline installation is shown in the figure below. The offsets required for the reference hubs must be determined based on the equipment and operations planned for the project. These offset distances may not be equal on each

Close-up of sensors for guiding the paving equipment

(Photo: Cement&BetonCentrum)

side of the pavement. It is critical that the contractor and surveyor clearly communicate, agree and verify that the offset and grade will achieve the desired result. Survey hubs should be set at an offset that will minimize disturbance from and to the construction processes [7]. The interval between stakes is also important, particularly on changes in the vertical profile. A maximum spacing between stakes of no more than 7.5 m on tangent sections will produce the best results. Decreasing this interval in horizontal and vertical changes in profile may be necessary and should be determined based upon the rate of change of curvature. In some cases, contractors place the stringline stakes at the future location of the transverse joints.

Achieving a smooth surface with slipform paving requires close attention to the set up and maintenance of the stringline. The stringline material, stakes, staking interval, splices and repositioning frequency all may impact the resulting pavement surface. In particular, the tension on the stringline is of vital importance to minimize sags that may lead to irregularities in the profile. The figure below shows surface irregularities 10 m long - corresponding with the spacing of stakes - which are due to insufficient tension on the stringline. Finally, the line rods supporting the stringlines should be solidly clamped to the stakes to avoid their displacement during the work. [8]

Reduced interval between stakes on a roundabout

(Photo: Cement&BetonCentrum)

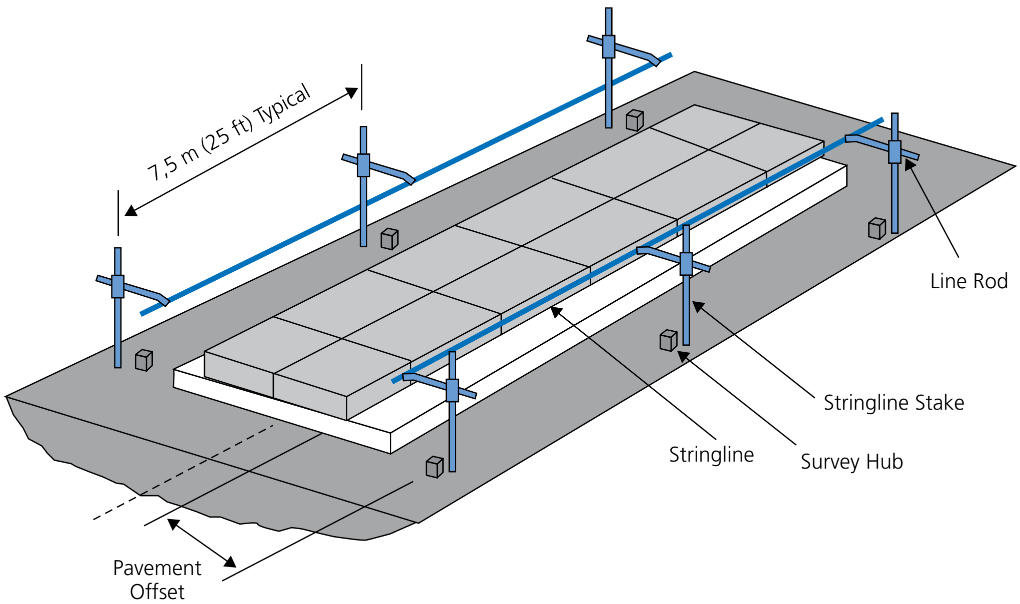
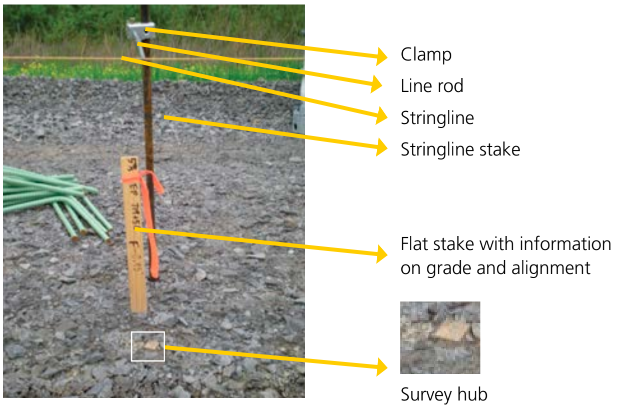
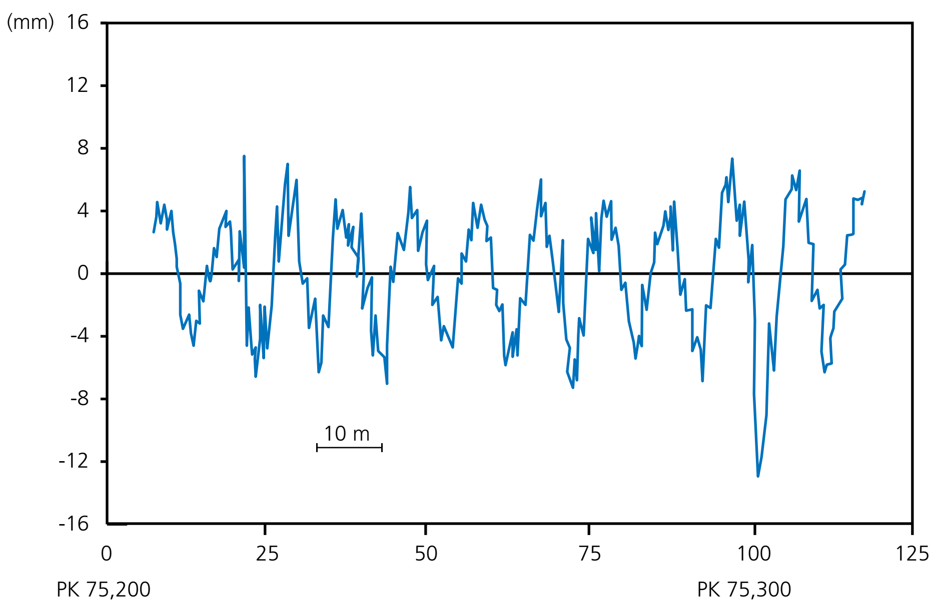


Diagram of typical stringline installation [1]

The stringline itself may be wire, cable, woven nylon, polyethylene rope, or another similar material. Whatever the material, it must be new or in good condition and checked periodically. Air temperature and relative humidity variations during the day affect the length of the line, causing sags between the stakes. The more tension that can be applied to the stringline, the less sag will occur even with substantial changes in weather conditions. Aircraft cable has been found to





Undulations in the profile of the outer edge of the hardened concrete due to inadequate tensioning of the stringline be an outstanding material for stringline [11], primarily because it is extremely durable, flexible and strong, allowing it to be placed under great tension without risk of breakage. Compared with nylon, it sags less, is less affected by weather (humidity), stretches less over time and requires less monitoring. However, nylon lines are lighter, have less risk of hand injuries (cuts), do not crimp and splices are simpler.

Splices and knots in the stringline should be reduced to a minimum. In any case they need to be clean and tight. Loose ends can cause the sensors to go astray, creating defects in the pavement surface. Wherever two separate lines meet to form a continuous run, the end treatment of each line requires particular care to prevent the sensors on the slipform machine from following the wrong line.

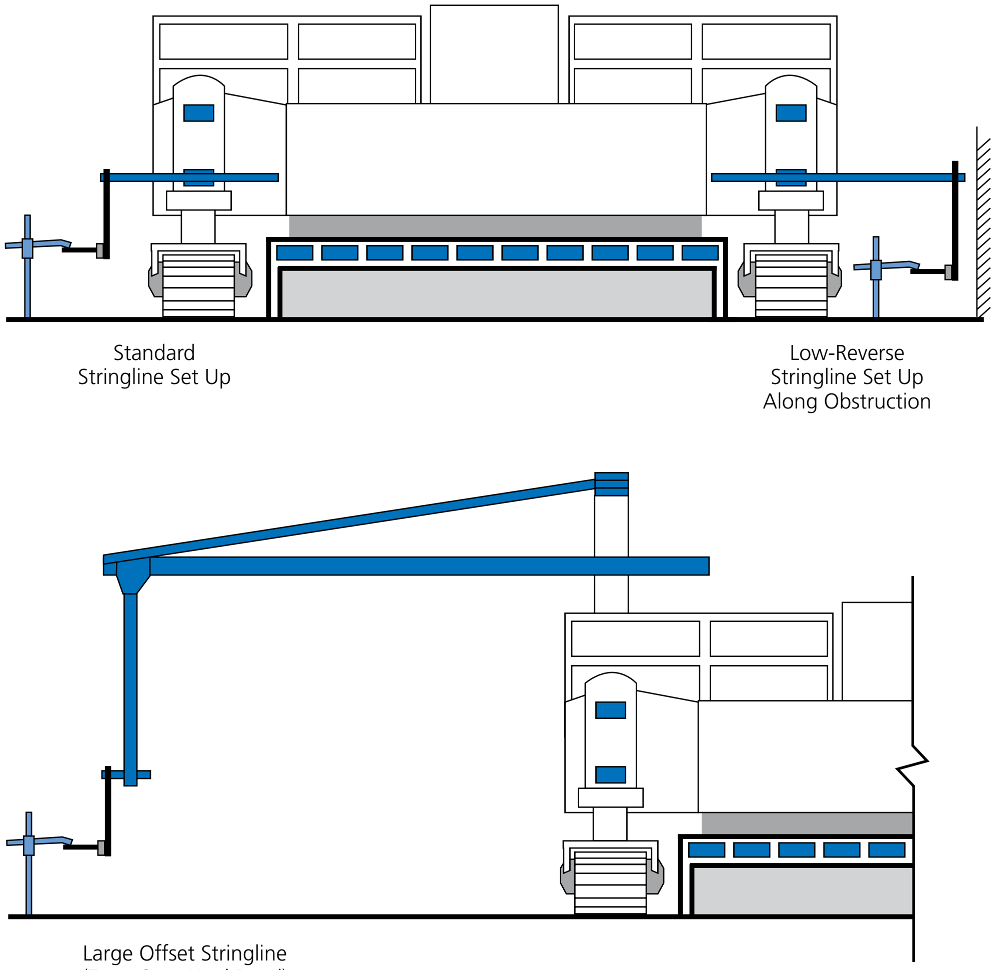
Stakes that secure the stringline should be rigid and long enough to be firm when driven into the subgrade. They should be solidly anchored to avoid their displacement during the work. There must be an adequate stake length exposed above grade to allow adjustment of the stringline to the desired height above the subgrade survey hub, typically 450-750 mm.

The staking system normally includes hand winches placed at intervals that are normally not more than about 300 m. The winches allow the line to be tightened to avoid stringline sagging between stakes. The stringline should be tensioned carefully because a line break may cause injuries.

Reducing the number of times a stringline must be setup during the project can lead to better smoothness control. Where possible it is advantageous to set up one stringline on each side of the paving area to serve all operations, including subgrade preparation, subgrade stabilization, subbase construction and pavement placement. For multi-operational usage, the stakes and strings must be offset further from the pavement area to keep them clear of the equipment and operations. However, some equipment modifications, such as the attachment of a truss or cantilever arm to the paver, also may be necessary so that the sensor wands can reach the stringlines. Various stringline set-up positions are shown below.

All personnel working near the stringline must be careful to avoid tripping over, nudging or otherwise touching the stringline. Some contractors increase the visibility

Hand winch to tighten the stringline



Stringline set up positions (ACPA)

of the stringline by tying on brightly coloured ribbons. Despite these precautions, equipment or personnel may disturb the line occasionally. After these instances, the crew should check and reposition the line immediately to avoid unevenness in the pavement.

In many instances, the haul road is next to the stringline. This arrangement necessitates regular inspection of the stringline by eye to determine if any heaving or settling of the grade disturbed the hubs and/or line stakes. It takes considerable experience to properly "eyeball" corrections to a stringline due to a deviation in the grade. When noticed, misaligned stakes should be repositioned without delay.

It is sometimes advantageous to check a stringline at night using light shone from vehicle headlights. This night-smoothing technique reduces visibility of background objects and eases the ability to focus solely on the stringline, which becomes illuminated by the headlights.

The use of averaging skis or lock-to-grade methods of grade control are generally not recommended where constructing a pavement under a tight smoothness specification. Except for thin overlays on smooth existing pavements, or for inlays, or for slabs on closely controlled stabilized subbases, the use of two stringlines will usually result in a smoother surface than can be achieved using an averaging ski or lock-to-grade methods. Two stringlines also are benefi-

General view and close up of a slipform paver using an averaging ski

cial for wide sections. If only one stringline were used, then small deviations in the stringline can produce large variations in the surface elevation on the other side of the paving machine.

2.4.4.3 Stringless paving

As mentioned above, conventional slipform concrete pavement construction uses a stringline on one or both sides of the paving train to ensure proper pavement elevation and alignment [15]. This approach requires space on each side of the paving machine to set the stringline. The placement and verification of the stringline is time intensive and limits access to the area in front of the slipform paver. Stringless control has the potential to provide the required guidance without the need for stringlines.

Several companies have developed stringless equipment control and guidance systems using technologies such as [13]:

- total stations or robotic station. This instrument automatically tracks the prism mounted on a surveyor's rod or on a machine;
- GPS survey instruments. They locate themselves using satellite signals and then locate control points. GPS is better at locating horizontal position than elevation so it is used in combination with other equipment for guiding stringless pavers.

A 3D stringless control system on a paving machine starts with the computer, which interfaces with the paving machine controller through a control area network (CAN). The computer has the 3D control software loaded with the project design file. The computer communicates with the total stations or GPS instruments to collect machine position information, used to calculate where the machine is on the site. The information is relayed to the machine controller via the CAN network. Operators do not direct the steering and elevation control of the machine during this process. The same technology is used to guide trimmers to ensure concrete thickness will be as specified. The accuracy of pavement location and surface elevation will be within the ±3 mm range.

Stringless paving offers many advantages:

- stringlines are eliminated, reducing cost, increasing jobsite manoeuvrability, and making the site safer for workers, especially in hazardous areas;
- good control of pavement thickness (and thus of concrete consumption) is achieved by using 3D machine control to build a pavement from the subgrade up;
- slipform pavers can adapt their trajectories to true vertical and horizontal curves and not to chords between stakes;
- can decrease the total time to complete a paving project;

- has shorter construction periods that disrupt traffic;
- increases traffic access along the road, especially on roads where the shoulders are limited;
- provides greater work access to the slipform paver and surrounding area;
- eliminates the need for stringline sensors on paving machines;
- eliminates the verification of the stringline tension during the construction;
- decreases the overall width of paving machines by eliminating need for sensors, making it easier and faster to cross bridges and other tight spots and providing additional space for vehicles in works under traffic.

Some contractors object [10] that if there are no stringlines, they cannot rely on the stringless system to keep the machine in the right place. In addition, there is nothing to check against. However, these fears seem to be unfounded taking into account the obtained results, and the choice between stringline or stringless methods is mainly based on cost considerations.

2.4.5 CONCRETE SUPPLY

During transport itself, segregation and precompaction of the mix should be avoided. Good grading of the mix, optimum moisture content and limited haul - preferably on good roads - should minimize this risk.

When concrete is transported in dump trucks, they should be covered to prevent drying or water gain from rain.

If after being discharged the concrete appears segregated, it is also advisable to conduct uniformity tests on coarse aggregate content.

Significant differences in aggregate content between samples of concrete from the same truck indicate that mixing consistency or concrete transport or dumping processes may need to be modified.

The time between the addition of water and depositing concrete in front of the paver must be checked to verify that the concrete can be batched, transported, and dumped on grade within specified time limits.

The concrete supply rate should match the progress of the laying machines, in order to avoid stoppage. In this respect (and others) it is always useful to have communication between the mixing plant and the work site. Feeding concrete to the paving machine consistently requires an adequate number of delivery trucks. The number of trucks will often dictate the slipform or placement speed. The entire cycle of mixing, discharging, traveling and depositing concrete must be designed for the mixing plant capacity, hauling distance, and spreader and paving machine capabilities.

There are several ways of discharging concrete. Some of them are listed below:

a) discharging directly on grade in front of the paver;

(Right photo: Gomaco)

(first two photos: IECA)

▲ b) onto belt placers and side loading spreaders;

c) into an open box placed at the side. Concrete is then transferred in front of the paver by means of a 360° excavator; ▼

Two layer construction

(Photo: Wirtgen)

d) in two-layer construction, the concrete of the upper layer can be discharged into a hopper connected to a set of belt conveyors allowing it to pass over the first machine paving the lower layer and then to be dumped in front of the second machine;

e) backhoe loaders can also be used to supplement a) or b).

The height of fall should be limited, e.g. to 1.5 m, in order to avoid precompacting the concrete by the dumping process itself, which may lead to irregularities in the pavement surface. In any case, the concrete should be spread so as to maintain a constant mass of concrete in front of the laying machines. It cannot be sufficiently emphasized that an even distribution of the concrete is of vital importance for the quality of work with respect to evenness. The manner in which the concrete is deposited in front of the paving operation is an important factor in this cycle and in creating a smooth pavement surface. The amount of concrete being carried in front of the paving machine must be controlled to assure that it is neither inadequate nor excessive. If it gets too high, it creates a pressure surge under the paving machine. The surge can cause the concrete behind the machine's finishing pan to swell, creating an uncorrectable surface bump. The slipform machine may even lose traction and steering. If there is not enough material placed in front of the paver, then the concrete head may be insufficient or the grout box may run empty, creating a low spot and voids or pockets in the pavement surface.

The concrete needs to be placed such that one side of the paving lane is not overloaded with concrete. Inadequate or inaccurate placement of concrete in front of the paver typically results in bumps or dips in localized surface areas, rather than bumps or dips across the entire paving width. This relationship has been found in comparing the smoothness profiles from each wheel path.

Depositing appropriate amount of concrete in front of the paving machine

When constructing single layer pavements the use of a separate distributing machine, eg a placer / spreader or an asphalt paver, although not strictly necessary, is advantageous, since it allows more steady progress without sudden stoppage of the concrete paver. When a spreader is used, it should not get too far ahead of the paver, eg not more than 7.5 m, and thus allow timely adjustment if the head of concrete at the paver gets too low or too high. Any action that may change the resistance of the paver to forward motion is detrimental; thrust by trucks or thrust on a feeder should be prevented.

Generally speaking, with a two-layer construction it should be easier to get a better final evenness because of the smaller amount of concrete that needs to be levelled. Moreover, this system makes it possible to vibrate dowels into the bottom layer without disturbing the evenness of the top layer. Also, potential problems caused by a non-uniform thickness of pavement in the cross section are minimized. However the two-layer paving process presents more challenges to the contractor in placing the two materials.

2.4.6 OPERATION OF THE PAVING MACHINES

The function of a paving machine is to spread, vibrate, consolidate and form the concrete into a profile as it moves forward. To maintain best practice policy, the paver must be fed with sufficient concrete that it does not have to keep stopping and starting.

Both with fixed formwork and with slipforms, steady progress of the laying machines without inadvertent stoppage is a guarantee of high-quality final evenness. The speed of progress of the laying machines should, therefore, be adjusted so as to minimise stoppage. This speed depends on the rate of concrete supply, but there are other considerations such as the evenness of the rolling paths, the consistency of the concrete, and sensor-jack adjustment in stringline systems. In practice, the optimum speed of progress of slipform pavers lies between 0.5 and 1.5 m/min.

Because a slipform paver forms the surface of the pavement directly, all factors influencing its operation have an impact on evenness:

Two-layer paving operation

- controlling the concrete head pressure in front of the paving mold;
- synchronising the vibrator frequency to the paver speed;
- positioning of the vibrator in relation to the mouth of the mold;
- ensuring correct sensitivity of the electronic sensors to match the job site conditions;
- continuous supply of concrete to allow the paver to maintain a steady forward movement without having to stop and start to wait for concrete.

Maintenance of the paving machine is extremely important. As the machine's hours of operation increase, the components will wear, which will affect the reaction time of the paver when the controls call for a correction during paving of super-elevation, transitions, vertical curves or any place where the hydraulic systems on the machine must react to changing elevations.

During operation, the primary adjustment a slipform paving machine operator can make is to the machine's forward speed and the frequency of its internal vibrators. If the concrete's plastic properties vary widely, requiring frequent adjustments of the placing speed or vibration frequency, the result will be unevenness in the surface.

Slipform pavers operate by extruding the concrete into the shape of the slab. All slipform paving equipment contains molding components. These components are the bottom of the "profile pan" or "forming plate" and the interior surfaces of the side forms. The subbase is the bottom of the mold. All of these elements confine the concrete and create the mold for its shape.

The most common example of extrusion is squeezing a tube of toothpaste. The squeeze provides the energy to move and consolidate the toothpaste; the top end of the tube is the mold. The toothpaste

Close-up at the vibrators of a slipform paver

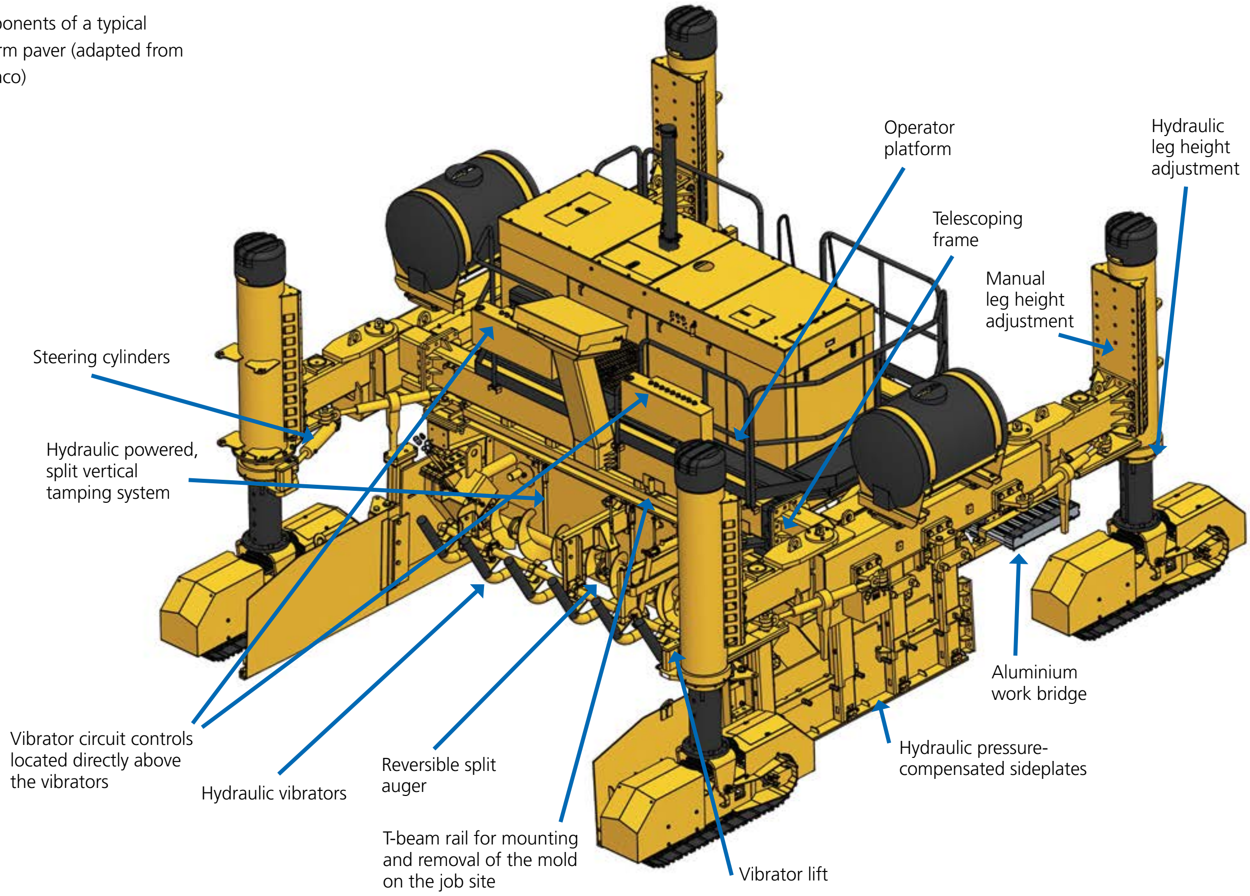
(Photo: Gomaco)

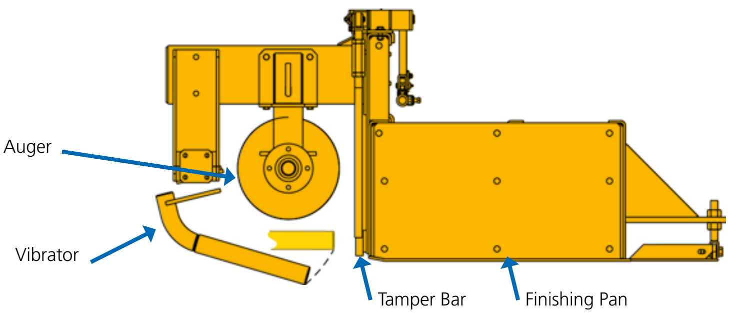
emerges from the tube consolidated and in the exact shape of the mold. The slipform paver produces similar results: concrete is squeezed through the mold to form the pavement. One major difference is that in slipform paving the mold moves, not the concrete.

A series of components mounted onto a slipform paver process the plastic concrete by filling the forms and creating a uniform shape. These components are the spreader auger (or spreader plow), strike-off, vibrators, tamper bar, profile pan, or any combination of these items.

- the front split auger and the spreader plow both serve to distribute the concrete uniformly to a predetermined width;
- the strike-off is vertically controlled to meter material into the mold;
- consolidation is provided by the vibrators mounted in the throat area of the mold;
- the tamper bar system evenly tamps down the concrete with the surface of the pan, and assists in consolidation;
- the spreading auger in the grout box ensures that segregation created by vibration is eliminated. It is also used to move concrete from the low side to the high side when paving super-elevation;
- the finishing pan (also known as a profile pan) serves to level the concrete.

Components of a typical slipform paver (adapted from Gomaco)





The most crucial area of concern in the slipform paving process is the front, or nose, of the finishing pan. At this point, vibrated, fluidised concrete is sheared off at the proper elevation to form the concrete slab. It is also where the uplifting forces that the concrete transmits to the machine concentrate. The key to a smooth paving job is to maintain uniform head pressure at the nose of the finishing pan. Changes in pressure at this point will cause the slipform machine to compensate by lifting or diving. Since the finishing pan cannot compensate adequately for large changes in pressure at the nose, a non-uniform surface and non-uniform consolidation can result.

The angle at which the nose of the finishing pan shears the concrete, also known as the angle of attack, is critical. Since the mix characteristics will determine how much energy the machine needs to put into the concrete to successfully complete the extrusion process, the best angle of attack will be determined by the concrete mixes. Achieving the proper angle of attack of the finishing pan means applying enough pressure to properly slipform the concrete, but not too much pressure, which — through hydrostatic forces — would lift the machine.

Just in front of the nose of the pan is the tamper bar. It performs secondary consolidation on the concrete mix and helps the performance of the finishing pan by moving large aggregates to just below the pavement surface at the critical shear point at the nose of the finishing pan. The thin layer of mortar created by the tamper bar at the surface between the concrete and the finishing pan lowers friction between the machine and the concrete, helping the slipform pan slide along the new pavement surface.

Vibrators mounted to the slipform machine are essential to fluidise the concrete (reduced face-to-face contact of particles) and make it easier to mold. The slipform paver can pass over fluidised concrete, its mass keeping the pan and side forms steady, to confine and shape the material.

Vibrators should be monitored to identify concrete mixture problems, such as segregation. Some adjustment to vibrator frequency is helpful, but increasing the frequency will not overcome poor equipment set up, poor alignment or poor mixtures.

When operating at a high frequency, vibrators may cause undesirable results, such as loss of air entrainment or vibrator trails in the surface of the pavement [27].

Damage and segregation to a mix can still occur below the surface, out of sight, when there is over-vibration.

Over-vibration effects can occur for a number of reasons. Some of them are:

- excessive vibrator frequency;
- reduced paver forward speed with constant vibrator frequency;
- concrete mix properties having poor workability.

A high frequency may make the paving operation appear better because the creamy, smooth cement and sand portion of the mix are vibrated to the top. The creamy mix creates a smooth finish but is detrimental to the service life of the pavement. Research results showed the specification for vibrator frequency of 5 000 to 8 000 VPM is appropriate.

Changes in the frequency of the vibrators and forward speed of the paver are of practical significance in achieving a smooth pavement as they may influence the surface.

Vibrator sensing systems are available to provide real-time readouts of frequency for all of the vibrators on a slipform paving machine. These units improve the uniformity of paving, through features such as:

- alarm settings to alert the operator of high or low frequencies, or out-of-range frequencies;

Vibrator trails may appear in the surface of pavement placed with harsh gap-graded mixtures requiring excessive vibration

- ambient temperature and relative humidity readings;
- programmable vibration frequency that self-corrects to changes in the concrete mixture;
- programmable paver speed settings for automatic reduction or increase of vibrator frequency with slowing or acceleration of the paving machine to eliminate internal segregation of the concrete;
- recording and downloading vibration data.

Vibrator frequency, spacing, and elevation may need adjustment if problems with compaction are encountered. Supplementary vibrators may be necessary at longitudinal construction joints.

The hydrostatic head, or amount of concrete above the vibrator, also affects the efficiency of an internal vibrator. The greater the hydrostatic head, the greater the effect the vibrator has on the compaction at the bottom of the slab. Some pavers are designed with a "grout box" between the strike-off and the finishing pan to confine the concrete and take advantage of this effect. Another benefit of confined vibration in the grout box is the reflection of vibration energy back into the mass of concrete. This lowers the energy required to fluidise the mix and prevents or limits segregation of the particles within the concrete. The grout box also provides a constant head of concrete in front of the nose of the finishing pan, further reducing the adjustments that the machine has to make in the extrusion process. A concrete level in the grout box of approximately 1.5 times the paving depth is recommended.

In summary, extrusion pressure, a key factor in achieving appropriate smoothness, is mainly influenced by:

- the weight of the machine;
- taper of side forms relative to the desired pavement edge planes (width and height of edge overbuild);
- angle of the profile pan relative to the desired pavement surface plane;
- vibrator power and frequency;
- paver speed;
- head of concrete (use of augers);
- concrete consistency.

In any case, stopping a slipform paver while concreting should be avoided as far as possible, even if it means slowing the machine to a crawl. Each stop will cause an irregularity in the concrete surface, usually resulting in a relatively significant deviation of short-range evenness in the area concerned. It is useful to record the location and time of any stops to help locate surface problems and correlate the operational activities with smoothness results.

If problems arise and the supply of concrete is delayed, constant communication between the plant and the paving operation allows the paver speed to be matched to available concrete delivery. If the paver is slowed, reduction of the vibration frequency is also likely to be necessary to maintain consistent extrusion pressure. This will depend upon the vibration frequency and paving speed considered to be "normal" for the operation.

Some pavers can be supplemented behind the finishing pan with an oscillating beam moving perpendicular to the direction of travel and/or a longitudinal finishing beam (also known as a super smoother) oscillating in parallel.

The transverse oscillating/tamping beam is necessary when dowels are inserted into the fresh concrete in single-layer pavements, in order to fill the voids created during the insertion process.

A correct installation and adjustment of the super smoother is needed; otherwise its effect can be detrimental rather than beneficial for smoothness.

2.4.7 CONCRETING ON HORIZONTAL CURVES

Horizontal curves are more difficult to construct smoothly than tangent sections because of super-elevation. As a result, unevenness is often more prevalent in transitions and fully super-elevated portions of a horizontal curve than on tangents. Similarly, along tangent sections a uniform or straight cross slope is easier to construct smoothly than one with a crown.

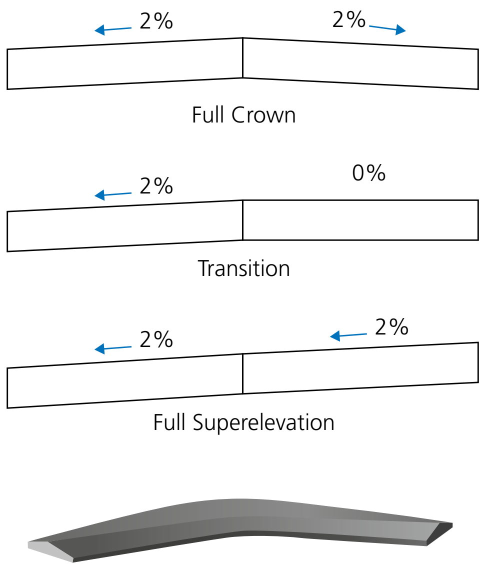
In curve transition sections, the finishing pan on a slipform paving machine must be adjusted to meet the varied cross-slope requirements of the curve. These adjustments are made by the hydraulic components of the slipform machine similarly to adjustments made for an unstable trackline. The equipment reacts to the changing requirements in a relatively incremental fashion.

As the degree of horizontal curvature increases, the potential for roughness within the curve also increases. To pave through curves, one side of a slipform machine must slow down relative to the other side, requiring more concrete to flow under the machine on the faster side. The result is a difference in the extrusion pressure and degree of vibration.

When the radius of curvature falls below 300 m, increased attention should be paid to the machine operation and the stringline staking interval. Staking intervals as low as 1.5 m have been used to meet specifications in horizontal radii of less than 30 m. As the staking interval decreases for horizontal curves, it is also recommended to reduce the spacing of the sensing wands.

Reduced stake interval in a curve

Some pavers can be equipped with a control system allowing for programmed transitions from a crown to a flat cross-slope in a super-elevation, or vice versa.



Transitioning for a superelevated curve

2.4.8 CONCRETING ON VERTICAL GRADES

The longitudinal gradient can influence the evenness of the pavement. Its effect is often perceived to be worse on sag vertical curves than on crest vertical curves. Although opinions differ in this matter, it is generally recommended to work downhill on gradients steeper than 4%. However, to avoid flow of the concrete, the consistency of the concrete and the speed of progress of the paver must be adapted, and care must be taken to always have a «wall» of bulk concrete before the paver. Moreover, downhill concreting may be difficult in confined, narrow and restricted-space job sites, e.g. in tunnels, since this can necessitate feeding trucks travelling in reverse a long distance uphill.

Some recommendations in this regard are listed below:

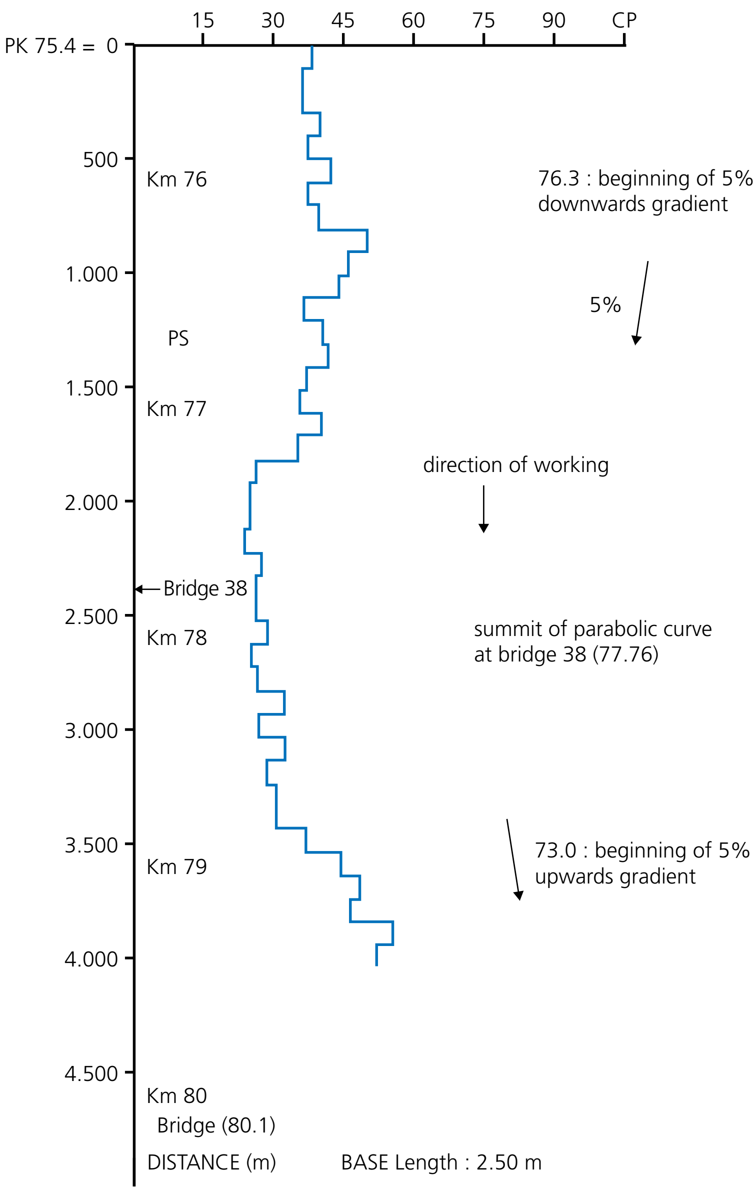
- reduce the slump of the concrete if it exceeds 15 – 25 mm. The need to make an adjustment depends upon whether it is difficult to maintain a uniform head of concrete in front of the paver;

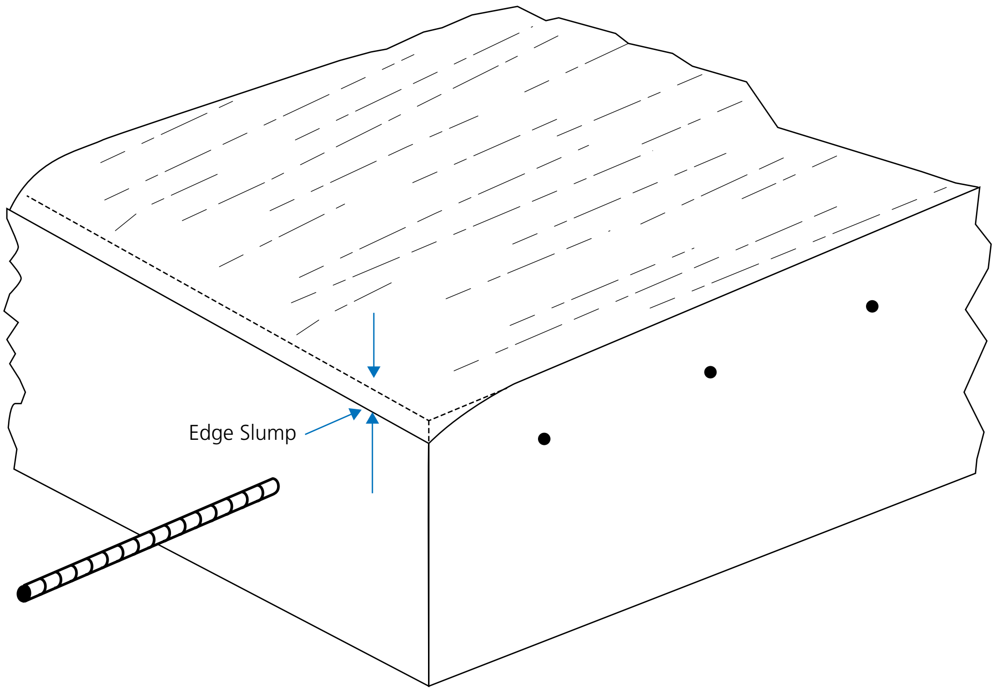
- adjust the finishing-pan angle of attack. On flat grades, the pan is usually positioned as close to parallel with the stringline as possible. In general, a draft of 10 – 15 mm is sufficient for most grades and will not cause undulations in the surface near embedded reinforcement;

- adjust the finishing-pan elevation. When paving up a steeper grade the pan elevation may be adjusted to about 25 mm below the surface grade. When paving down a steeper slope the pan may be adjusted to about 25 mm above the surface grade. This adjustment must be made carefully to avoid undulations caused by embedded items such as dowel baskets.

With the adequate measures, works have been completed with success even on gradients of 11%. The graph of the following figure shows the influence of a longitudinal gradient on short-range evenness: it can be seen that, on gradients of the order of 5%, downhill concreting tends to improve evenness while uphill concreting has an adverse effect [8].

Influence of vertical gradient on the short-range evenness coefficient (base length: 2.5 m) [8]





Edge slump

2.4.9 EDGE SLUMP

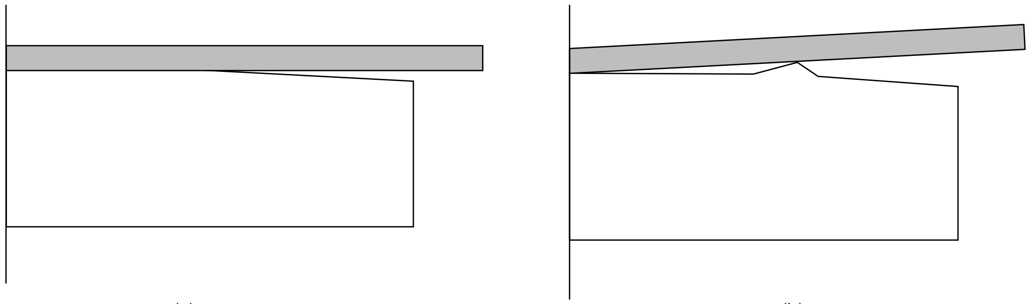
When a slipform paver pulls forward, there is a tendency for the unsupported edge to slump down, with depression extending inwards on the slab. If excessive edge slump is occurring, adjustment is needed in the concrete mixture, the paving equipment, or the paving operation. Edge slump is a serious defect, especially when the pavement is constructed in partial widths, because it creates an area for ponding of water and could affect joint performance.

Some slipform pavers offer edge slump control to accommodate slump by means of hydraulic or manual adjustments in the finishing pan.

When the edge slump is detected before initial set of the concrete, a plastic repair can be attempted. Should it not be possible to do this in a timely manner, it may be necessary to allow the affected slabs to harden and then perform partial or full depth repairs. They must be carried out correctly to ensure durability of the repaired area. It is emphasised that edge slump should appear only in isolated spots and not be a routine occurrence. If excessive edge slump happens, then the paving must be stopped until the problem is corrected. Excessive edge slump is an indication of incorrect concrete mixture proportioning, inadequate concrete placement, or defective equipment operation.

Typical specifications require that edge slump not exceed 6 mm over 15% of the joint length and that edge slump be no greater than 10 mm. Checking for edge slump requires a straight edge and level adjusted for the cross slope as shown in figure (a). Edge slump can be measured on either fresh or hardened concrete. The straight edge needs to be of sufficient length, typically 3 m, to support itself on the central

Local repair of an edge failure



(a) (b)

Measuring edge slump

portion of the slab and away from the area of edge slump, typically of 300 to 600 mm. Attention should be paid to the fact that small bumps or deviations, exaggerated in figure (b), might yield incorrect results.

Edge slump must be measured at frequent intervals. Increasing the coarse aggregate content, decreasing the water content, and/or decreasing the mortar content can reduce edge slump. Paver side form batter can sometimes be adjusted to compensate for edge slump. Reducing paver speed may also help reduce edge slump.

In this regard, it should be stressed that insertion of tie bars by hand in the fresh concrete often causes the edge of the plastic concrete to drop down and requires constant remedial work [28]. Therefore several public administrations do not allow this method.

Hydraulic insertion of tie bars into the fresh concrete

(Photos: Cement&BetonCentrum)

2.4.10 DOWELS AND REINFORCEMENT

Even when the pavement design includes reinforcement and doweled joints, it should be possible to achieve outstanding surface smoothness. However, in some cases problems may occur.

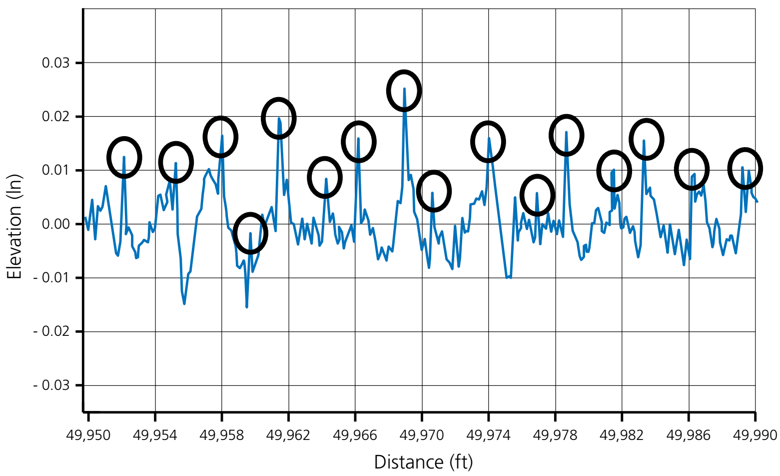
Four major causes of unevenness that can be associated with the use of dowels or reinforcement are described below:

- Lack of consolidation - Lack of consolidation to achieve a uniform concrete density within the dowel basket area may create a rough surface, because concrete may settle or dip over the dowels. In extreme cases where high-slump concrete is used, this effect may cause a crack to form directly above the dowel, as the dowel causes uneven settlement. This phenomenon is termed subsidence cracking.
- Reinforcement ripple – This occurs when concrete is restrained by the reinforcing bars, resulting in a ripple in the surface, with the surface slightly lower near each bar than in the area between bars. This happens in one of two ways: (1) longitudinal depressions are caused when longitudinal bars limit the restitution of surface level behind the finishing pan by restraining the rebound of concrete beneath the bars, and (2) transverse ripple is caused by the transverse bars in the same way, or can also be caused by the damming effect of transverse bars upon the upsurge flow of concrete behind the finishing pan. The prominence of surface rippling depends upon the finishing techniques and the depth of cover to the reinforcement, with less cover producing more prominent rippling.
- Spring-back - Spring-back is a term to describe an extrusion pressure problem affecting the dowel basket assemblies, in a fashion similar to distributed steel. It occurs when the basket assembly deflects and rebounds after the slipform paver finishing pan passes overhead and the extrusion pressure is released. The result is a slight hump in the concrete surface just ahead of the basket. Spring-back is more apt to occur on steeper grades and when there is too much draft in the pan. It may also occur when the basket assembly is too high.
- Damming - In certain conditions, a basket assembly or transverse steel can act as a dam on the grade. Generally, this occurs when paving down steep grades or on lesser grades with a low friction paving surface (subbase). The result is variance in the concrete surface in the form of humps at the basket or transverse steel.

Damming and reinforcement ripple are the most common of these four sources of unevenness.

Slipform construction of a continuously reinforced pavement

Reinforcement ripple in coincidence with the transverse bars of a continuously reinforced concrete pavement with limited concrete cover (in this case every 90 cm) [21]



It should be pointed out that the occurrence of these problems can be largely reduced through paving train adjustments and the use of improved finishing techniques.

Contraction-joint dowel assemblies should be firmly fastened to the subbase, e.g. by using steel staking pins in granular layers and nailing clips for stabilised materials. Care in fastening the baskets ensures they will not tip or be shoved out of position during paving. In addition, it has been observed that placing some concrete over dowel assemblies before passage of the paving machine eliminates dowel assembly shoving and extrusion pressure effects.

The concrete mixture should be proportioned to ensure proper consolidation around dowels and reinforcement without excessive vibration. This is achieved through optimisation techniques to develop mixtures containing well-graded aggregates. These mixtures are not harsh and unworkable, flow easily when vibrated and consolidate well around embedded fixtures and reinforcement. Coarse, gap-graded mixtures typically require more vibration to consolidate.

An alternate to placement of dowel bars in baskets is an automatic dowel bar insertion unit mounted in the slipform paver. Mid-mounted dowel insertion equipment has been shown to properly insert dowels to a level of accuracy as good as or better than baskets. In addition to freeing up the subbase surface ahead of the paving operation, dowel insertion can eliminate the rippling, spring-back and damming problems.

Dowel bar positions need to be verified when the dowel bar inserter is used for transverse contraction joints. Excessive mortar and lack of coarse aggregate over dowel bars indicate excessive vibration from inserter prongs. Shadowing or excessive bleed water over inserted dowels after placement and finishing are indicative of plastic settlement (depressions at surface), excessive vibration (excessive bleed water and mortar), inadequate vibration (poorly closed surface) or inadequate concrete mixture.

Positioning of dowels: fastening of the dowel basket –placing concrete upon the dowel assembly

Dowel bar inserters (Wirtgen – Gomaco – G&Z)

Self-loading tie bar inserters mounted on slipform pavers can be used along longitudinal sawed contraction joints when paving multiple lanes. Injectors push rebar into plastic concrete and vibrate the concrete above bars. Distance meters are used to trigger the tie bar insertion at predetermined spacing. Longitudinal positioning of bars needs to be observed to ensure that the minimum specified distance from transverse joints is maintained.

Inadequate compaction of concrete on top of the inserted dowel, leading to voids in the pavement

2.4.11 EMBEDDED ITEMS

Embedded items such as utility boxouts, cast-in-place fixtures, traffic signal handholds and drainage structures may also affect the pavement surface. These items require extra handwork, vibration and finishing efforts to embed them into the surrounding pavement surface. This extra effort is done after the passing of the paving equipment, which disrupts the surface created by the paving machine.

Ideally, in-pavement objects should be in position before placing the concrete to minimize any handwork. However, in many cases it is necessary or advantageous for the contractor to use the prepared grade to haul concrete to the paving equipment, requiring placement of fixtures as work progresses.

For fixed-form paving, the top of box-out forms should be set just below the final surface elevation of the pavement. For slipform paving, the top surface of a box-out must be 12-25 mm below the finished height of the slab. This allows a slipform paver to pass freely over the box-out with vibrator clearance adjustments. Just after the paving equipment passes over the box-out or fixture, workers raise its position to coincide with the pavement surface. This requires using a construction bridge that spans the pavement.

Particular attention may also be necessary for finishing around boxed-out fixtures and cast-in-place fixtures. Ideally, the height adjustment and supplemental vibration around the object are completed before workers need to finish the pavement

Construction of an embedded item in the pavement

surface. If properly positioned, the object should easily blend into the surrounding pavement. However, some adjustment may be necessary to blend the fixture into the surface if it is too high or too low.

2.4.12 FINISHING AND TEXTURING THE SURFACE

Care should be taken to achieve good evenness before carrying out the surface finishing, for example by using a longitudinal oscillating finishing beam or, if necessary, a jute burlap cloth to smooth out any remaining small undulations.

The surface needs to be examined in front of the paver screed or float to ensure that the surface is not tearing. Tearing of the surface is associated with:

- excessive concrete slump loss;
- too low a concrete slump;
- a poorly adjusted paving machine;
- a paver speed that is too high.

Closing tearing cracks during finishing operations may not prevent them from reflecting to the surface.

The surface also needs to be examined behind the paver screed or tube float to ensure that it is closed. Difficulty in closing the surface is indicative of one or more of the following:

- premature concrete stiffening (possible admixture incompatibility);
- insufficient paste/mortar content;
- vibrator elevations set too low;
- paving speed too high;
- inadequate concrete quantities maintained in the grout box.

Checking the surface behind the paving equipment with a 3- to 5-m hand-operated straightedge is also a recommended procedure. Successive straight edging should overlap by one-half the length of the straightedge to ensure that the tool removes high spots and fills low spots in the surface. The straightedge can, depending on the workability of the concrete, also be used to remove or reduce noticeable bumps by employing a scraping motion.

Hand finishing of the pavement surface using bullfloats is only necessary where the

Finishing with a long-handled float

surface left from the paving equipment contains voids or imperfections. In general, it is best to limit hand finishing to the extent possible.

Important items related to finishing are:

1. Minimising the need for concrete finishing by:

- selecting a workable concrete mixture;
- properly operating the paving equipment.

2. Avoiding excessive hand finishing, as it increases the amount of water at the surface and can affect surface smoothness and concrete durability.

3. If longitudinal floating is the only method to produce an acceptably "closed" surface, this is an indication that some corrections are needed for the concrete mixture and/or paving equipment, for instance:

- too small a volume contained in the grout box and/or concrete setting up in the grout box;
- fine-to-coarse aggregate volume or paste volume too low;
- the finishing pan angle needing adjustment;
- the paver speed being too high;
- vibrators needing adjustment.

4. If water is to be used to assist with finishing – which should only be done locally and in exceptional cases - it needs to be fogged, not sprayed, over the surface and should not be worked into the surface with floats.

5. Too much paste at the surface results from:

- too much water applied to the surface;
- over-vibration (high frequency);
- paver speed too slow for vibratory effort;
- over-finishing.

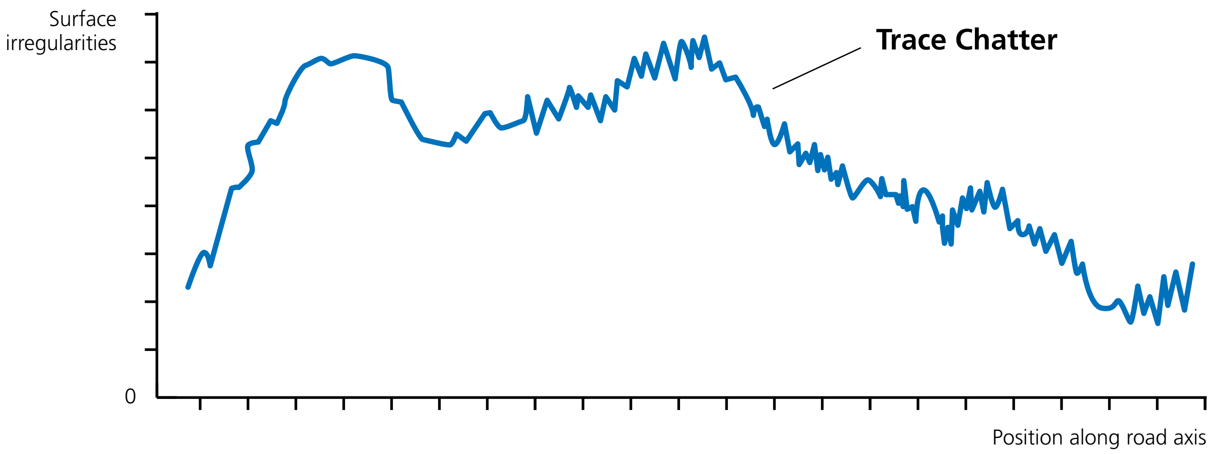
The wavelengths of irregularities caused by the surface treatment should, in principle, have no adverse effect on riding comfort. Nevertheless, the surface treatment may produce or reveal irregularities with a wavelength ranging between 50 and 250 mm (i.e. megatexture) and an amplitude of as much as 5 mm, which can generate vibrations and increase the level of rolling noise. This type of defect is sometimes known as surface chatter. Different causes are possible, e.g. when mechanical equipment is used to transversely texture the pavement, uneven pressure on the texturing tool can make one of its sides impart deeper striations than the other.

Some measures can be adopted to eliminate surface chatter:

- careful control of the set up and operation of equipment;

- checking the surface behind the paving equipment with a 3- to 5-m hand-operated straightedge. Experienced finishers can

California profilograph trace showing chatter from a deep transverse tine texture (ACPA)



use the straightedge to remove noticeable bumps by employing a scraping motion. Alternatively, a long-handled float can be used to smooth bumps and irregularities in the surface.

The following methods are used for texturing new concrete pavements:

- plastic brushing/brooming;
- transverse and longitudinal dragging of a burlap or other types of materials (e.g. synthetic turf);
- transverse and longitudinal tining;
- transverse and longitudinal grooving;
- exposed aggregate concrete surfacing.

It must be noted that the transverse finishing techniques can lead to high rolling noise levels and should therefore only be used on pavements trafficked at low speed. The surface texture should in principle not influence the roughness of the pavement. Vehicle tires bridge the relatively small striations of the concrete pavement surface.

However, if texture is mechanically imparted, the texturing machine must be well adjusted and the texturing device (brush, rake, etc.) must run on the surface evenly.

Finally, it should be mentioned that in some works the pavement has been textured by diamond grinding [24] or milling [5], or by a combination of grinding and grooving - known as Next Generation Concrete Surface (NGCS) - before opening to traffic for the first time, with no other treatment of the surface. Milling requires the joints to be previously filled with mortar to prevent them from spalling. Although these techniques result in a good surface evenness, they are more expensive than texturing the plastic concrete or exposing the aggregate. Therefore, they are generally used as corrective treatments of pavements in service, as described later.

2.4.13 CURING

Improper curing can affect surface evenness by causing differential or increasing irreversible shrinkage [20]. Drying shrinkage is defined as the reduction in concrete volume resulting from a loss of water from the concrete after hardening. Significant irreversible drying occurs in a concrete pavement only to a shallow depth (approx. 50 mm). The drying shrinkage at the surface is affected by early-age curing conditions. The drying shrinkage at the bottom of the slab is significantly lower due to the high relative humidity in the pores at that portion of the slab. Differences in irreversible shrinkage between the top of the slab and the bottom of the slab result in permanent differences in shrinkage strains between the top of the slab and the bottom of the slab, which causes the slab to curl or warp.

Curing is usually performed by applying a curing compound. Curing compound coverage rates must be established prior to construction. The application of the curing compound needs to be uniform along the pavement surface and vertical edges. A non-uniform application is indicative of spray nozzles set too low, clogged nozzles, cure rig speed set too fast, insufficient mixing of curing compound, and/or an insufficient number of passes.

Texture and curing machine

Protection of the fresh concrete by means of a curing compound or a plastic sheet

Another efficient curing method is covering the concrete surface with a plastic sheet. This is often applied for exposed aggregate concrete surfaces. In that case the plastic sheet should be ballasted in order to keep it in place, even in the case of strong winds. After removal of the plastic sheet, in case of exposed aggregate concrete, the surface should be cured again with curing compound.

2.4.14 CONSTRUCTION OF JOINTS

In most countries, moulding in the plastic concrete ("wet-forming") has been abandoned for transverse joints in high-volume roads. Specifications generally require such joints to be sawn in the hardened concrete, which is considered as the best practice. However, wet-forming of longitudinal joints is still used in a number of countries.

Concerning end-of-day and stop-end construction joints, it should be emphasised that they require particular care, especially with respect to evenness, since they are one of the most consistent contributors to unevenness of concrete pavements. This is because the paver must stop at these locations at the end of a day of work or at an interruption for a bridge, intersection or leave-out. The most common practice is to place a form (also known as header) to create the joint. The forming of the joint in this manner increases the chance of a

Pave-through and saw-back to smooth concrete

bump in the surface due to the handwork necessary to blend the mechanized paving surface with the hand poured area.

An alternative to avoid hand forming of construction joints in JPCP is to use a cut-back method to create them. For this method, the paver operator continues paving until all available concrete is placed. The following morning a full-depth, transverse saw cut is made at the point where the surface depression ends, which may be 1.5 m or more from the end of the hardened concrete slab. The end material is then removed to the saw cut. This method is less labour-intensive and produces a smoother-riding construction joint than when using the form and hand finishing technique.

In both cases, dowels are grouted and glued into holes that are drilled into the smooth butt-face joint to ensure a proper load transfer. To prevent early drilling for dowel instalment, hollow plastic tubes on supports can be installed to allow dowel fitting before the next morning concrete pour. A minimal clearance between these tubes and the dowels is needed as this may have a negative effect on the load transfer efficiency of the dowels.

Doweled construction joint

Some pavers are provided with vertical hinged sideplates with hydraulic control for ease in start-up from an existing slab, allowing the split sideplates to open and close. This provides less labour and a smoother transition to the new slab. The sideplates can be raised or lowered to negotiate headers and other obstacles.

2.4.15 EDUCATING AND MOTIVATING THE CREW

Regardless of the processes or practices that are known to influence pavement smoothness, personnel are needed to make it happen. Management practices that create a sense of ownership for the personnel enhance the crew's desire to improve their performance and results.

Crew training is vital, especially in areas that affect smoothness directly. For instance, stringline personnel need maths skills and a keen eye, while operators need to understand what equipment functions enhance or detract from a smooth surface. The crew need to focus their attention on these priorities daily (and even constantly) in order to consistently achieve excellent results.

If the project contract provides monetary incentives for achieving above-average smoothness, contracting firms should consider sharing some earned incentive pay from the project with the entire crew. This sharing principle instills a team attitude and rallies the crew on a single quality-driven focus.

3. ANALYSIS OF THE PARAMETERS THAT MAY AFFECT THE EVENNESS OF CONCRETE PAVEMENTS IN SERVICE

3.1 STRUCTURAL DESIGN OF THE PAVEMENT

The input parameters for the thickness design of a concrete pavement relate to

- the actions of traffic and temperature which the pavement will have to bear during its service life;
- the bearing capacity of the subgrade along the alignment;
- the characteristics of the concrete and the materials used in the underlying layers;
- the seasonal conditions that may affect the mechanical properties of the materials and the subgrade, e.g. variations in bearing capacity due to freezing and thawing effects or rising water tables.

If the pavement is correctly designed, these parameters will, as a rule, have no impact on evenness. On the other hand, a poor design of the road structure or the concrete pavement will lead to cracks in the concrete slab or excessive deformation of the subgrade soil and consequent deformation of the road profile.

In the case of jointed plain concrete pavements, slab dimensions are dictated mainly by the thickness of the pavement and the effect of the temperature gradients. Slab length should be limited for example to 4 or 5 m, to avoid random cracking that may lead to a deterioration of surface evenness in the short or medium term.

Apart from the road structure itself, water that is able to accumulate between the concrete slab and the subbase will also affect the behaviour of the concrete pavement. Under the dynamic pressure of traffic loads, this water may cause erosion at the interface between the subbase and the pavement, and mud pumping at transverse or edge-of-carriageway joints; the resulting defects are differences in level, slab faulting, etc.

Preventive measures against pumping and the detrimental effects of water include [6]:

- applying and maintaining seals in transverse and longitudinal joints;
- installing appropriate drainage systems;
- using selected materials in the subbase and the hard shoulder;
- use of an asphalt interlayer between the subbase and the concrete pavement.

Water "traps" at the edges of the slab must be avoided at all costs, and traffic should be kept away from the nearside edge of the slab (for example, by giving the pavement extra width, tying the hard shoulder to the slab, etc.).

3.2 DESIGN OF JOINTS

One of the main reasons for the bad reputation of older concrete pavements for safety and comfort are systematic differences in level at the joints, which are caused by a pumping phenomenon. Modern concrete pavement design has largely obviated this type of defect by:

- abandoning expansion joints virtually everywhere in favour of contraction joints;
- reducing slab length;
- using bound foundations and load transfer by dowels as soon as traffic reaches a certain volume. Dowels should be adequately designed to avoid breakage by fatigue (generally dowels of 25 mm in diameter are used in highways), and accurately installed to prevent damage to the concrete around joints;
- constructing continuously reinforced concrete pavements.

Opinions differ on the necessity of sealing joints. Some consider this to be an important factor in combating pumping, while in other countries the preference is to construct concrete pavements with unsealed joints.

Whatever the case may be, for the reasons given above it is absolutely necessary either to seal the joints to prevent water entry under the slab and/or provide an effective drainage system for seepage water.

3.3 NATURE AND ERODIBILITY OF THE SUBBASE

The choice of subbase materials is very important for the later behaviour of the concrete pavement, as they must allow the construction of a sufficient and even bearing course under the slab, and not be erodible in the presence of water.

The materials most frequently used are cement-bound graded aggregates and lean concrete. Experience has shown that the provision of a bituminous interface layer between the subbase and the concrete pavement benefits the long-term behaviour of the pavement, especially in the case of continuously reinforced concrete.

3.4 INFLUENCE OF HEAVY VEHICLES

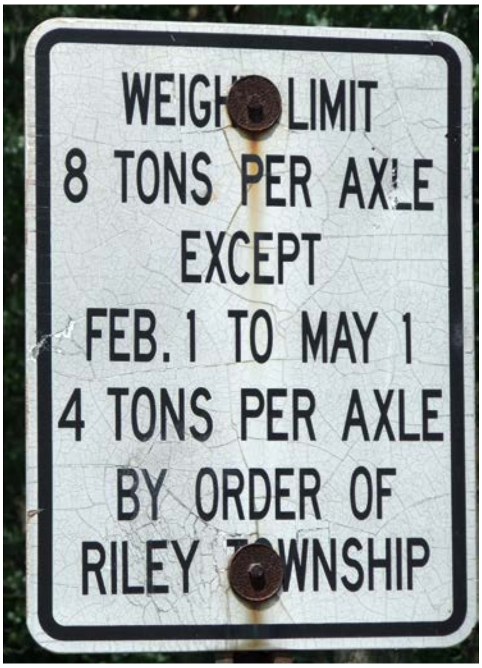
Heavy traffic plays an important part in the pavement deterioration process. In this respect, it should be recalled that any overloads not accounted for in the design calculations considerably increase the damaging effect of traffic on rigid pavements.

Traffic-related factors that may affect the evenness of concrete pavements in service are:

- the legal limits for axle loads;
- vehicles travelling close to the free edge of the slab;
- channelised traffic on slip roads;
- the use of studded tires in winter;
- heavy vehicle traffic in thawing periods, on low volume roads where the bearing capacity of subgrade may diminish significantly.

The means to combat the damaging effects of traffic are:

- intensified checks on axle weights; stronger pavement design to allow for any overloads;
- providing extra widths or even constructing the hard shoulder in concrete;
- using high performance concretes capable of resisting wear by studded tires (for example through incorporation of silica fume and with a compressive strength of 75 to 100 MPa);
- limiting weights during thaw conditions.



3.5 INFLUENCE OF MOVEMENTS OF THE SUBGRADE SOIL OR THE EMBANKMENT

Unevenness at the surface of a concrete pavement may also be caused by deformation of the subgrade, especially in the presence of the following types of soil:

- plastic clay;
- compressible or deformable soils;
- frost-susceptible soils;
- poorly compacted embankments, mainly at bridge approaches.

Constructing concrete roads on such soils calls for the following precautions or remedial measures:

- careful project design to eliminate or limit the above-mentioned effects;
- correct structural design, including design against frost;
- adequate drainage of the road platform;
- soil treatment with lime or cement (new pavements)
- injection of cement or resin grout (old pavements) under the concrete slabs;
- construction of transition slabs at bridge approaches;
- use of dowels at transverse joints;
- use of a continuously reinforced concrete pavement.

3.6 CURLING AND WARPING

Both terms are often used interchangeably for concrete pavements [14] and are defined as curvature induced in the concrete pavement slab as a result of a temperature and/or moisture gradient.

A temperature gradient is present when the surface of the slab has a temperature that is different from that at the bottom. If the top of the slab is warmer (daytime conditions), a downward curvature (corners lower than the central part of the slab) will develop as the top expands relative to the bottom. The opposite occurs at night when the slab surface is cooler than the bottom and the slab develops upward curl. As the temperature gradient typically cycles once in the course of a day, the effects are often referred to as diurnal.

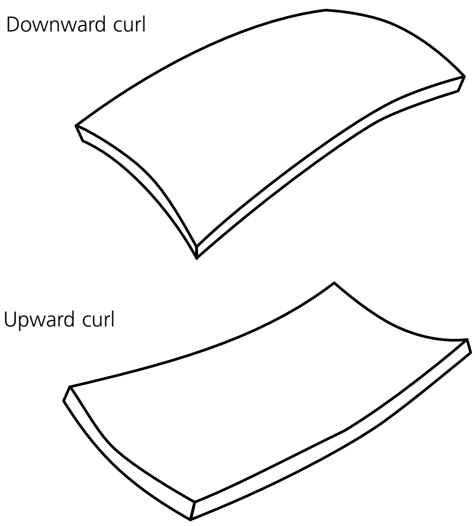
Different thermal gradients are present in a concrete pavement over a daily period:

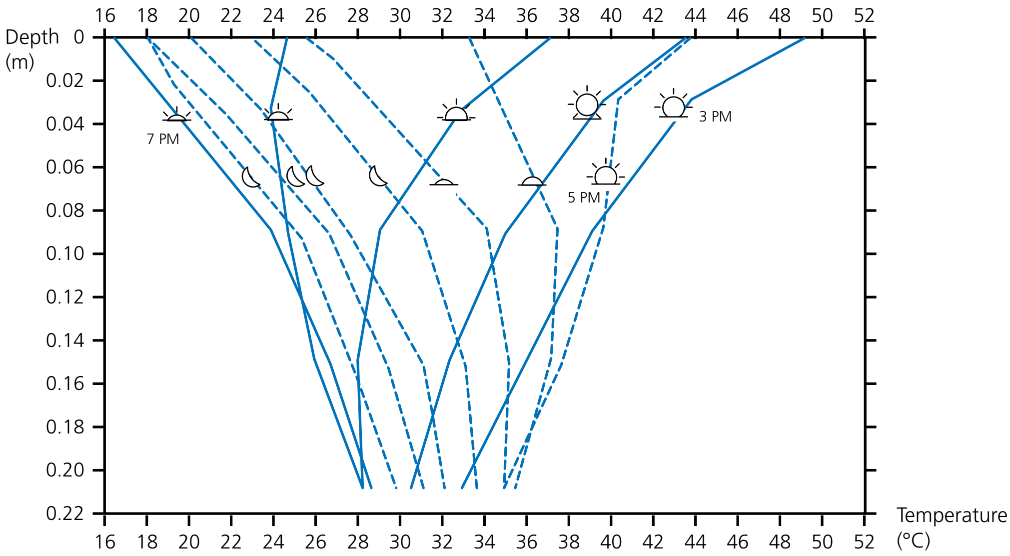
- early morning: maximum negative temperature gradient;
- mid-morning: approximate zero temperature gradient;
- mid afternoon: maximum positive temperature gradient;
- early evening: approximate zero temperature gradient.

A second possible cause is a moisture gradient in the slab. After the slab is cast, the surface begins to dry and eventually undergoes wetting and drying cycles depending on the local environment. The bottom of the slab often remains near or at saturation. As a result, the warping induced curvature is almost always upward, and will increase with time, but stabilising after some years.

Some studies [21] [4] have shown that curling/warping can be important contributors to IRI of jointed concrete pavements both in the long term and in the short term. The diurnal impact of slab suggests that it may be prudent for more emphasis to be placed on the timing of unevenness measurement within specifications, particularly for administrations working under incentive-disincentive specifications. This observation could also apply to network-level roughness measurements for maintenance programming as it is likely that the estimated functional condition (evenness) of the pavement network at the time of the survey may vary significantly depending on the timing of testing. Therefore, this issue

Slab curling





Internal temperature distribution at every 2 hours during a daily cycle (autumn) [2]

must be dealt with on a site-by-site basis since it has been demonstrated that the diurnal and seasonal effects vary significantly between sites.

The use of shorter slabs or dowelled joints are design elements that can help mitigate the magnitude of long-term upward curvature in jointed concrete pavements, reducing its impact on evenness. Alternatively, the elimination of transverse joints through the use of continuously reinforced concrete pavement is quite effective at minimising upward curvature as the effective slab length is very short, being the distance between the naturally occurring transverse cracks (e.g., 0.9 to 2.5 m) [17].

The development of long-term slab curvature is largely controlled by the drying shrinkage characteristics of the fresh (plastic) concrete. As the top of the slab dries and undergoes cycles of wetting and drying, the bottom of the slab remains near or at saturation.

Measures to mitigate the negative impacts of long-term slab curvature on evenness are:

- use concrete constituents that reduce the ultimate drying shrinkage;
- adopt proper curing practices on all exposed surfaces, minimising moisture loss at early ages.

3.7 CONCLUSIONS

Additional unevenness on concrete pavements in service is caused mainly by the following factors:

- a pumping phenomenon that may lead to step faulting, cracks, etc.;
- inadequate pavement design and/or poor drainage, in conjunction with the presence of heavy traffic;
- settlement or deformation of the subgrade or the embankment;
- surface damage to the concrete pavement (for example scaling due to frost and de-icing chemicals, wear by studded tires, etc.);
- curling and warping;
- local patch repair works.

It follows that the development of evenness during the service life of the pavement integrates the design and construction standards alluded to in the preceding sections, as well as pavement quality as perceived by the road user. Measuring evenness and its development therefore produces an essential parameter in the assessment of an overall quality index for concrete pavements.

4. TECHNIQUES FOR RESTORING EVENNESS

The objective of this chapter is to briefly review a number of techniques used to restore the evenness of concrete pavements and discuss their fields of application, advantages and disadvantages, etc., in the light of experience gained in various countries.

4.1 PLANING BY DIAMOND GRINDING

Diamond grinding treatment is a cutting process that uses a rotating profiled drum which is made up of a number of circular, diamond-coated blades arranged to create a series of continuous longitudinal grooves in the pavement [6]. The drum is attached to a self-levelling frame with a long wheelbase to span irregularities, which can be precisely adjusted (tolerance 2 mm). The working direction is always longitudinal. The working width is generally between 0.6 m and 1.2 m.

During operation, the drum spins rapidly and is applied with pressure onto the pavement surface, and pulled along the pavement in the direction of traffic. A thin layer (3-10 mm) is removed from the surface. Water is applied to the cutting interface from an on-board tank to cool the diamond blades and control the dust that is created. When grinding, closely-spaced diamond saw blades are used. The same technique and equipment is used for diamond grooving. However, while the purpose of grinding is mainly to restore ride quality and texture, grooving is generally used to reduce hydroplaning and accidents by providing runoff channels for surface water. In terms of design, the main difference between grinding and grooving is in the distance between the grooves – about 6 to 10 times higher in the case of grooving.

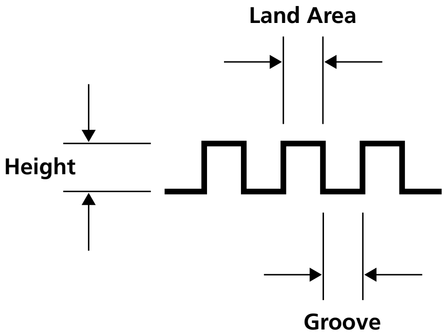
A diamond-ground pavement has a longitudinal texture with corrugations that are parallel to the outside pavement edge and have a narrow ridge, corduroy-type appearance.

Fields of application:

- elimination of faulting at joints;
- elimination of unevenness by rutting due to studded tyres;
- rolling noise reduction;
- pavement preservation in combination with dowel bar retrofit;
- bump cutting in a continuous operation.

If, in design, the option of diamond grinding is foreseen as a future treatment, it is necessary to provide an increased design thickness.

Diamond grinding machine



Transverse profile of the texture of a diamond ground pavement (FHWA)

A particular application is to restore unevenness created by studded tyres. It consists of milling tracks 800 mm wide and 35 mm deep to include the ruts, and filling them with very high strength concrete [8].

4.2 PLANING BY MILLING

The milling process uses an upward-rotating profiled drum to remove surface material. The milling drums are constructed from hundreds of point attack tools arranged in a grid pattern with spacing depending on the depth. Similarly to what happens with grinding or grooving, a thin layer (3-10 mm) is also removed from the surface.

Milling drums are made according to a wide variety of criteria depending on the requirements of the application, from the standard milling drum to special versions such as micro-milling drums [31].

The different milling drum types differ in their tool spacing and the maximum possible milling depth, which are determined by the application. Micro-milling drums are currently the preferred option for evenness restoration.

The main differences between both types of milling drums are summarised in the following table.

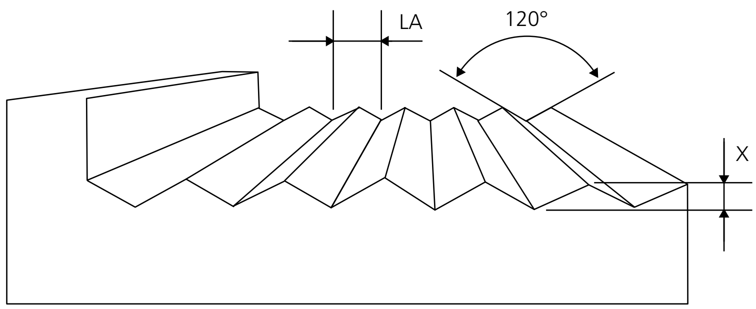
Milling drum types

Milling drum type	Tool spacing	Max. milling depth
Standard milling drums	12 mm 15 mm 18 mm	up to 35 mm
Micro-fine milling drums	3 mm 5 mm 6 mm	up to 30 mm

Both milling and micro-milling create a longitudinal texture with a transverse profile in the surface of the pavement, similar to that of a flattened cutting edge of a saw, which is largely determined by the tool spacing.

Machine for fine milling and milling drum

(Photos: Wirtgen)



Transverse profile of the texture of a milled or micro-milled pavement (Wirtgen)

The technique is also used on a large scale on overlay jobs where preliminary planing is required to rectify the road profile, or in the case of thin bonded overlays.

Local corrections to evenness can also be made with small bush hammering machines of 30 to 45 cm in width.

4.3 COMPARISON BETWEEN DIAMOND GRINDING AND MILLING

Milling and grinding are used both in asphalt and concrete pavements. Their main applications are:

- to reduce the noise level of the existing surface;
- to provide a smooth riding surface that is often as good or better than a new pavement. In concrete pavements. Smooth ride is achieved by removing bumps created by the paver, eliminating faulting at joints and cracks, removing construction curling and moisture-gradient warping of the slabs, and other construction- or environment-related roughness;
- to enhance surface texture and friction, consequently improving safety.

When comparing both techniques, it should be mentioned that standard pavement grinders are very effective for removing longitudinal waves which are shorter than their wheelbase (4 to 5 m), but larger unevenness – wavelengths of over 5 m - is copied to the new surface profile. This effect has been observed in a number of works, e.g. in a Belgian section of the E40 European Motorway [3].

In modern milling and grinding machines, a large variety of sensors can be attached: cable sensors, hydraulic cylinder sensors, ultrasonic sensors, sonic ski sensors, laser sensors, 3D sensors etc. They can be installed on one or both sides of the machine, at several points. Slope sensors enable surfaces to be created with any predefined cross slope. Multiplex systems can combine several sensors placed on one or both machine sides. Using the average value of the connected sensors, the current milling depth can be precisely calculated. Short, medium and large longitudinal waves can thus be smoothened out.

The main disadvantage of milling in comparison with diamond grinding is possible joint spalling [16], but this can be prevented with a proper filling of joints with mortar a few days before the treatment, to protect joint edges. The mortar needs to be cut out immediately after the operation and the joints need resealing. The effectiveness of this measure is known since the 1970s [12]. The involved cost is a factor to be considered when selecting one or other technique. The surface texture and joint spalling are strongly related to the linear working speed of the milling machine. Milling can also lead to micro-cracks in the concrete pavement, which is not the case with diamond grinding.

On the other hand, milling is faster than grinding and milling machines are usually more available than grinding ones.

In addition, it should be pointed out that evenness restoration, by either milling or diamond grinding, is a very demanding technique. The choice of the corrective tools (diamond blades or picks) must be adapted to the nature of the aggregates in the concrete - in particular their abrasiveness - to avoid early wear. Worn tools should be replaced as soon as possible, in order to improve both the effectiveness and the output of the operation, as well as the uniformity of the treated surface.

Both grinding and milling require a careful continuous monitoring and need to be carried out by highly qualified personnel.

4.4 SLAB LIFTING BY GROUTING

Injection with cement grout is used in several countries to stabilise or lift concrete slabs [19]. The grout is injected into holes 4 to 5 cm in diameter drilled through the pavement. The pressure applied is generally between 1 and 4 bars. The grout must be fluid and workable throughout the operation. The slab movement must be constantly checked during the lifting process. If grout is being squeezed out of adjoining drill-holes before the lifting process has been completed, these holes must be temporarily plugged using suitable stoppers.

Injection of the grout

Generally, national specifications exist for a minimum compressive strength for opening to traffic and/or at 28 days.

Slab stabilisation can also be carried out with silicate resins and expansion resins (foams) with very rapid hardening characteristics for the filling of thin voids. The time for opening the road to traffic is determined by the manufacturer's specifications. Silicate resins are normally formulated in such a way that the roads can be opened to traffic immediately after execution of the work.

Slab lifting by cement grouting has made it possible to restore the evenness of continuously reinforced or plain concrete pavements subject to severe subsidence as a result of differential settlement of the underlying structure (for example, in the vicinity of bridges or in soft soils). In Belgium, slabs have been lifted up to 20 cm over stretches of about 100 m on several motorways in continuously reinforced concrete on settlement areas of unstable subgrade. In such cases, work should be carried out in stages at a rate of 2 to 3 cm per injection step (otherwise, there would be a risk of the slab cracking).

Grouting work must be entrusted to specialist contractors, as the technique is delicate (risk of slab cracking, danger of filling cable ducts or drains, etc.). Traffic can generally be allowed 6 to 10 hours after injection, depending on the ambient temperature. In urgent situations, rapid-hardening injection grants can be used.

The durability of the grout lifting depends not only on the quality of execution but also on the measures taken to avoid later faulting, such as: better drainage, filling of joints, addition of dowels, avoiding too heavy traffic etc.

BIBLIOGRAPHY

THE BASIC REFERENCE DOCUMENT FOR THIS PUBLICATION WAS:

[0] PIARC "Achieving and maintaining the evenness of concrete pavements". Report 07.03 B, Paris, France, 1991.

OTHER REFERENCES:

[1] AMERICAN CONCRETE PAVEMENT ASSOCIATION "Constructing Smooth Concrete Pavements", Publication TB004.02P, Skokie, Illinois, USA, 2002

[2] BLANCO J., SALSILLI R., VALENZUELA R. "Slab behaviour of plain undoweled concrete pavements", CROW Workshop on Theoretical Design of Concrete Pavements, Epen, The Netherlands, 5 – 6 June 1986

[3] CAESTECKER C., HELEVEN L. "Grinding of a Transversely Grooved Cement Concrete Pavement of the European Motorway E 40 at Bierbeek", 5th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, West Lafayette, Indiana, USA, 1993

[4] CHANG G.K. et al. "Quantifying the Impact of Jointed Concrete Pavement Curling and Warping on Pavement Unevenness", 6th Symposium on Pavement Surface Characteristics (SURF), Portoroz, Slovenia, October 2008. http://www.roadprofile.com/download/SURF2008_Paper_JCP_Curl.pdf

[5] DIAZ MINGUELA J., BARTOLOMÉ C., ESCANCIANO J.F. "A new road with a micromilled concrete pavement and a bridge over the Esla river in Leon (Spain)", 12th International Symposium of Concrete Roads, Prague, Czech Republic, September 2014

[6] FEDERAL HIGHWAY ADMINISTRATION "Concrete Pavement Rehabilitation - Guide for Diamond Grinding", Washington D.C., USA, 2001
http://www.fhwa.dot.gov/pavement/concrete/diamond.cfm

[7] FICK, G., TAYLOR, P., CHRISTMAN, R., RUIZ, J. M. "Field Reference Manual for Quality Concrete Pavements", Publication No. FHWA-HIF-13-059, Federal Highway Administration, Washington D.C., USA, 2012

[8] FUCHS, F., GORSKI, M.B. "Evaluation de l'uni de revêtements en béton de ciment et étude des moyens visant à la réalisation d'un uni de qualité", 5e Symposium international des Routes en Béton. Thème B, 17-26, Aachen, 1986

[9] GERARDI, T. "Airfield Concrete Pavement Smoothness – A Handbook", Report IPRF-01-G-002-02-4, Innovative Pavement Research Foundation, Skokie, Illinois, USA, April 2007
http://www.iprf.org/products/IPRF%20Report%2002-4%20_Final%20Publication%2004%2006%2007.pdf

[10] GOMACO INTERNATIONAL LTD., "A 3D Quiz: You're familiar with GOMACO 3D... True or False?". GOMACO World 39.2 - November 2011
https://www.gomaco.com/Resources/leica.html

[11] KOHN, S.D., TAYABJI, S. et al "Best Practices for Airport Portland Cement Concrete Pavement Construction (Rigid Airport Pavement)" Report IPRF-01-G-002-1 Innovative Pavement Research Foundation, Washington D.C., USA, 2003

[12] LUCE P.T. "Texturing existing concrete pavement", Research Project 78 TI-537, Michigan Transportation Commission, Lansing, Michigan, USA, October 1979
https://www.michigan.gov/documents/mdot/RC-1127_418226_7.pdf

[13] 3 NASVIK, J. "Pavement Layout and Control", Roadbuilding Supplement 2012, Concrete Construction, Rosemont, Illinois, USA, 2012
http://www.concreteconstruction.net/paving/pavement-layout-and-control.aspx

[14] NATIONAL CONCRETE PAVEMENT TECHNOLOGY CENTER "Concrete Pavement Curling and Warping: Observations and Mitigation", Moving Advancements into Practice (MAP) Brief, Iowa State University, Ames, Iowa, USA, April 2015

[15] NATIONAL CONCRETE PAVEMENT TECHNOLOGY CENTER "Stringless Paving", Ames, Iowa, USA, 2004
http://www.ctre.iastate.edu/pubs/t2summaries/stringless_paving.pdf

[16] NEAL B.F., WOODSTROM J.H. "Evaluation of Cold Planers For Grinding PCC Pavements", Report No. FHWA-CA-TL-78-15, California Department of Transportation, Sacramento, California, USA, 1978
http://www.dot.ca.gov/newtech/researchreports/1978-1980/78-15.pdf

[17] OH H.J. et al "Effect of curling behavior on surface smoothness of continuously reinforced concrete pavement", 12th International Symposium on Concrete Roads, Prague, Czech Republic, September 2014

[18] PERERA, R. W., KOHN, S. D. "Issues in Pavement Smoothness: A Summary Report", NCHRP Web Document 42 (Project 20-51[1]): Contractor`s Final Report, NCHRP Project 20-51[1], Transportation Research Board, Washington D.C., USA, March 2002
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_webdoc_42.pdf

[19] PIARC "Best Practice Guide For Maintenance of Concrete Roads". Report 2013R06EN, Paris, France, 2013

[20] RAO S., ROESLER J.R. "Characterizing effective built in curling from concrete pavement field measurements", Journal of Transportation Engineering, Vol. 131, No.4, American Society of Civil Engineering, Reston, Virginia, USA, 2005

[21] RASMUSSEN R.O. et al "How to build smooth concrete roads and measure success the moment you pave", 12th International Symposium of Concrete Roads, Prague, Czech Republic, September 2014

[22] RASMUSSEN R.O. "Innovations in Concrete Paving", 2012 Virginia Concrete Conference, Richmond, Virginia, March 8-9, 2012.
http://www.virginiadot.org/business/resources/Materials/Virginia_Concrete_Presentations/2012/1p - Innovations in concrete_paving.pdf

[23] RASMUSSEN R.O. et al "Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction", SHRP 2 Report S2-R06E-RR-1, Transportation Research Board, Washington D.C., USA, 2013
http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-R06E-RR-1.pdf

[24] RIFFEL S. "CRCP with ground texture – Experiences and results of the Geseke access road pilot project", 12th International Symposium of Concrete Roads, Prague, Czech Republic, September 2014

[25] SAYERS, M.W., GILLESPIE T.D., QUEIROZ C.A.V. "The International Road Roughness Experiment Establishing Correlation and a Calibration Standard for Measurements", World Bank Technical Paper number 45, Washington D.C., USA, 1986

[26] SAYERS, M.W., KARAMIHAS, S. "The Little Book of Profiling", University of Michigan Transportation Research Institute, Ann Arbor, Michigan, USA, 1998
http://www.umtri.umich.edu/content/LittleBook98R.pdf

[27] STEFFES, R., TYMKOWICZ, S. "Vibrator Trails in Slipformed Pavements", Concrete Construction, April 01, 1997

[28] TEXAS DEPARTMENT OF TRANSPORTATION "Pavement Design Guide", Austin, Texas, USA, 2011

[29] THE TRANSTEC GROUP "Profile Viewing and Analysis Software", Austin, Texas, USA, 2012
http://www.roadprofile.com/download/ProVAL-Intro-English.pdf

[30] THE TRANSTEC GROUP "Understanding Smoothness Specifications", Austin, Texas, USA, 2012
http://www.smoothpavements.com/content.aspx?id=1

[31] WIRTGEN GmbH "Wirtgen cold milling manual", Windhagen (Germany), 2013

Published by:

EUPAVE
European Concrete
Paving Association
Vorstlaan 68 boulevard du Souverain
1170 Brussels
T + 32 2 790 42 06
F + 32 2 640 06 70
info@eupave.eu
www.eupave.eu

Author: C. Jofré

Photos: FEBELCEM unless otherwise mentioned –
Cover photos: front: InformationsZentrum Beton,
Germany; back: André Nullens for FEBELCEM

February 2017