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# Shrinkage and Swelling of Concrete without Capillary Condensed Water

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## Abstract

Different types of cement-based mortars have been prepared and then impregnated with liquid silane. Water desorption and adsorption branches of the sorption isotherm have been measured on both untreated and water repellent mortar specimens. Water repellent treatment prevents filling of capillary pores by capillary condensation. Pore walls of capillaries are covered by a film of silicon resin. At relative humidity close to 100 % a small amount of water can be stored in coarse capillary pores. Nano-pores in the gel built up by the hydration products can not be treated in the conventional way because of geometrical mismatch of pore size and silane molecules.

Shrinkage of untreated and water repellent mortar is practically identical. This means that capillary condensed water has little, if any, influence on hygral length change of cement-based materials. These findings are in good agreement with predictions of the Munich model. According to this model shrinkage is controlled by the colloidal interaction between water and the gel particles of the hydration products. This interaction is at the origin of a disjoining pressure which depends on the relative humidity of the surrounding air. According to the results presented in this contribution disjoining pressure is independent on the presence of cappilary condensed water.

**Keywords:** Shrinkage, Swelling, Water repellent treatment, Capillary condensation, Disjoining pressure, Munich model.

## *Schwinden und Quellen des Betons ohne kapillar kondensiertes Wasser*

## *Zusammenfassung*

*Unterschiedliche Zement gebundene Mörtel wurden hergestellt und ein Teil der Proben wurde mit flüssigem Silan imprägniert. Die Desorptionsäste und die Adsorptionsäste der Wasser-Sorptionsisotherme wurden an unbehandelten und hydrophobierten Proben experimentell bestimmt. Wie vorherzusehen, konnte festgestellt werden, dass die Kapillarporen in hydrophobierten Proben nicht durch Kapillarkondensation gefüllt werden können. Die Wände der Kapillarporen sind mit Silkonharz bedeckt. Bei einer relativen Feuchtigkeit nahe bei 100 % kann in groben Poren dennoch eine kleine Menge Wasser gespeichert werden. Die Nanoporen, die während der Hydratation des Zements im Zementgel entstehen, können mit dem verwendeten Silan wegen seiner Molekülgröße jedoch nicht hydrophobiert werden.*

*Das Schwinden unbehandelter und hydrophobierter Mörtelproben ist nahezu identisch. Das bedeutet, dass der kapillare Unterdruck des kapillar kondensierten Wassers, wenn überhaupt, nur einen vernachlässigbar kleinen Einfluss auf das Schwinden Zement gebundener Werkstoffe wie Mörtel und Beton hat. Diese Ergebnisse sind in guter Übereinstimmung mit den Aussagen des Münchner Modells. Nach diesem Modell ist Schwinden die Folge einer kolloidalen Wechselwirkung zwischen den Gelpartikeln der Hydratationsprodukte und dem Wasser. Diese Wechselwirkung manifestiert sich in Form eines Spaltdruckes zwischen den Gelpartikeln und dieser Spaltdruck hängt von der relativen Feuchtigkeit der umgebenden Luft ab. Der Spaltdruck ist danach auch unabhängig davon, ob kapillar kondensiertes Wasser im porösen Gefüge existiert oder nicht.*

***Stichwörter:*** *Schwinden, Quellen, Hydrophobieren, Kapillarkondensation, Spaltdruck, Münchner Modell*

## 1 Introduction

Water repellent treatment of a porous material such as mortar or concrete changes the usual interaction between the porous system and the humidity of the environment substantially. Quite different aims can be achieved by surface treatment of porous building materials with a water repellent agent. As capillary suction is reduced considerably, uptake of water and salt solutions can be minimised. As a consequence frost resistance is enhanced. If the penetration depth of the water repellent agent is sufficient a chloride barrier can be built up by water repellent treatment [1].

Obviously the average moisture content of a structural element of reinforced concrete in hygral equilibrium with a given climate can be reduced by water repellent surface treatment. This has been studied by numerous authors in the past (see for instance [2, 3]). The influence of water repellent treatment on shrinkage and swelling, however, has widely been neglected so far.

There are at least two reasons why we should know more about hygral length changes after water repellent treatment: (1) If shrinkage is reduced to the same extent as moisture content, high shear stresses have to be expected in the interface between the water repellent treated und the untreated zones in mortar or concrete. These stresses could create cracks and finally could lead to spalling off of the surface near zone. This process has been used frequently to explain damage observed on natural stone monuments after treatment with water repellent agents. Does this also happen in concrete? (2) Water repellent treatment changes the distribution of the absorbed water in a characteristic way. Capillary condensation essentially is prevented. Reliable experimental results may allow us to better understand shrinkage mechanisms and to verify or falsify existing hypotheses on the origin of shrinkage.

In this contribution results of test series to study water sorption and shrinkage of water repellent treated and untreated mortar specimens shall be presented and discussed.

## 2 Experimental

### 2.1 Adsorption and Desorption

The sorption isotherm describes well the hygral interaction between a porous material and the surrounding air with respect to variations of relative humidity. The time to reach hygral equilibrium of cement-based materials with usual dimensions is comparatively long and it is well known that there is a marked hysteresis between the adsorption and the desorption branch. Therefore thin slices of mortar with a thickness of 5 mm and a water-cement ratio of 0.45 have been prepared. Half of the mortar specimens have been impregnated with silane. Part of the water repellent and of the untreated specimens were dried at 105 °C and the remaining part has been stored in water. Then the dry mortar slices have been placed in climate boxes with constant relative humidity and temperature until they had reached hygral equilibrium. The relative humidity has been kept constant by saturated salt solutions. Mortar specimens were placed stepwise in boxes with increasing relative humidity up to 100 %. The equilibrium moisture content has been measured at each fixed relative humidity by weighing the samples. In this way the adsorption branch of the sorption isotherm has been determined. The water saturated samples were placed in similar boxes, the relative humidity has been lowered stepwise. Again the equilibrium water content has been determined by weighing and in this way the desorption branch of the sorption isotherm has been obtained [4]

For a second test series, two types of mortar have been prepared. The water-cement ratio has been chosen to be 0.4 and 0.5 and river sand with a maximum aggregate size of 4 mm has been used [5]. All mortar slices have been preconditioned at RH = 60 %. Then half of the slices have been impregnated with silane. After polymerisation they were all placed in a climate box with RH = 96 % until hygral equilibrium had been reached. Finally the relative humidity has been lowered stepwise down to RH = 23 %. At each chosen relative humidity the specimens were kept until hygral equilibrium had been reached.

### 2.2 Shrinkage and Swelling

In order to study the influence of water repellent treatment on shrinkage and swelling five different types of mortar have been prepared. Cubes with an edge length of 150 mm have been cast with each type of mortar. The water-cement ratio and the cement content of the mortars are given in Table 1. River sand with a maximum aggregate size of 4 mm has been used. From each cube 12 cores with a diameter of 20 mm have been drilled. At the centre of both circular ends of the cylinders metallic measuring sockets for a dial gauge have been glued. In this way weight and length changes of the cylinders while exposed to air with different relative humidity could be measured.

**Table 1:** Water-cement ratio and cement content of the five different types of mortar

| Notation | Water-cement ratio | Cement content kg/m$^3$ |
|---|---|---|
| A | 0.4 | 500 |
| B1 | 0.5 | 400 |
| B2 | 0.5 | 500 |
| B3 | 0.5 | 600 |
| C | 0.6 | 500 |

All cylinders were stored in water until an age of seven days. Then they were transferred to a climate box in which a relative humidity of 60 % was kept constant. Water loss and the length change have been measured as function of the drying time. After 40 days half of the cylinders were placed in liquid silane (isobutyltrietoxysilane) for 24 hours. This period was long enough to impregnate the volume of all cylinders completely. Impregnated and untreated cylinders were then kept in the box with RH = 60 % for another 100 days. This time was sufficient to reach hygral equilibrium and for complete polymerisation of silane. Then all cylinders were transferred to a box with RH=100 %. Swelling and water up-take of both water repellent and untreated mortar samples have been measured on water repellent and untreated cylinders.

The hygral length change and water loss have also been measured on the water repellent and untreated specimens of the second test series (W/C = 0.4 and 0.5) which were dried stepwise from RH = 96 % down to RH = 23 %.

## 3 Results and Discussion

### 3.1 Adsorption and Desorption

The sorption isotherms of the water repellent and untreated mortar with W/C = 0.45 are shown in Fig. 1 (see also [4, 6]). It can be clearly seen that the water repellent mortar absorbs less water than the untreated mortar. The difference is obviously more pronounced at high relative humidity. Above RH = 55 % water uptake of cement-based materials is essentially due to capillary condensation. Quite obviously most capillaries can not be filled with water after water repellent treatment. At a relative humidity close to 100 % a comparatively small amount of water can be taken up in coarse pores. The surface

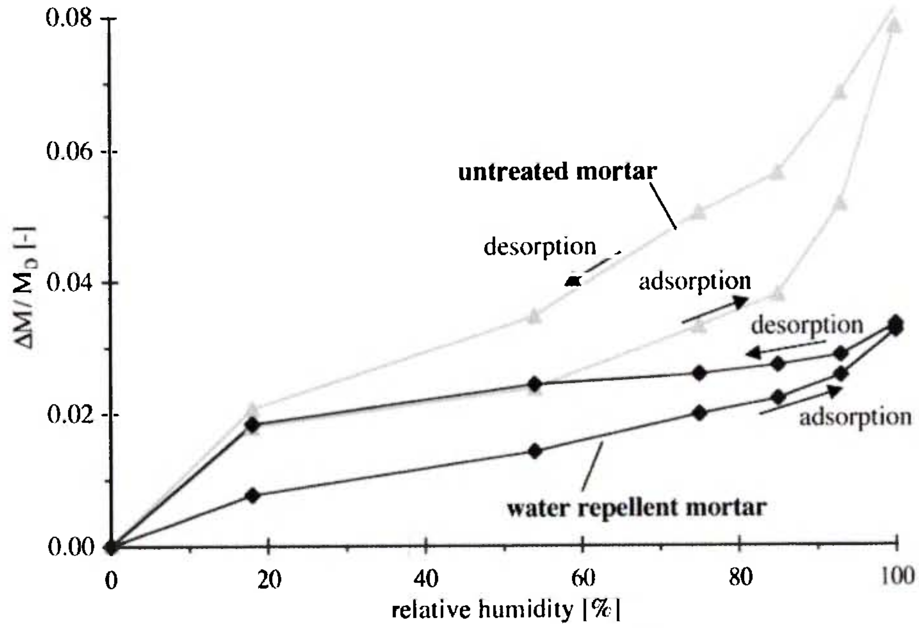

**Figure 1:** Sorption isotherms of water repellent and untreated cement mortar with W/C = 0.45

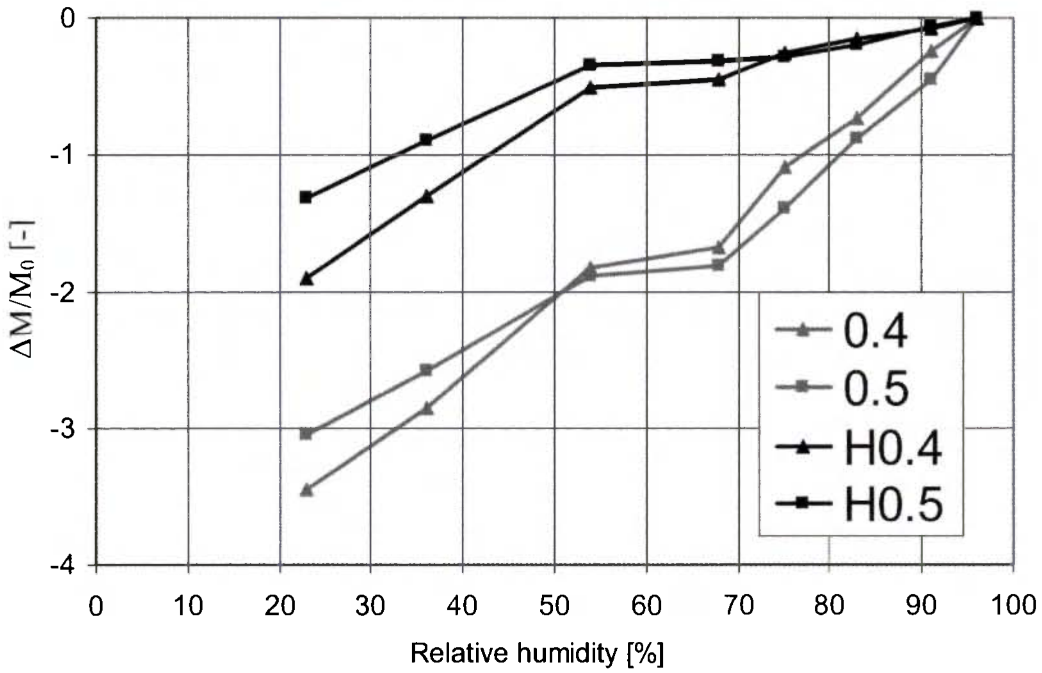

**Figure 2:** Desorption branch of the sorption isotherm of water repellent (H) and untreated mortar. Mortar specimens with W/C = 0.4 and 0.5 have been tested.

treatment which has been applied here most probably does not prevent water storage in coarse pores totally. We may imagine that the silicon resin film has a limited range of efficiency in a porous system and water droplets can be formed, in case they are sufficiently far away of a water repellent surface.

The desorption branch of mortar specimens with W/C = 0.4 and W/C = 0.5 after water repellent surface treatment and in the untreated state has also been determined experimentally. Results are shown in Fig. 2. It is quite obvious that in agreement with results shown in Fig. 1 water repellent mortar looses little water when drying from RH = 96 % to RH = 55 % takes place. If drying is continued, however, to even lower relative humidity, for instance down to RH = 23 %, water loss of water repellent and untreated mortar is nearly the same. A major difference of the desorption branches of the sorption isotherm of treated and untreated mortar is observed in the region of capillary condensation. Thus we may conclude that water repellent treatment essentially prevents capillary condensation of cement-based materials. This fact is also at the origin of the low hygral diffusion coefficient of water repellent mortar and concrete [7].

### 3.2 Shrinkage and Swelling

Five different mortars (see Table 1), water repellent treated and untreated, have been dried to equilibrium with RH = 60 %. Then they have been placed in a climate box with relative humidity close to 100 %. The water uptake and swelling have been measured until equilibrium had been reached [4]. Results are shown in Fig. 3 and Fig 4. As can be seen the water uptake of water repellent treated mortar is small compared to the uptake of the untreated companion specimens. This is in agreement with results shown in Fig. 1. The water uptake of the untreated mortar increases with increasing W/C and at the same W/C it increases with increasing cement content. This is a clear indication again, that in the high humidity range capillary pores of untreated cement-based materials are getting filled with water by capillary condensation. In the case of water repellent mortar, however, the available capillary space has a negligible influence on the amount of adsorbed water only. Most of the water repellent treated capillaries can not be filled with water. The interfacial energy between the coated pore walls and the water prevents capillary condensation as predicted by the Kelvin equation. In very large pores a comparatively small amount of water can still be stored.

Swelling of mortar as observed on the same mortar cylinders is shown in Fig. 4. At a first glance it may

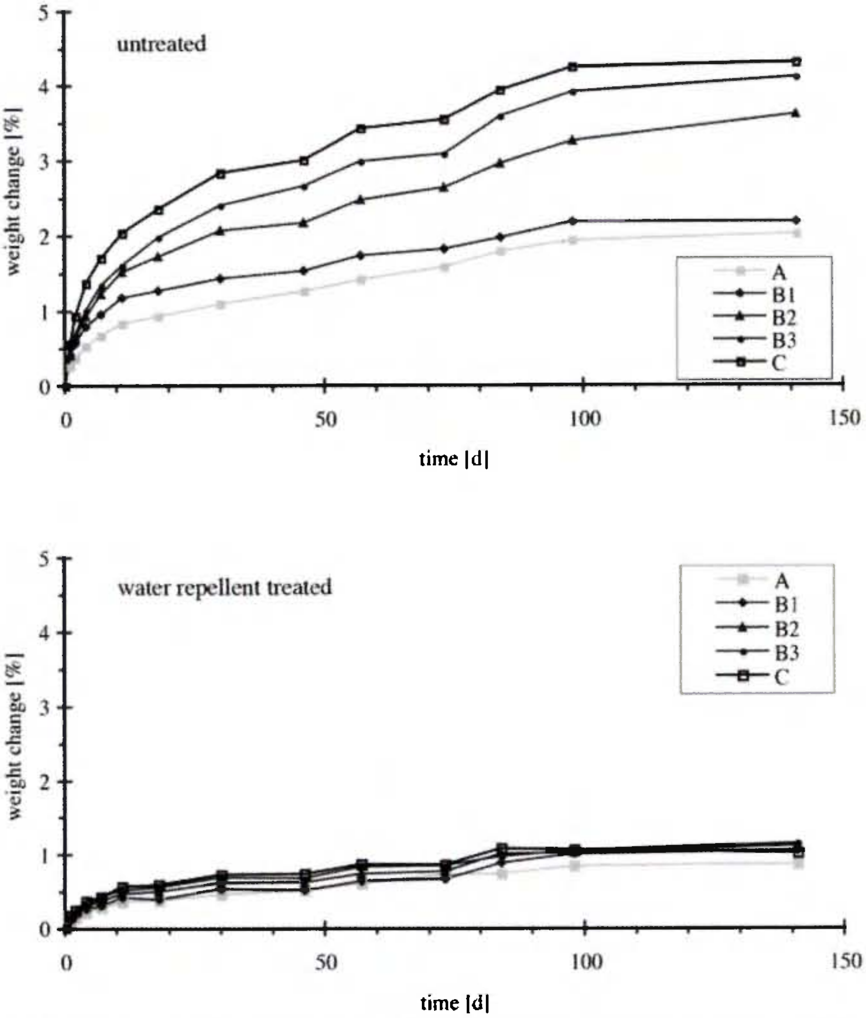

**Figure 3:** Water uptake of five different types of water repellent and untreated mortar samples, which were first equilibrated with a relative humidity of 60 % and then placed in a climate box with a relative humidity close to 100 %.

or ought to be surprising for many to see that swelling is nearly independent on the circumstance if capillary pores are being filled with water or not. From this observation we may conclude, however, that capillary absorbed water and capillary pressure have very limited influence on shrinkage or swelling if at all. The origin of hygral length changes must be explained essentially by the action of disjoining pressure in the nano-pores [8-13]. The disjoining pressure in the cement gel depends on the surrounding relative humidity [14-17]. Details of this complex interaction will be discussed elsewhere. Water repellent agents can in fact not interact with the nano-pores of the hydration products as silane molecules are geometrically too big ($d_S \approx$ 2.4 nm) and their interaction radius is even much bigger [18]. Therefore water repellent treatment has a small effect on shrinkage.

In Fig. 2 the desorption branches of water repellent and untreated mortar specimens with W/C = 0.4 and W/C = 0.5 are represented. On identical specimens shrinkage has been measured in the same humidity range. Results are shown in Fig. 5. Shrinkage values plotted in Fig. 5 represent hygral length changes in equilibrium with the indicated relative humidity. When drying from RH = 96 % to about RH = 68 % takes place, water repellent specimens show slightly less shrinkage than the untreated mortar while further drying down to RH = 23 % leads to identical shrinkage of all specimens which have been tested. Within the accuracy of the experiments, however, shrinkage of water repellent and untreated mortar can be considered to be practically the same for both types of mortar.

But most important, it can be seen again, that neither removal of water from capillary pores nor capillary condensation into the pore system have a significant influence on hygral length change of cement-based materials. Hygral length change is governed by colloidal interaction between pore water

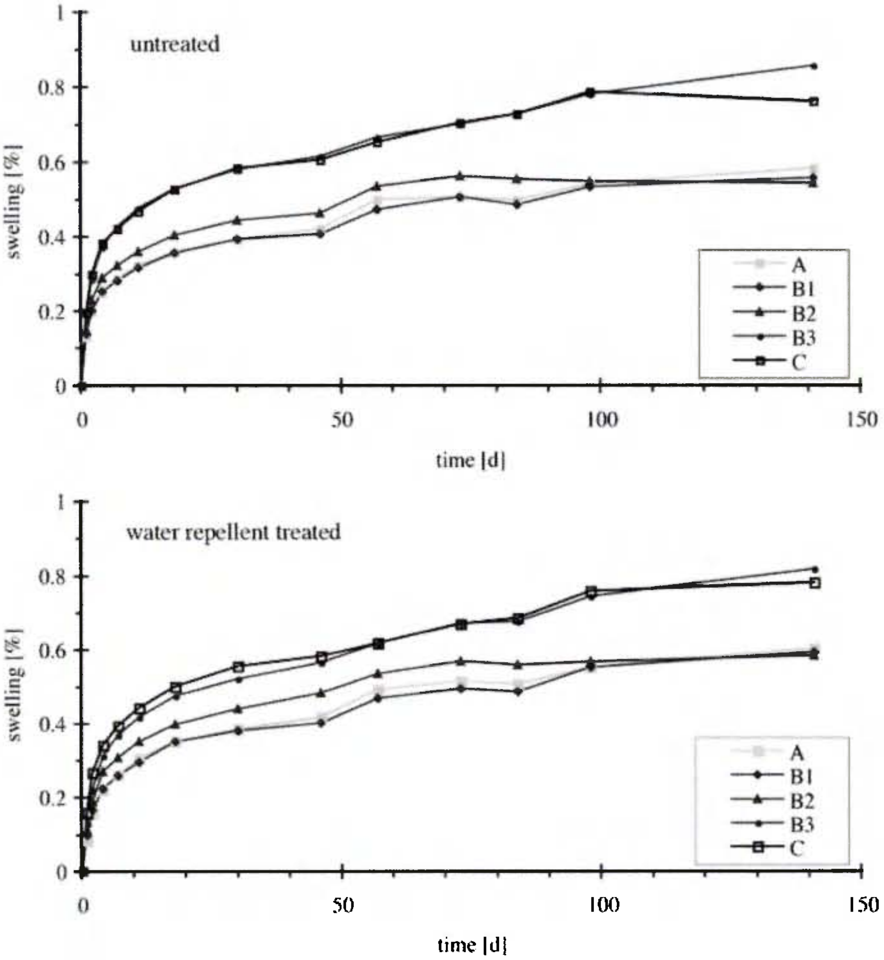

**Figure 4:** Swelling of water repellent treated and untreated mortar specimens when re-humidified from an equilibrium with RH = 60 % to RH 100%.

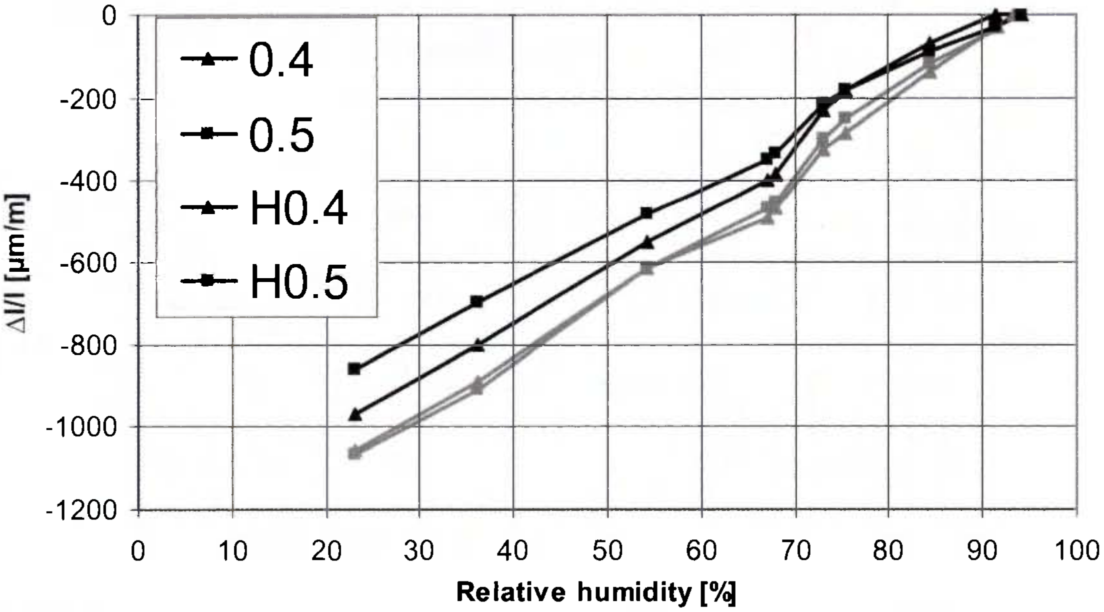

**Figure 5:** Shrinkage of water repellent (H) and untreated mortar with W/C = 0.4 and 0.5.

and the gel particles instead. This complex colloidal interaction can be characterised by a disjoining pressure. Disjoining pressure is a complex physical phenomenon which is composed of several surface interactions [16,17].

Due to the size of silane molecules nano-pores below a critical radius can not be treated with this water repellent agent. Disjoining pressure is the result of the complex interaction between water and the solid surfaces in nano-pores. After water repellent treatment coarsest nano-pores will not be water filled at high relative humidity just as capillary pores remain empty. As a consequence a disjoining pressure can not be established in coarsest nano-pores. This may be an explanation for the comparatively small difference of shrinkage observed on water repellent and untreated mortar specimens at relative humidity higher than 70 %.

## 4 Conclusions

Results presented in this contribution allow the following conclusions to be drawn:

- Water repellent treatment of cement-based materials prevents capillary condensation in mortar. A comparatively small amount of water can still be stored in the porous system at relative humidity close to 100 %.
- Molecules of water repellent agents such as silane are too big and therefore can not enter nano-pores because of geometrical incompatibility. In the untreated nanopores disjoining pressure can be built up.
- Shrinkage of cement-based materials is hardly influenced by water repellent treatment. It is practically independent of the presence of capillary condensed water. This is considered to be a strong indication that shrinkage of concrete is controlled by the disjoining pressure in the nano-pores of the hydration products and not by capillary under-pressure.

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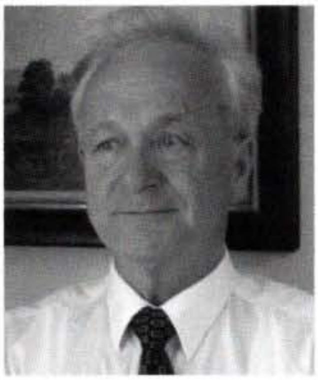

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