PRESTRESSED CONCRETE PAVEMENTS

A. Seruga
Departament of Civil Engineering, Krakow University of Technology
Aseruga@imikb.wil.pk.edu.pl

A. Smaga
Departament of Civil Engineering, Krakow University of Technology
Asmaga@imikb.wil.pk.edu.pl

R. Szydłowski
Departament of Civil Engineering, Krakow University of Technology
Rszydlowski@imikb.wil.pk.edu.pl

ABSTRACT

In this paper the results of laboratory investigation preceding realization of continuous prestressed concrete pavement at Krakow – Balice Airport are presented. Three concrete slabs of dimentions 1.0 m × 3.6 m × 0.16 m were realized in the Laboratory of Technological University of Krakow. Two of them were prestressed by unbounded steel tendons 7 □5 mm to 50 % of full prestressing force 20 hours after concreting. Full prestressing was realized 20 hours later. The concrete strains and prestressing force were monitoring over 28 days. Set of concrete samples was taken in the same time, and development of concrete mechanical properties in day-time was determined.

KEY WORDS

CONCRETE, PAVEMENT, PRESTRESS, PRESTRESSED CONCRETE PAVEMENT, AIRPORT PAVEMENT.

1. INTRODUCTION

The load-carrying capacity of concrete pavement slabs can be significantly increased by prestressing. Prestressing induces compressive stresses in the concrete of pavements slabs. These stresses modify the structural behavior of these members and considerably improve their capacity to sustain bending deformations without cracking.

Given adequate consideration to the design of joints and the placement of reinforcement, long prestressed slabs with substantially smaller thicknesses than those of conventionally reinforced pavements carrying the same loads, can be constructed practically without cracks.

It has long been known that transverse joints in plain and lightly reinforced concrete pavements are sources of structural weakness. Many of the problems in concrete pavements such as cracking, faulting, pumping, and spalling occur at the joints and adversely affect the riding quality of the pavement. In addition, most of the maintenance work is needed at the joints. One approach to limiting joint problems is to use pavements without joints except at the extreme ends, which is the case in continuously reinforced concrete pavements (CRCP). Another approach is to use transverse joints spaced at greater distances, which is the case in the prestressed concrete pavement.

A properly designed and constructed prestressed concrete pavement can provide a smooth surface free of cracks and with few transverse joints. In spite of these advantages, the use of prestressed concrete pavements has not been widespread in the World for the following reasons:

- not many pavement engineers are familiar with the methods of design and construction of prestressed concrete pavements,

- an adequate evaluation of the performance of this type of pavement under various load and environmental conditions is not available,
- the use of relatively high magnitudes of prestressing forces, both in the longitudinal and transverse directions, has been expensive. This has discouraged the widespread use of prestressed concrete pavement.This is in spite of the economic advantages of this type of pavement as a result of its lesser thickness and of its potential for less maintenance as compared to nonprestressed pavements.

The magnitudes of the prestressing stresses and the corresponding amounts of prestressing steel can be reduced considerably, as compared to the amounts that have been commonly used, if proper attention is paid to the following two important factors:

- The use of low friction media or treatments between the pavement and the supporting media reduces the tensile stresses due to friction that develop during slab contraction when temperature drop. The reduction of friction allows a similar reduction in the amount of the required prestressing forces,
- The consideration of the favourable distribution of shrinkage stresses through the thickness of the slab due to the moisture differential between the bottom and top surfaces (away from the slab edges) reduces the stresses from vehicular loads. These residual stresses, which are compressive at the bottom of the slab: counteract a large part of the tensile stresses due to vehicular loads and thus reduce the amount of prestressing steel.

Investigations of prestressed concrete pavements have shown that a favourable prestress distribution can be used in slabs on ground to produce the high load – carrying capacities of these pavements. Most of the methods of calculating stresses in concrete pavements are based on Westergaard's theoretical procedures and the empirical results of the AASHO Road Test. Both are mainly concerned with determining a thickness adequate to carry wheel loads. Neither method incorporates directly the stresses resulting from restraint of movements or deflections caused by temperature and moisture variations. The resulting design thickness is, in most cases, sufficient to carry traffic loads. However, little attention has been directed toward preventing cracks in conventional pavement designs.

Procedures for quantitatively determining the time - dependent gradient restraint stresses and their distribution on pavement cross-sections evolved from the investigation of prestressed concrete for slabs at the University of Missouri at Rolla from 1956 to 1958, which was cosponsored by the FHWA and the Missouri State Highway Department (ACI Committee 325, 1988). The research included prestress to 3,5 MPa magnitude. The results indicate that creep deformations are lower at the bottom than at the top of the pavement. This information can be used to determine the restraints of slowly changing moisture warping, as well as deformations under prestress from an early age and thereafter. The resultant concentration of compressive stress toward the bottom of prestressed pavements due to the combined effect of prestressing and differential shrinkage are valuable characteristics of prestressed pavements.

This finding makes it possible for the designer to consider the environmental stresses from temperature and moisture gradients as well as prestress in resisting traffic loads. This is especially true in the interior of prestressed pavements, which usually consist of large slabs cast over membrane sheets. While water can evaporate freely from the top surface ot these slabs, the bottom surface is permanently covered and movement of water from this surface is restricted.

2. TIME - DEPENDENT DEFORMATIONS AND RESTRAINT STRESSES IN PRESTRESSED PAVEMENTS

2.1. Seasonal length changes of prestressed slabs

Changes in pavement length depend primarily on the temperature changes in the concrete, the swelling of the concrete that usually takes place during the cold season because of fluctuation in moisture content, and the restraints to movement due to subgrade friction. The coefficient of thermal expansion in conrete is mainly dependent on the thermal coefficient of the coarse agregate, which varies from about 4.5 $\cdot 10^{-6}/^{0}C$ for high – grade limenstone to about 11.7 $\cdot 10^{-6}/^{0}C$ for acceptable types of siliceous rocks. Neat cement has a somewhat higher thermal coefficient. The measured value of thermal coefficient of concrete is also dependent on age, temperature, and moisture content. Hence the thermal properties of a pavement undergo seasonal changes. The seasonal changes in thermal coefficient have an effect on the seasonal change in length. Ideally, the actual values of thermal coefficients should be determined for each project. Such an approach would be advantageous from the particular application standpoint as well as to accumulate data for future use. Where this is not possible, it is considered appropriate to use the thermal coefficient for fully saturated conditions for predicting the winter length changes, about 1.5 times this value for predicting the summer length changes, and an intermediate value for the other seasonal length changes.

The seasonal length changes of slabs due to temperature should be decreased by the amount of seasonal swelling (which is independent of the amount of prestress). The unit deformation of this swelling has not been observed to be less than $100 \cdot 10^{-6}$.

Frictional restraints don't exert a major influence on the seasonal temperature movements, but friction stress is a major concern in the design of long slabs. The minimum required design value is 0,5 for the average friction coefficient under prestressed pavements of about 180 m maximum slab lengths. A friction coefficient of this magnitude is attainable by using a double layer of high slip polyethylene under the concrete pavement. This high – slip polyethylene contains a friction reducing agent between the two layers and should be placed on a well compacted and leveled subbase.

Friction on frozen subgrades can vary significantly and friction coefficient of not less than 0,7 should be considered at low temperatures. If friction – reducing layers are not used under the pavement, higher values must be considered for the coefiicient of friction. The appropriate value to be used should be obtained from the investigations conducted on site.

2.2. Noncyclic length changes from shrinkage and prestress plastic creep

The long - time total deformations from the prestress are assumed proportional to the average prestress on the cross-sections of the pavement slab and proportional to the slab length. The prestressed froces are decreased by the friction restraint stresses during the night contraction and are increreased during the day expansion. Accordingly, the nominal concrete prestress in the slab can be assumed to be active throughout the slab length. Sustained modulus of elasticity values at different ages suffice for computation of the total progressive length change due to prestress.

Longer slabs will generally be designed with higher prestress at the ends than the shorter slabs to maintain a specified minimum effective prestress at mid - length of the contracting slabs. If the prestressing is applied at the short gaps between the prestressed slabs, joint widths can be adjusted during the placement of the expansion joints for the drying shrinkage, prestress application and creep that occur during the early age, up to about one month.

2.3. Deformations and restraints of warping

Deformations under prestress, applied at an early age and remaining relatively constant thereafter, are clearly subject to creep deformations (Sargious, Ghali, 1986). In many cases the immediate strains of prestress cannot be seperated from the creep in pavements subject to variations in temperature occuring at the time of stress application.

The sustained modulus of elasticity E_s includes the effects of both the immediate elastic deformations and the deformations due to creep. The sustained modulus has the same units as the elastic modulus, although its valne is smaller and decreases with time under stress. ACI Committee 209, in its interpretation of creep and shrinkage behavior of concrete, has attempted to further simplify these behaviors by considering the concept of age - adjusted effective modulus. Its value depends upon the secant modulus of elasticity E_c, the creep coefficient ϕ, and an aging coefficient χ which ranges between 0.6 and 0.9.

$$\bar{E_C} = \frac{E_c}{1+\chi \cdot \phi} \tag{1}$$

Creep of concrete depends upon the moisture content and it cannot be assumed that its effects are the same at the top and bottom surfaces of large pavement slabs. The bottom portions are at or near full saturation, while the top part are at a lower moisture content most of the time. Accordingly, different values of the creep coefficient should be used in calculating the sustained modulus of elasticity at the top (E_{ST}) and bottom (E_{SB}) surfaces of the slab when the stress distribution on sections that are fully restrained are estimated. These sections are away from the ends and must have the same deformations at top and bottom to remain flat without deflections.

The shrinkage of large concrete members that dry from only one surface, such as is the case in a pavement, was investigated by Carlson. He found that 0,30 m slab exposed to drying from two sides at 50 % relative humidity for a two month period lost less than 20 % of its evaporable moisture. This slab is equivalent to a 0,15 m pavement exposed to drying from one side only. Using another method of measurement, it was found that in one month concrete more that 19 mm from the surface contained more than 80 % of its moisture, and below 76 mm deep no moisture change at all was noticeable from the inital evaporable moisture content. However, care should be used in the interpretation of these results since local temperatture and humidity conditions could have an effect on moisture content.

2.4. Prestress distribution on pavement sections

An investigations of prestressed concrete for pavements at the University of Missouri at Rolla, included observations of six prestressed slabs under four levels of constant stress for two years. Measurements on slab thickness of 0,14 and 0,20 m of non - air - entrained and air - entrained concrete were conducted at four levels of post-tensioning: 0 (control); 0.7 ; 2.1 and 3.45 MPa nominal prestress. The load was held constant by spring assemblies and applied at mid - depth. The surface of each slab was instrumented over 5.33 m length in which careful slope changes could be obtained for the full length. Length changes at the surface were projected to mid - depth and to the bottom of the slabs to obtain a complete record of curvatures along each slab, as well as detailed recordings of temperature and length changes.

The time dependent deformations were linearly related to the three levels prestress and provided information on the sustained modulus values at the tops and bottoms of the slabs for both thicknesses. Slab without prestress showed fair linearity between the shrinkage, and swelling deformations at the top and bottom as well, but less shrinkage in comparison with the prestressed slabs, probably due to less effective end sealing.

Shrinkage strain of the top of the slabs was about 14×10^{-5} during the first month. Affer the first month swelling occurred at both the top and bottom, at about 10×10^{-5} at the top, and between 5 and 10×10^{-5} at the bottom.

3. DESIGN CONSIDERATIONS

The design of PCP can be conducted following the guidelines in the literature, although a standardized design methodology is not available yet. To overcome this situation, pavement designers follow the existing guidelines that in the end provide valid and applicable results. The design of a PCP section requires a full understanding of a series of concepts that affect the quality of the pavement and its performance. The PCP design considerations will affect the pavement during its entire service life. The two basic design considerastions are the factors affecting the design and design variables.

3.1. Factors affecting design

In general, the factors that have the greatest influence on the design of a PCP are the same factors that affect the design conventional pavements. These factors include the effect of traffic loads, environmental conditions (e.g. ambient temperature and moisture), concrete temperature and tempreature gradient, and friction resistance caused by the slab supporting layer. In addition to these factors, the design of PCP has to account for the effect of prestresses and slab movement. All these factors must be considered in the design of PCP to ensure that the final product will meet the expectations of a high - performance concrete pavement.

3.1.1. Traffic loads

Traffic loads generate compressive and tensile stresses at the top and bottom fibers of pavement slabs. Due to the relatively high resistance of concrete to compressive stresses, the critical stresses in a pavement slab are tensile stresses. The magnitude of these tensile stresses depends on the magnitude of the applied wheel loads and the strength of the supporting layer underneath the slab or subbase.

3.1.2. Temperature effects

The effects of temperature on concrete pavements are of particular interest for designers, especially in the case of PCP, where long slabs are constructed. Horizontal movement of the slabs is resisted by the slab itself and the friction that is created between the bottom of the slab and the subbase. This friction resistance between layers has to be considered in the design because it affects the magnitude of stresses developed in the bottom of the slab, prestress losses, and joint widths between PCP slabs.

Curling of the slabs is caused by several factors, such as the temperature differential between the top and bottom fibers of the slab, concrete compressive strength, modulus of elasticity, slab thickness, and joint spacing.

3.1.3. Moisture effects

Similar to temperature gradients in pavements, moisture gradients cause warping stresses in pavements. During nonrainy conditions, moisture content in pavements increases gradually from the bottom to the top because moisture escapes from the top surface of the pavement. This difference in moisture across the depth of the pavement causes curling of the slabs. When this happens, tensile stresses develop in the top of the slab, and compressive stresses take place in the bottom fiber. This effect is beneficial at mid - depth of the PCP slab because compressive stresses in the bottom of the pavement tend to counteract tensile stresses due to friction between the slab and its subbase. However, this effect can be detrimental for the top fiber of the slab near the ends, where additional tensile stresses from thermal curling are presented during the cooler part of the daily temperature cycle.

Another factor that has to be considered in the design and construction of PCP is shrinkage due to rapid moisture loss at an early age. The moisture loss causes shrinkage cracking, which can lead to the appearance of distresses and premature pavement failure.

3.1.4. Friction resistance

Daily and seasonal temperature changes cause expansion and contraction of pavements. These horizontal movements create a frictional resistance between the bottom of the slab and the top surface of the subbase. In concrete pavement this resistance is very significant and has to be quantified for design purposes. The frictional resistance depends on the coefficient of friction, the length of the slab, and the modulus of elasticity of the concrete. In long prestressed slabs this resistance is considered to be evenly distributed on the cross section of the slab and be broken into three components: bearing, adhesion and shear. Bearing force is represented by the weight of slab on the layer underneath. Its direction depends on the surface texture, moisture condition and temperature. Adhesion is the component that results from the attraction of the slab to the support layer and its magnitude depends also on the moisture and temperature conditions of the supporting layer. The shear constituent depends on the surface characteristics of two layers in contact when movement begins. Its magnitude is proportional to the magnitude of the bearing component.

In a PCP frictional resistance has another effect and causes a decrease in the amount of compressive stress transferred to the concrete from post - tensioning. The reduction of post - - tensioning force along the slab requires that a higher post - tensioning force be applied at the ends of the slab. To reduce the effect of frictional resistance, which causes tensile stresses in the pavement and reduces the amount of prestress transferred to the concrete during post - tensioning, a friction - reducing membrane is placed beneath the PCP slab to lower the coefficient of friction between the pavement slab and supporting base.

3.1.5. Prestress losses

Prestress losses are very critical for the design of PCP. Therefore they have to be estimated. Essentially, the strength of a PCP is dependent on the precompression applied to the concrete from prestressing. The losses to be calculated to ensure that the required prestress level is maintained over the length of the slab and, most important, over the design life of the pavement. The prestress losses can be from 15 to 20 % of the applied prestress force in a PCP that is well - constructed and post - tensioned.

3.1.6. Transverse prestress

Transverse prestress is an essential component of PCP. The absence of transverse prestress in this type of pavement resulted in extensive longitudinal cracking after exposure to traffic in most of the cases. The transverse prestress resists the applied wheel loads, preventing longitudinal pavement cracking and possible disconnection of separately placed pavements lanes or pavement strips. Therefore, it is critical that transverse prestress be incorporated in any PCP.

3.1.7. Joint movement

Horizontal movement of the slabs is caused by expansion and contraction of the concrete due to daily and seasonal temperature cycles. It was concluded from the instrumentations that horizontal movements can reach significant values if concrete slabs are very long. The literature findings showed that the length of PCP slabs should not exceed 180 m to avoid excessive horizontal movement at the expansion joints. In general, the expansion joint width requirements usually govern the permissible slab length.

One critical aspect in the design and construction of PCP is related to the expansion joint. It should be designed so that full closure never happens. Otherwise, it will cause crushing of the concrete near the joint. During construction, an initial joint opening must be provided to avoid this situation and also to allow seals to be accommodated. This initial opening varies, depending on the slab length and the season in which the pavement is constructed. Joint opening has to be evaluated for construction during the critical conditions of summer and winter. If the pavement is constructed during the spring or the autumn, the expected movements will fall between the ones calculated for the other two critical conditions. In general, an expansion joint should never open more than 0.1 m. This will ensure good riding quality and will prevent an excess debris from getting inside the joint.

3.2. Design variables

The variables that must be considered in any PCP design include analysis of foundation strength and embankment properties, pavement thickness, magnitude of prestress, slab length and width.

3.2.1. Foundation strength and embankment properties

Foundation strength has a very significant effect on the performance of pavement. Although the relationship between the foundation strength and the performance of conventional concrete pavements has been thoroughly explored, PCP still need to be researched in this field. The design of PCP assumes the same relationships associated with a conventional concrete pavement. Two of these relationships are as follows:

- For given load, the stress in a pavement is inversely proportional to the strength of the supporting foundation.
- The ability of the pavement to withstand repetitive loads is directly proportional to the strength of the supporting foundation.

The first relationship means that, as the supporting foundations becomes weaker, the stresses generated in the pavement by wheel loads increase. In other words, if the supporting layer is weak, cracking and failure of the pavement will occur rapidly. If the supporting layer is strong, the chances of cracking and failure of the pavement are much less likely to happen. The second relationship suggest that a pavement with a weaker supporting foundations will fatigue and eventually fail faster than a pavement with a stronger supporting foundation.

With regard to embankments, it is very important to verify the characteristics of the soil used for their construction. Problem have been found in embankments constructed with plastic soils with swelling potential. Expansion and contraction of the soil in the embankment will cause a rapid deterioration of the riding quality of the pavement and possible loss of support, which will ultimately affect the performance of the pavement. Therefore, it is essential to know the plasticity characteristies of the soils to be used in embankments and to understand their ability to swell and shrink at a given density, moisture and loading conditions when exposed to traffic loads.

3.2.2. Pavement thickness

The design thickness for conventional concrete pavements is generally dependent on foundation strength, concrete strength and the number and magnitude of wheel load repetitions. However, for PCP there is greater flexibility with the pavement thickness selection. For every design there is a range of thicknesses that might be used and in most cases it is possible to simply select a desired pavement thickness and adjust the amount of prestress in the pavement to meet the design criteria.

Prestressed slabs have considerably greater load carrying capacity than indications based on flexural strength by the amount of prestress. The failure load is much higher than the load that produces the first crack at the bottom of the pavement. Furthermore, if the load that caused the bottom crack is removed, the prestress closes the crack and the pavement regains most of its rigidity. This is the characteristic that gives PCP a potential structural adventage over conventional concrete pavements, since they can carry traffic loading beyound the purely elastic range of normal concrete. The use of this concept can result in slab thicknesses considerably thinner than conventional pavements carrying the same loads.

A practical limit for PCP thickness seems to be a value not less than 50 to 60 % of the thickness that would be used for urban street applicalions and not less than 60 to 65 % of the thickness that would be used in a CRCP in major highways. Thickness of less than 0,15 m are generally not recommended, except for light traffic conditions.

3.2.3. Magnitude of prestress

The magnitude of prestress varies along the length of the pavement owing to prestress losses. In general, the magnitude of prestress must be such that the compressive stress at all points along the length and width of the pavement is greater than or equal to the minimum compressive stress required to meet the fatigue requirements over the life of the pavement. The fatigue requirements are a function of the number of load repetitions and foundation strength.

The compressive stress at any point along the length of the pavement can be expressed as a critical stress combination of the magnitude of the applied prestress, stress generated by applied wheel loads, curling stress resulting from temperature differential over the depth the slab and friction stress caused by the supporting layer resistance. This combination of stresses is given by equation (2) below:

$$\sigma_{cR} = \sigma_p + \sigma_w + \sigma_c + \sigma_F \tag{2}$$

where: σ_{cR} - critical stress combination,
σ_p - effective prestress at the critical location,
σ_w - stress generated by applied wheel load,
σ_c - curling stress caused by temperature differential through the slab,
σ_F - friction stress caused by slab - base interaction.

Stresses are different in the top and bottom of the slab, requiring both to be analyzed. Curling stresses are assumed to be equal and opposite (tensile [+] versus compressive [-]) in the top and bottom of the slab. Stresses caused by wheel loads are assumed to be tensile (+) in the bottom of the slab and zero in the top. Friction between slab and subbase causes both tensile (+) and compressive (-) stresses, depending on the movement of the slab, and is assumed to be uniform over the pavement depth. Although the stresses vary along the length of the pavement, the only two points at which the stresses must be evaluated are at the ends of the slab and at midslab.

3.2.4. Slab length

The length of the slab is governed by the expansion joint width requirements. As the length of the slab increases, the amount of expansion and contraction movement caused by temperature changes also increases, resulting in wider (or narrower) expansion joint width. Among the factors to consider with regard to the length of slabs, economics and riding quality are probably the most important. As for economics, it is clearly understood that the longer the slabs, the fewer expansion joints will be required. Expansion joints are a significant cost component of PCP. Likewise, as the slab length is increased, the more prestress is needed and consequently the prestressing cost is increased. Furthermore, as the slab length is increased, the expansion joint widths also increase, thereby affecting the riding quality of the pavement. Conversely, as the slab length is decreased, the number of expansion joints increases, again affecting both riding quality and economics. Therefore, a good balance has to be found between the economics and quality of the PCP by selecting an optimal slab length.

3.2.5. Slab width

The slab width (or pavement strip width) is delimited by the exterior edges of the finished pavement, in transverse direction. Although slab width does not affect substantially the structural design of the PCP, it has a great impact on the constructability of the project. This slab width is controlled by various factors, such as location of the pavement, equipment limitations and traffic management. The location of the pavement is important because it is necessary to know the number of pavement strips that will accommodate the total width of the pavement, which depends on the number of lanes and pavement shoulders. It is important to plan ahead the order in which strips will be constructed and then post - tensioned together.

Special consideration must be given to the pavement shoulders. It is always desirable to construct a PCP in which the shoulders are built monolithically with traffic lanes. If it is constructed in this way, wheel loads will always be on the interior of the pavement and the critical edge loading condition will not be an issue.

4. ELASTIC DESIGN OF PCP

The design of PCP requires the compliance with two criteria:

- Critical tensile stresses at the critical location (bottom fiber of the PCP) must not cause a fatigue failure of the prestressed slab.
- The combination of wheel loads, temperature differential across the depth of the slab, and moisture stresses should never be greater than the combined concrete flexural strength and residual prestress to avoid cracking of the concrete.

The first criterion is known as the fatigue loading design and deals with the estimation of the PCP pavement and its required prestress. The thickness design for fatigue loading is a crucial part of the PCP thickness design process, where all the data already available are used with a single purpose, that is, to determine an appropriate PCP thickness that will withstand traffic conditions. Therefore, the cross-section of the existing pavement, the back-calculated elastic properties of the pavement, and projected traffic are used in combination with assumed design parameters for the estimation of the thickness of the PCP slab and its required prestress.

The second criterion is known as the elastic design for environmental stresses and wheel loads. The final or effective prestress applied to the PCP should meet both criteria. The design for environmental stresses and loading of the PCP can be mathematically expressed by following equation:

$$f + \sigma_p \geq \sigma_t + \sigma_c + \sigma_F \qquad (3)$$

where: f - allowable flexural stress in the concrete,
σ_p - effective prestress at the critical location,
σ_t - stress caused by applied wheel load,
σ_c - curling stress due to temperature differential through the slab,
σ_F - friction stress between slab and supporting layer.

Equation (3) is a variation of equation (2). The PCP slabs of the existing pavement (overlay) and the new pavement on the median will include prestressed concrete in their full width. This means that the shoulder areas will also be considered in the design as an integral part of the PCP slab. Therefore, the critical condition to be analyzed in the design is the bottom fiber of the PCP slab, where tensile stresses due to traffic, curling, and friction are additive.

5. PROGRAM, RESULTS OF INVESTIGATIONS AND CONCLUSIONS

Stresses induced in the Post-Tensioned Concrete Pavements should not exceed the compressive strength of the concrete. During construction stresses must be applied before the concrete reached its maximum compressive strength. Construction stressing resists the formation of shrinkage cracks. However, tensioning to design may cause compressive failure of the concrete. Therefore, tensioning of post-tension strands should be executed in stages.

Special attention needs to be given to the stressing operation. The strand cannot be stressed to design until the concrete has gained sufficient strength. Since cracking occurs from a change volume, thermal gradient, and subgrade restraint, it is imperative to apply first stage tensioning to the tendons at the earliest time practical, usually within 24 hours. Some small cracks may form before initial jacking; however, they would close upon application of the jacking force. The second application of stressing should be done within 24 hours of the previous operation. Last the final jacking should be done when the concrete strength has reached at least 20.7 MPa (ACI Committee 325, 1988), independent of the amount of time. It is imperative not to jack the strand beyond the strength of the concrete. Jacking forces should be determined by considering the size and thickness of bearing plate end anchors and minimum concrete strength necessary to withstand the force applied. It may be necessary to increase the size of the end anchor bearing plate to distribute high bearing stresses at the slab edges.

Preliminary investigation, preceding realization of continuous post-tensioned concrete pavement in John Paul II Airport, Kraków, have been done in Laboratory of Institute for Building Materials and Structures of Kraków University of Technology.

The aim of investigation was to evaluate the strain and stress states in concrete slabs of cross section 0.16 m × 1.0 m and 3.6 m in length, under different stages of prestressing. Three concrete slabs were constructed. Anchorage steel plates has been stabilised on the front surfaces of tested elements instead of normal reinforcement in anchorage zone. To minimize the friction forces two layers of polyethylene between slab and subbase have been used. Two of three slabs have been prestressed by unbonded steel tendons 7□5 mm in longitudinal direction. Slab 1 was prestressed by two tendons applied at the ends of slab in the distance 0.5 m. In case of slab 2 four post-tensioning tendons were applied in the distance 0.25 m. General view of slab 1 is shown on Figure 1. Slab 3 was nonprestressed, for monitoring shrinkage, thermal strains and friction resistance what has allowed to separate the creep strains from the results obtained in Slab 2. The prestressing was realized in two stages. I stage - about 50 % of final prestress force was applied 20 hours after casting, II stage - the prestressing force was improved to final value 40 hours after casting. The average value of prestressing force and corresponding values of concrete stresses are set in Table 1. $\square_{c,b}$ and $\square_{c,t}$ signs calculated concrete stresses at the bottom and the top slab surfaces respectively.

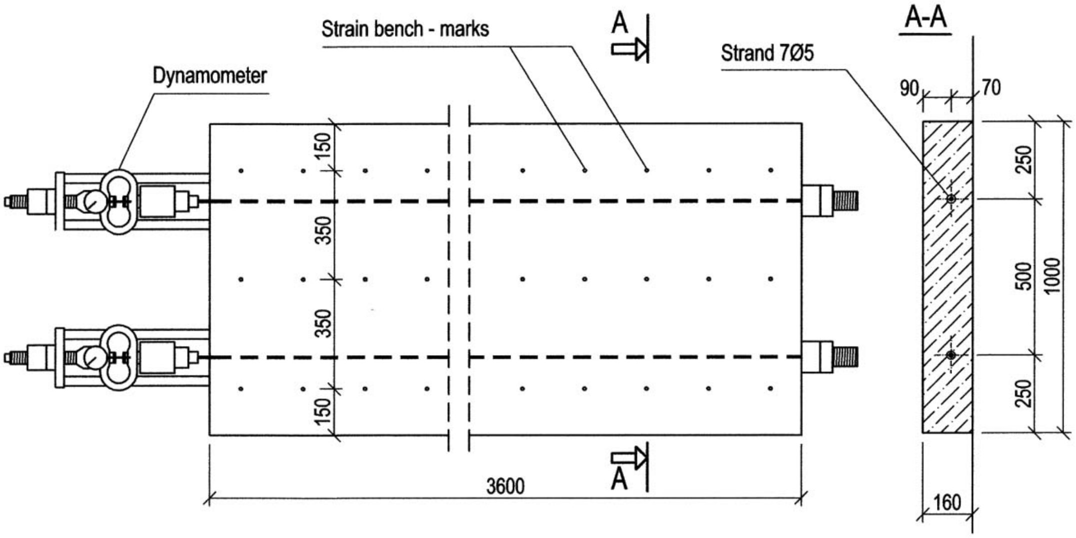

Figure 1 – General view of slab 1 (all dimensions in mm)

The special air-entrained concrete mixture designed for prestress concrete structures has been used. Portland cement CEM I MSR NA 42.5 have been used in quantity 440 kg/m^3, w/c = 0.37. Because of the necessity of improving the concrete modulus of elasticity, basalt aggregate has been used. The concrete has been tested before and during the investigations. Following mechanical properties of concrete have been determined at 12, 18, 24, 36, 48 hours and 3, 7, 28 days before the investigations:

- compressive strength (cube samples 150 mm × 150 mm ×150 mm),
- compressive strength (cylindrical samples □150 mm × 300 mm),
- axial tensile strength (cylindrical samples □150 mm × 300 mm),
- splitting tensile strength (cube samples 150 mm × 150 mm ×150 mm),
- modulus of ruptures (beam samples 150 mm × 150 mm × 600 mm), two points bending,
- modulus of elasticity of concrete (cylindrical samples □150 mm × 300 mm),
- concrete shrinkage (beam samples 100 mm × 100 mm × 500 mm).

The results of these tests are shown in Figures 2 ÷ 5.

The following variables were monitoring during the load time:

- prestressing forces in tendons,
- concrete strains and temperature distribution at three levels of middle span cross-section: 20 mm above the bottom surface, mid-depth of slab and 20 mm under the top surface,
- concrete strains on the top concrete surface in three lines in the longitudinal direction,
- slab contraction on the level of prestressing tendons (inductive 10 mm displacement transducers).

The prestressing force has been released 28 days after concreting but the monitoring has been conducted for several days yet. The initial and final forces as well as the prestressing losses values are presented in Table 2. P_0 denotes the initial force in the tendons, and P_t denotes the force in the tendons 20 hours later and 28 days from the time of prestressing. The prestressing tendons were situated in cross-section with eccentricity equal to 10 mm (Figure 1 and 8).

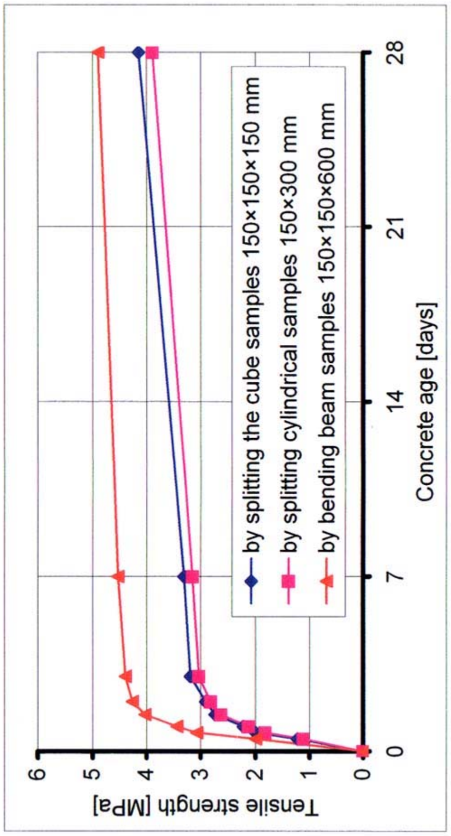

Figure 3 – Development of tensile strength in day-time

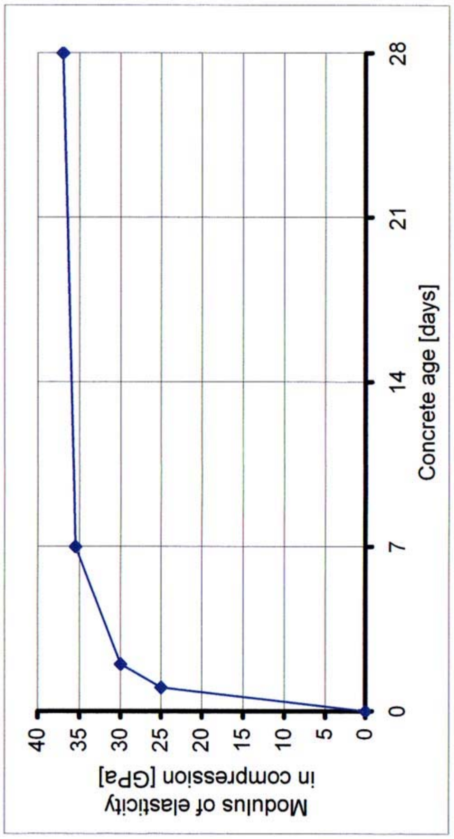

Figure 5 – Development of modulus of elasticity in day-time

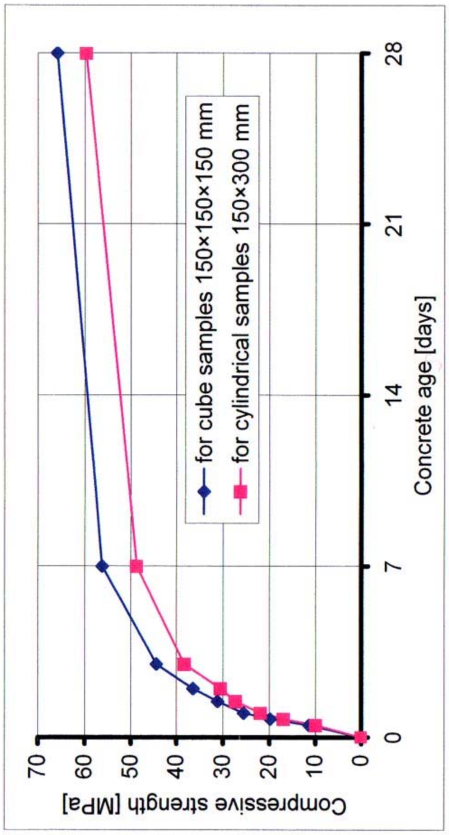

Figure 2 – Development of compressive strength in day-time

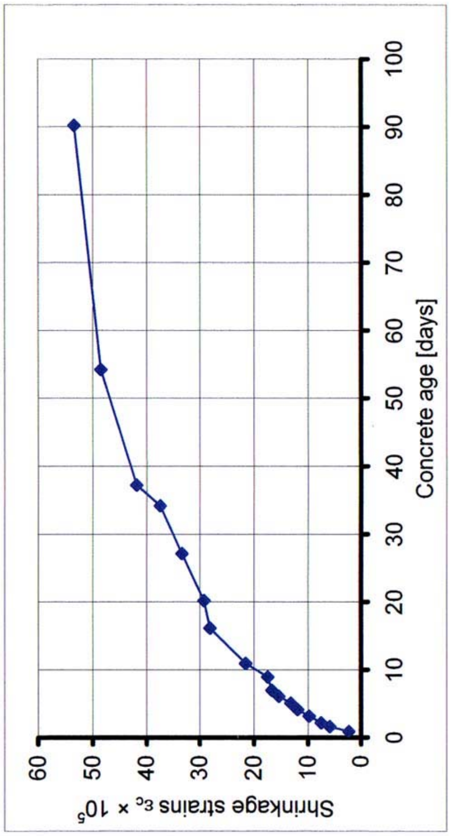

Figure 4 – Development of shrinkage strains in day-time

Table 1 – Average values of prestressing force in tendon and concrete stress values

Number of slab	I stage of load			II stage of load		
	P_{01} [kN]	□$_{c,b}$ [MPa]	□$_{c,t}$ [MPa]	P_{02} [kN]	□$_{c,b}$ [MPa]	□$_{c,t}$ [MPa]
Slab 1	100.1	1.72	0.78	189.9	3.26	1.48
Slab 2	99.0	3.40	1.55	189.4	6.61	2.96

□$_{c,b}$ – bottom surface, □$_{c,t}$ – top surface

Table 2 – Initial as well as final forces and values of prestressing loss

Number of slab	I stage of load			II stage of load		
	Start (20h)	End (40h)	Force loss	Start (40h)	End (28 days)	Force loss
	P_0 [kN]	P_t [kN]	□P [%]	P_0 [kN]	P_t [kN]	□P [%]
Slab 1	100.1	98.9	1.3	189.9	183.3	3.5
Slab 2	99.0	96.7	2.3	189.4	182.9	3.4

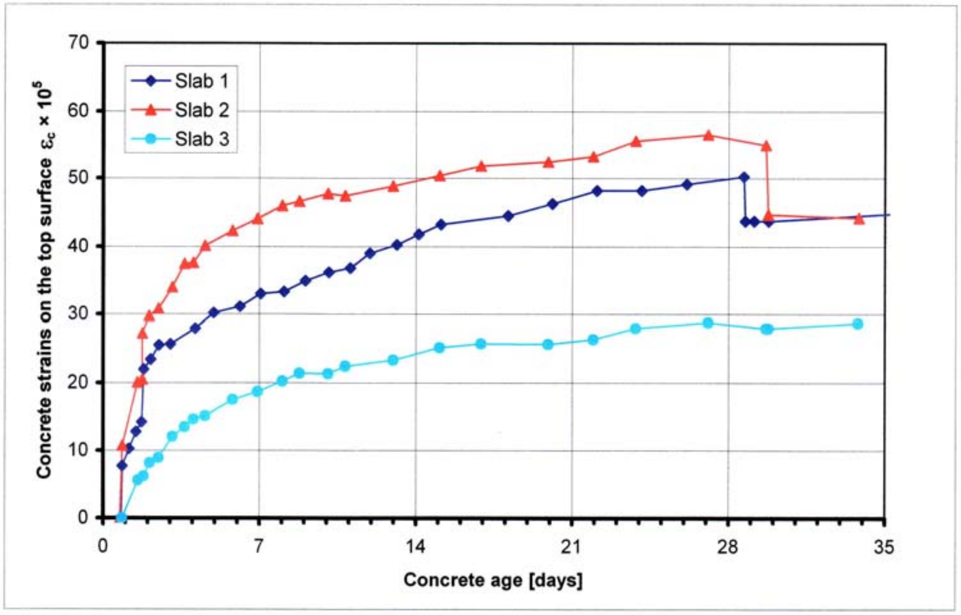

Figure 6 – Concrete strains on the top surface

The compressive strength of concrete at the first stage of prestressing was equal to 18.2 MPa (cylindrical samples) and at the second (final) stage of prestressing was equal to 26.9 MPa (cylindrical samples). The modulus of rupture of concrete was equal to 3.3 MPa at first and 4.4 MPa at second stage of prestressing. The secant modulus of elasticity of concrete was equal to 23 GPa, 28 GPa and 37,5 GPa after 24 hours, 48 hours and 28 days respectively.

The distributions of concrete strains measured on the top surface of tested slabs are presented in Figure 6. The readings has been done by means of standard DEMEC type 200 mm strain gauges. The measuring points were located at the distance 200 mm in three lines in the longitudinal direction.

The distributions of shrinkage and thermal strains measured at three levels of middle span cross-section: 20 mm above the bottom surface, mid-depth of slab and 20 mm under the top surface (monitoring only on the Slab 3) are presented at the lower part of Figure 7. The complete concrete strains including the thermal, shrinkage and creep strains are presented at the upper part of Figure 7 (Slab 2). Creep strains, calculated from deduction the mentioned above results (thicker lines) are also presented in this figure.

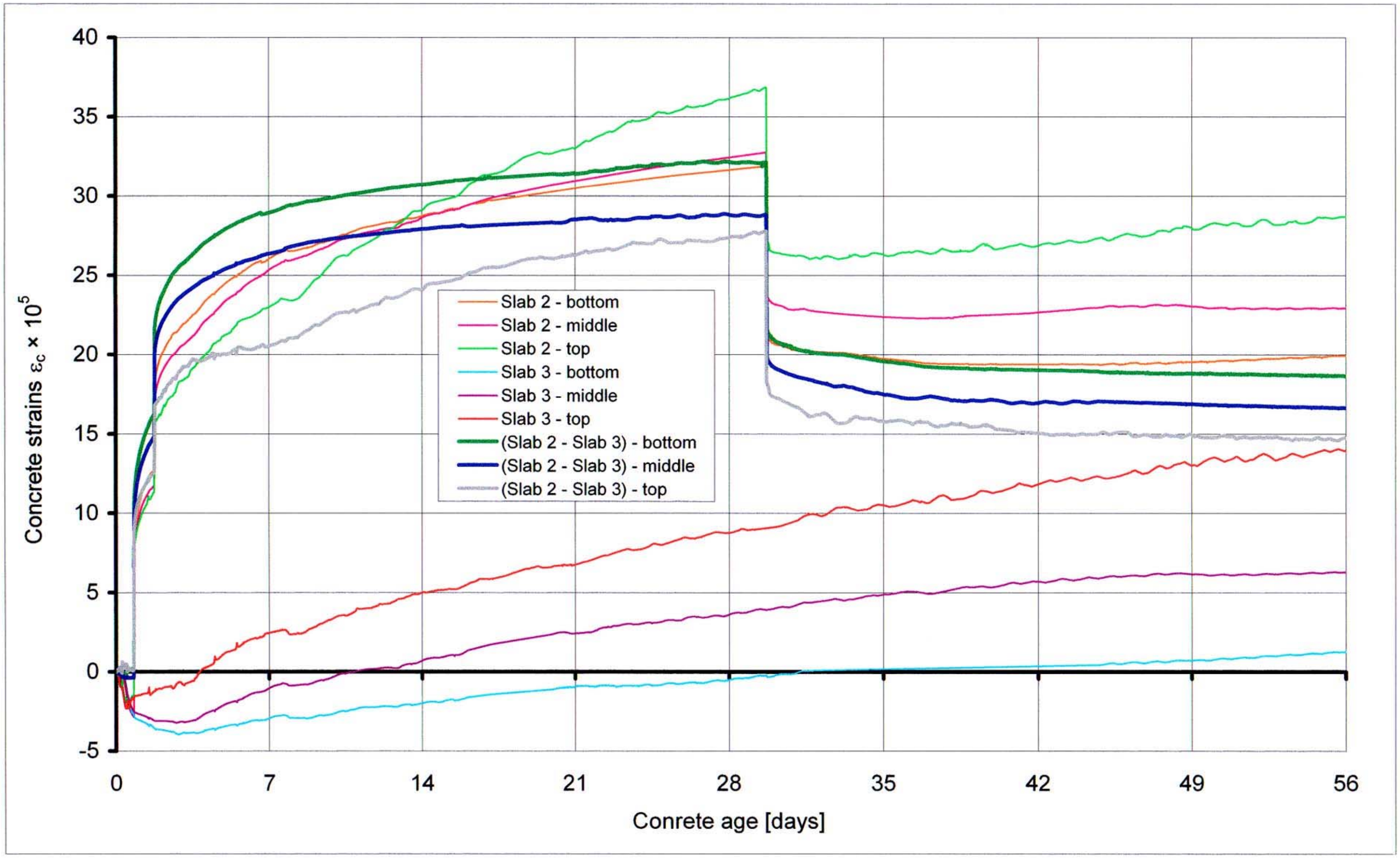

Figure 7 – Development of concrete strains at three levels of middle span cross-section

Table 3 – Instantaneous and time-dependent concrete strains $\square_c \times 10^5$

Sample number - depth	Loading I stage		Time-dependent I stage		Loading II stage		Time-dependent II stage		Unloading	
	start	end	start	end	start	end	start	end	start	end
Slab 2 -bottom	-2.4	7.6		12.7		18		31.9		21.3
Slab 2 - middle	-2.8	7.1		11.8		16.9		32.7		23.8
Slab 2 - top	-1.5	7.1		11.4		15.7		37.1		27.3
Slab 3 - bottom	-2.7			-3.6				-0.2		
Slab 3 - middle	-2.5			-3.1				3.9		
Slab 3 - top	-1.6			-1.2				9.2		

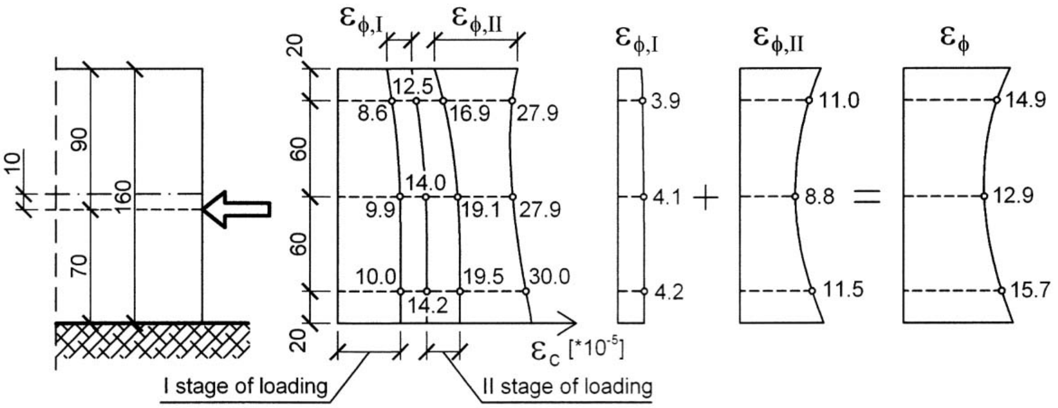

Figure 8 – Instantaneous and creep strains due to prestressing of Slab 2

The strains values of concrete at the three levels on cross-section of Slab 2 and Slab 3 measured during the investigation are listed in Table 3. Based on these values the distributions of concrete strains (instantaneous and time-dependent) recorded in each stage of prestressing and between them on cross-section are presented in Figure 8.

The creep coefficient □ (equation (1)) depends on the moisture content that is different at the top and the bottom surfaces. Unfortunately, it has no possibility to measure these parameters to calculate sustained modulus. As described in the preceding paragraph 2.3 the sustained modulus values maybe obtain from the known stresses (from prestress) and the observed deformations at any time.

Taking into consideration the concrete stress equal to 2.96 MPa and concrete strains (after 28 days) equal to 28.7×10^{-5} (Figure 8) at the top surface, it has calculated sustained modulus equal to 10.3 GPa. Similarly, from concrete stress equal to 6.61 MPa and concrete strains equal to 31.0×10^{-5} at the bottom surface, it has received sustained modulus equal to 21.3 GPa. Obtained values of sustained modulus are lower than ones suggested by ACI Committee 325 for determination the cross-section distribution of long time stresses due to prestress and warping in the design of prestressed pavements. It should be emphasis that in laboratory testing there are no environmental conditions.

The investigations have shown that it is possible to post-tension the concrete pavements after 20 hours from casting. In spite of so early tensioning in case of concrete with high secant modulus of elasticity, it is possible to sustain small instantaneous concrete deformations. In our case it was 1.2 mm in the first stage and 0.62 mm in the second stage of prestress (Figure 9).

Further investigations in situ are needs to evaluate the influence of curling, moisture and thermal effects as well as the influence of two-directional post-tensioning on time-dependent strains and prestress losses.

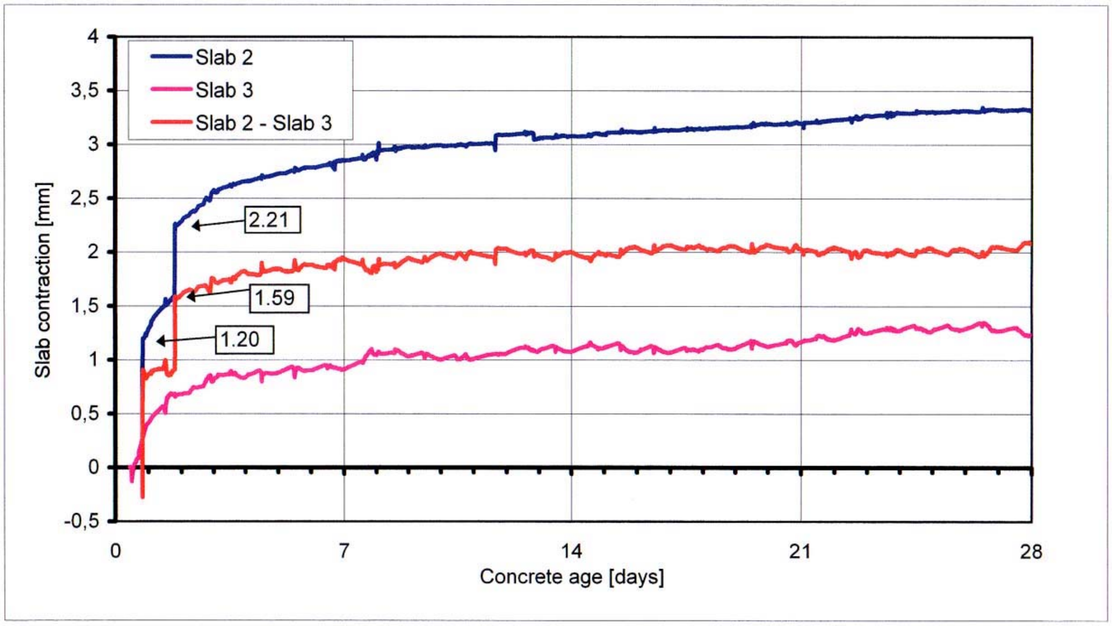

Figure 9 – Contraction of slab 2 and slab 3

REFERENCES

ACI Committee 325 (1988) “Recommendations for Designing Prestressed Concrete Pavements”. ACI Structural Journal, July-August 1988, pp 451-471.

SARGIOUS, Michael; GHALI, Amin (1986) “Stresses in Prestressed and Nonprestressed pavements and Slabs On Grade Due to Differential Shinkage and Creep”. ACI Journal, September-October 1986, pp 772-776.

SZYDŁOWSKI, Rafał (2005) “Strains of early-age concrete due to prestress”. 6th PchD Students of Building Depratments Conference, Gliwice-Wisła, November 17-18, 2005. Zeszyty Naukowe Politechniki Śląskiej, Budownictwo, z.104, 2005, pp 347-354 (in polish).

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