DETERMINATION OF SHRINKAGE STRESSES IN CONCRETE FLOOR COATINGS

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ABSTRACT

Durability of concrete floors is a major problem in many industrial facilities nowadays. Particular attention is paid to the wear resistance of floors and different surface hardeners are used to improve this property. There are situations where floor surface separates from the subbase and delamination takes place. Surface hardeners and subbases have different shrinkages, which should be taken into consideration as one of the reasons that can weaken floor structure.

The aim of this study was to explore the shrinkage of different surface hardeners, to calculate shrinkage stresses and to compare them with the shrinkage of concrete. Determination of shrinkage was carried out by two methods: length change measurement and semi-destructive hole-drilling according to the standards ASTM C490 and ASTM E837-08, respectively. Shrinkage stresses depend on the modulus of elasticity and Poisson's ratio of hardeners which affect shrinkage stresses in the system subbase-coating.

Test results showed that surface hardeners had higher shrinkage than plain concrete. The difference in shrinkage stresses becomes more significant when a surface hardener is poured onto the hardened subbase.

Key words: shrinkage stresses, surface hardeners, concrete floors, length change measurements, hole-drilling method

INTRODUCTION

High quality surface hardeners are applied on the concrete floor base to prolong the floor's service life. Solid waste management has the highest requirements for floors because continuous friction with heavy machinery and contact with different chemical compounds take place. These processes accelerate deterioration of the quality of most common concrete floors. Frequent repair and maintenance are expensive, not to mention the holdups of business activity (Kurtz, 1998).

During solidification of mixtures tensile shrinkage stresses are induced, which can cause crack formation and surface layer delamination.

A dry-shake hardener is applied to freshly poured concrete and rubbed into complete monolithic surface. Since a dry-shake hardener consists of quartz sand and cement, it can be assumed that its shrinkage takes place similarly to that of concrete.

Shrinkage of concrete can be divided into two different stages: early and late age shrinkage. Early stage shrinkage of concrete is defined as the first 24 hours when fresh concrete is cast. Later age, or long term shrinkage, refers to volume changes of concrete after 24 hours (Holt, 2001).

Early stage shrinkage can be divided into two types: plastic and autogeneous. Plastic shrinkage takes place in the first hours of curing when the evaporation speed of water is higher than the speed of the migration of water from the inside to surface. Bleed water rises to concrete surface and is exposed to the environment and evaporation. Long term shrinkage can be divided into three types: autogeneous, drying, and carbonation. Autogeneous shrinkage is defined as volume change of concrete without moisture transfer to the surrounding environment. Drying shrinkage is decrease of concrete volume caused by water loss. Early stage drying shrinkage can be reduced by proper curing conditions and surface handling, ensuring stronger finish and uniform hardening. Carbonation occurs when cement paste in hardened concrete reacts with moisture and carbon dioxide in the air.

Three series of specimens were prepared using different dry-shake hardeners and a mixture was made by adding water to powder. The dry-shake hardeners used in the experiments were Qualitop Master (QT) and Qualidur Premix (QD) by Rocland (Qualitop, 2010; Qualidur, 2010) and Monoshake TF (MS) manufactured by DCP Baltics (Monoshake TF, 2006). One series of specimens were prepared from industrial concrete class C25/30 (PC). Shrinkage strain was investigated for different materials (mixtures). The moduli of elasticity and Poisson's ratios for hardeners and for concrete and the calibration coefficients of the hole-drilling method rosette were determined for calculation of shrinkage stresses.

EXPERIMENTAL PROCEDURE AND METHOD

Specimens were prepared according to the standard (ASTM C490, 2008). Measurements of the specimens were (75×75×285) mm^3. A special mould has been designed and manufactured from plastic and was used to cast these specimens. Gauge studs were fixed to each end of a specimen for measurement of length change. Each mould was equipped by the end plate to hold the studs properly in place during the curing period. The gauge length between the bottom ends of the studs was 250 mm.
The measuring equipment (Fig. 1) was designed and manufactured for determining the length change of the specimens.

Figure 1. Equipment for measuring the length change of the specimens

Length change was measured by the digital dial gauge *Mitutoyo ID-C112B* to 0.001 mm.
Four series of experiments were carried out, each consisting of 12 specimens. One series of specimens were prepared from industrial concrete class C25/30. The water/cement ratio was 0.5. Mix details of concrete are presented in Table 1.

Table 1

Mix details of PC

Material	Quantity
Cement CEM II A-T 42.5 R	344.5 kg/m^3
Sand	1124.0 kg/m^3
Gravel, 4-12 mm	482.7 kg/m^3
Gravel, 8-16 mm	394.0 kg/m^3
Water	172.1 dm^3

For calculation, the needed moduli of elasticity and the Poisson's ratios of the investigated hardeners and concrete were determined. Wire strain gauges with a length of base 20 mm, resistance 200 Ω and gauge factor 2.0 were glued in the longitudinal (LSG) and transverse (TSG) directions onto the two opposite sides of the specimen (see Fig. 2 a). The specimen was loaded up to 49 kN by the compressive testing machine *П-20*. (Fig. 2 b).
The hole-drilling method was used to check the results obtained by measuring length change. This is one of the most widely used semi-destructive methods for determining residual and shrinkage stresses (ASTM E837-08, 2009). Relieved strains were measured with a strain gauge rosette (SGR) (*Vishay Micro-Measurements EA 06-125RE-120*) which was glued onto the specimen with the two-component adhesive *M-Bond 200* and a hole was drilled through the geometric centre of the rosette (Fig 3a). The rosette was wired and connected to the *Vishay Strain Indicator and Recorder Model P3*. The specimen was placed in a rig which had been specially designed and manufactured for this study (Fig. 3b).

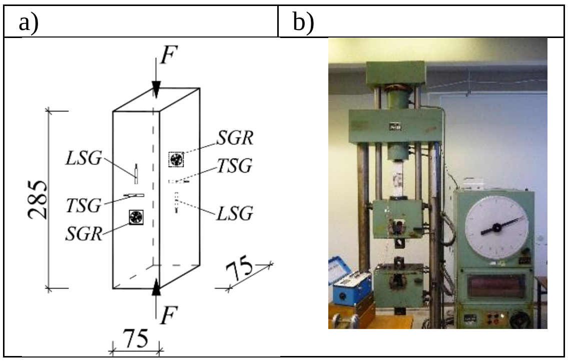

Figure 2. Scheme (a) and photo (b) of the compressive test

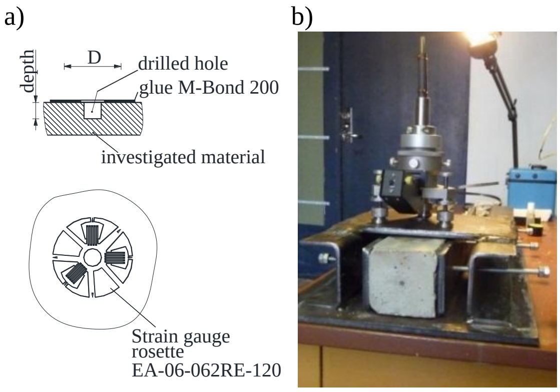

Figure 3. The hole-drilling technique (a) and rig for fixing a specimen (b)

Calibration constants $\bar{a}$ and $\bar{b}$ for the SGR *EA 06-125RE-120* were calculated according to the standard (ASTM E837-08, 2009) from the measured strains obtained from the compressive test. The maximum load was 49 kN (stress 8.71 N/mm^2). Loading was done before and after drilling a hole into SGR. Hole drilling was conducted using a 1.53 mm increment and the hole was drilled to a depth of 4.59 mm, i.e. corresponding to three increments. After each increment the readings were allowed to stabilize for 120 seconds before recording. The obtained values of calibration constants are presented in Table 2. Constants are necessary for calculation of residual stresses, because they are dependent on material properties.

RESULTS AND DISCUSSION

The major part of this study was carried out within a Master's course. The duration of shrinkage was 60 days. In this period of time the shrinkage of concrete is 80% (Holt, 2001). During measurements the humidity and temperature in the storage room remained uniform for 60 days. Thereafter, central heating was turned off for the spring season and the conditions of the storage room affected the results of measurements.

In the case of short term measurements, experimental data can be approximated by the following analytical equation (1) (Kiviste, 2011)

$$s(t) = c_1 \cdot \ln\left(1.0 + t^{c_2}\right), \quad (1)$$

where t – time, days;
c_1, c_2 – dimensionless parameters.

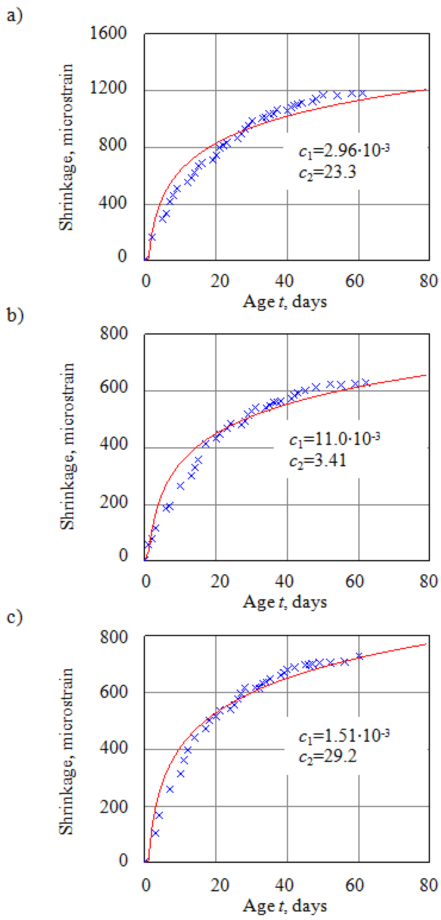

Figure 4. Experimental data and the curve of approximation for the specimens cast from a) MS; b) QT; c) QD

The purpose was to find unknown constants so that the measured displacements $s(t)$ could be approximated in the best way. This problem was solved by using the regression function *genfit (vx, vy, vg, F)* of the mathematical program *Mathcad 15.0* (Makarov, 2008).

The results of the measurements and the approximation curves are presented in Figs. 4 and 5.

The specimens of QT and QD did not practically reveal changes in shrinkage, but the shrinkage of MS was about two times as high at the same age.

The shrinkage of PC was the smallest compared to the shrinkage of surface hardeners. It can be seen that the values of the currently studied shrinkage strain of the hardeners QT and QD and the values of the previously investigated shrinkage strain of concrete containing 0.51% of crimped steel fibres are practically similar, see paper (Kiviste, 2011).

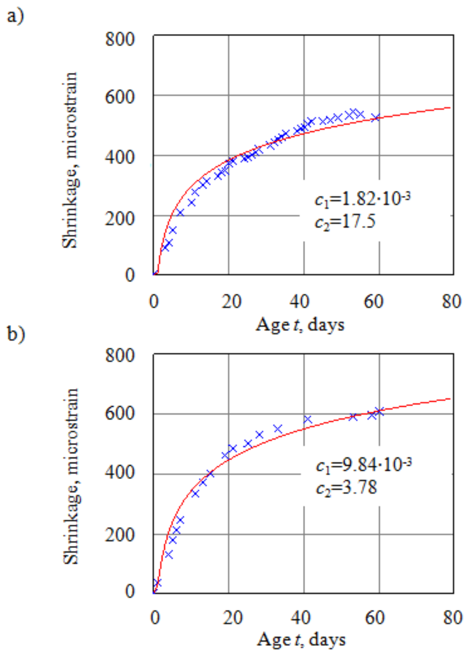

Figure 5. Experimental data and the curve of approximation for the specimens cast from a) PC; b) PC containing crimped fibres 0.51%

Consequently, this kind of hardener on fibre reinforced concrete floor has small shrinkage stresses.

Note that the determined numerical values of hardeners can be used for determining shrinkage stresses on concrete floors covered with surface hardeners.

It is evident that the determined moduli of elasticity and Poisson's ratios are quite similar, whereas the calibration coefficients differ to some degree.

We assume that in the case of free shrinkage the stresses of specimens are absent (i.e. equal to zero). However, as we measured 1.59 N/mm^2 in the surface layer of MS, 0.48 N/mm^2 in the surface layer of QT, -0.25 N/mm^2 in the surface layer of QD and 0.48 N/mm^2 in the surface layer of PC, using hole drilling. The results are measured in the surface layer because the hole depth is relatively small compared to specimen dimensions. The results remained within experimental uncertainty except one MS, they can be taken equal to zero in the following example of applications.

Table 2

Determined modulus of elasticity, Poisson's ratio and calibration coefficients $\bar{a}$ and $\bar{b}$ for the type of rosette used

Material	Modulus of elasticity E, GPa	Poisson's ratio μ	Depth/D = 0.45	
			$\bar{a}$	$\bar{b}$
MS	21.9	0.14	0.259	0.569
QT	26.9	0.19	0.222	0.625
QD	26.9	0.19	0.381	0.822
PC	27.1	0.19	0.346	0.717

EXAMPLE OF APPLICATIONS

For example, shrinkage stresses in the system subbase (concrete floor) – coating (hardener) can be calculated after a certain number of days have passed from pouring, assuming that shrinkage stresses are distributed uniformly through the coating and subbase (Fig. 6).

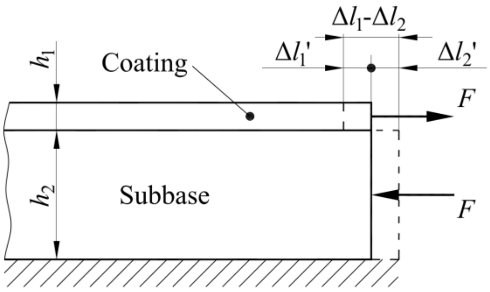

Figure 6. A fragment of the edge region of hardened concrete floor and formation of F generated by shrinkage

Shrinkage strain of the system subbase-coating

$$\Delta\varepsilon = \frac{\Delta l_1 - \Delta l_2}{l}, \tag{2}$$

where Δl_1 – shrinkage of coating;
Δl_2 – shrinkage of subbase.

Such differential shrinkage rate usually produces tensile stresses which are relieved by cracking of the coating.
Compatibility equation (3) in the case of equilibrium of the initial forces assuming that Poisson's ratio $\mu_1 = \mu_2 = \mu$ (valid condition $\Delta l_1 - \Delta l_2 = \Delta l'_1 + \Delta l'_2$) yields

$$\Delta\varepsilon = F\left(\frac{1-\mu}{E_2 h_2} + \frac{1-\mu}{E_1 h_1}\right), \tag{3}$$

where F can be calculated and the shrinkage stresses per unit width of the hardener and the floor are expressed as equation (4)

$$\sigma_1 = \frac{F}{h_1}, \quad \sigma_2 = -\frac{F}{h_2}, \tag{4}$$

where σ_1 – shrinkage stress in coating, N/mm^2;
σ_2 – shrinkage stress in subbase, N/mm^2.

Stress gradients are induced between the surface hardener and the substrate, however, arising stresses have unequal values due to the different cross-sections of the hardener and the substrate. Stress gradients diminish when a surface hardener is applied onto freshly poured concrete. Again, the smaller is the difference between the shrinkage of coating and subbase, the lower shrinkage stresses arise. The purpose is to minimise differential shrinkage stresses.
When the hardener QD was set on a fresh plain concrete floor the obtained shrinkage stresses were after 60 days of pouring: σ_1 = 5.7 N/mm^2 (tensile), σ_2 = 1.1 N/mm^2 (compressive).
The preceding results were obtained, when h_1 = 15 mm, h_2 = 80 mm, Δl_1 = 0.182 mm, Δl_2 = 0.131 mm, μ = 0.19, $E_1 = 26.9\cdot10^3$ N/mm^2, $E_2 = 27.1\cdot10^3$ N/mm^2.
Calculated (tensile) stresses are quite close to the coating's flexural strength (8 N/mm^2) (Qualidur, 2010). This is one of the main reasons why cracks are induced.

CONCLUSIONS

The following conclusions were made on the basis of the experiments:

- The shrinkage of concrete was the least compared to the shrinkage of surface hardeners. This is the reason why tensile shrinkage stresses arise in concrete floors coated with surface hardeners.
- Formation of shrinkage stresses can be postponed by reducing plastic shrinkage, which emerges during the first hours when concrete is in the liquid state. Faster evaporation of water causes larger shrinkage and hence higher shrinkage stresses.
- The modulus of elasticity, the Poisson's ratio, calibration coefficients $\bar{a}$ and $\bar{b}$ for the type of rosette used were determined.
- An example of applications is presented where presumable stresses are calculated in QD and PC.
- This analysis was limited to the data obtained from the above described experiments.

ACKNOWLEDGEMENT

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