



# LUND UNIVERSITY

## Energy storage by repeated desorption and adsorption in hardened Portland cement paste

Fagerlund, Göran

1994

[Link to publication](#)

*Citation for published version (APA):*

Fagerlund, G. (1994). *Energy storage by repeated desorption and adsorption in hardened Portland cement paste*. (Report TVBM (Intern 7000-rapport); Vol. 7072). Division of Building Materials, LTH, Lund University.

*Total number of authors:*

1

### General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

### Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117  
221 00 Lund  
+46 46-222 00 00

CODEN: LUTVDG/(TVBM-7072)/1-14/1994

---

ISSN 0348-7911

**ENERGY STORAGE BY REPEATED DESORPTION AND  
ADSORPTION IN HARDENED PORTLAND  
CEMENT PASTE**

Göran Fagerlund

Report TVBM-7072  
Lund March 1994

---

<b>Content</b>	<b>Page</b>
1. Preface	1
2. Theoretical principles	1
3. Energy storage capacity	4
3.1 Storage in pure cement gel	4
3.2 Storage in cement paste	4
4. The design of a sorption heat storage	7
5. Solar energy	9
References	9
Figures	10
Appendix: Some comments on economy	12

## 1. Preface

The high internal specific surface of so-called cement gel which is the hydration product of portland cement might make hardened portland cement paste a suitable material for long-term storage of heat by repeated desorption and sorption of water vapour. As shown in the report the specific surface of cement gel is about  $1,8 \cdot 10^5$  m<sup>2</sup>/kg of dry cement paste. Other measurements indicate an even bigger specific surface. The energy storage potential in 1 m<sup>3</sup> of cement gel therefore is about  $9 \cdot 10^5$  kJ. This corresponds to the energy in 23 litres of fuel oil. The values are based on a heat of adsorption that is calculated from the sorption isotherm assuming the BET-equation can be applied. The true value of the heat of adsorption might be measured directly by calorimetry.

It is also assumed that no severe ageing of the cement paste takes place during the years the energy storage is used, decreasing its specific surface. Such a mechanism is carbonation that might cause a coarsening of the cement gel.

A cement paste energy storage must probably be designed as a honeycomb structure consisting of thin cement paste walls enclosing channels through which dry or moist air is flowing, either loading the storage or unloading it. Loading might be achieved by a solar energy collector.

No analysis is made in the report of the economical and technical feasibility of an energy storage based on sorption in cement paste. Some simplified reasoning concerning economy is however made in the Appendix.

The report except the Appendix is in essence a translation of an unpublished manuscript that was written in Swedish already in 1985; /1/.

## 2. Theoretical principles

The internal surface of so-called *cement gel* in mature portland cement paste accessible to adsorption of water vapour is very large. It is of the order of size  $2 \cdot 10^5$  m<sup>2</sup> per kg of cement gel. The amount of adsorbate on the internal surface at equilibrium depends on the surrounding relative humidity ( $p/p_s$  or RH). It is described by the sorption isotherm the appearance of which is shown in Fig 1 for a certain cement paste at different degrees of hydration. The quantity  $V_m$  in kg per kg of dry material is the amount of adsorbate corresponding to the situation where the entire internal surface is covered by one monolayer of adsorbate. This corresponds to a RH of about 18 % irrespectively of the water/cement ratio and age of the cement paste. The quantity  $w$  in kg per kg of dry material is the amount of adsorbed water vapour at the actual RH.

A mature cement paste with a w/c-ratio of 0,39 will at the maximum possible hydration consist only of fine-porous cement gel. The adsorption in such a paste is described by the so called *gel isotherm* shown by the dashed curve in Fig 1. The number of adsorbed layers is about 4 at full saturation occurring at 100 % RH. In younger cement pastes, that are not fully hydrated or in cement pastes with w/c-ratio above

0,39, there are also coarser pores, so-called *capillary pores*, in which capillary condensation occurs. Therefore, a larger number of adsorbed layers can develop in such pastes. This does, however, not mean that the amount of adsorbate is bigger in

such pastes; viz. the total internal surface area increases with increasing amount of hydration products -cement gel. Therefore, the internal surface area increases with increasing amount of cement, i.e. with decreasing w/c-ratio of the cement paste. The relation between the water/cement ratio and the specific surface is treated in section 3.

The sorption isotherm can be described by the BET-equation:

$$w/V_m = C \cdot \Phi / (1 - \Phi) \cdot (1 - \Phi + C \cdot \Phi) \quad (1)$$

Where

$w$	the adsorbed water (kg per kg of dry material)
$V_m$	the monolayer capacity (kg per kg of dry material)
$\Phi$	the relative humidity ( $0 \leq \Phi \leq 1$ )
$C$	the "adsorption coefficient"

The adsorption coefficient  $C$  depends on the heat of adsorption of the first monolayer. Since  $w_a/V_m = 1$  at  $\Phi = 0,18$  (see Fig 1), the coefficient  $C$  obtains the value 21.

The coefficient  $C$  is related to the heat of adsorption  $E_1$  of the first adsorbed monolayer; /2/:

$$C = \exp\{(E_1 - L)/(R \cdot T)\} \quad (2)$$

Where

$L$	the heat of vapourization of bulk water ( $4,06 \cdot 10^4$ kJ/kmole)
$R$	the gas constant (8,314 kJ/kmole)
$T$	The absolute temperature (K)

With the values  $C=21$  and  $T=293$  K ( $20^\circ\text{C}$ ) inserted one obtains:

$$E_1 = 4,80 \cdot 10^4 \text{ kJ/kmole}$$

This means that the heat of adsorption of the first monolayer is larger than the heat of condensation of water vapour to liquid water which is  $4,06 \cdot 10^4$  kJ/kmole. The adsorbed water molecule in the first monolayer is therefore bound firmer to the surface than in bulk water. The heat of adsorption  $E_1$  more closely corresponds to the direct condensation (sublimation) of water vapour to ice. The heat of condensation  $E_{g \rightarrow s}$  of this transformation is:

$$E_{g \rightarrow s} = E_{g \rightarrow l} + E_{l \rightarrow s} = 4,06 \cdot 10^4 + 0,60 \cdot 10^4 = 4,66 \cdot 10^4 \text{ kJ/kmole} \quad (3)$$

Adsorption in the 2nd and higher layers is accompanied by a heat of adsorption that is of the same order of size as that of condensation of vapour to bulk water; i.e.  $4,06 \cdot 10^4$  kJ/kmole

Therefore, each kg of water that is condensating in a cement paste gives off an amount of heat that is:

1st layer :  $4,80 \cdot 10^4 / 18 = 2670$  kJ/kg  
 2nd and higher layers:  $4,06 \cdot 10^4 / 18 = 2260$  kJ/kg

The energy given off at burning of 1 kg of fuel oil is about 42 MJ/kg. Therefore, condensation of 1 kg of water corresponds to the following amount of oil:

1st layer : 0,064 kg of oil per kg of condensed water  
 2nd and higher layers: 0,054 kg of oil per kg of condensed water

*Energy storage* in a "battery" of cement paste can be achieved by letting dry air flow through the paste causing a drying of the paste. This consumes energy. The drying can for example be done during summer by air that has been heated and thereby dried by heat from a solar energy collector. It can also be done every time during the year when there is solar energy available for lowering the RH and increasing the temperature of the air used for drying the battery.

*Energy outtake* from the cement paste battery is achieved by letting moist air condensate in the pre-dried battery. Thereby, energy is released that can be utilized for heating the house. The air should not be too cold since the moisture carrying capacity of the air is reduced when the temperature is reduced.

A sorption battery of cement paste can therefore be used as a sort of combined heat exchanger, air conditioner and heat storage. The latter function is discussed in this paper.

Since the energy is stored in the form of a *potential possibility* of condensation of moisture no ageing of the storage takes place. Therefore, energy can easily be stored from summer to winter without losses. This is a very great advantage in comparison with traditional ways of storing energy as heat in water, rock, ground etc. In such storage a gradual inevitable cooling gradually reduces the energy stored reducing the possible time of energy storage.

The sorption battery most closely resembles the heat storage by condensation in zeolites which are silicate materials with very high internal specific surface. The principles are exactly the same as the ones described here but the practical execution ought to be much more expensive since zeolites are more expensive and sorption batteries based on zeolites cannot be easily produced in the same manner as can cement paste batteries. The method also resembles heat storage in salt batteries where the phase transition from melt to crystallinity give a possibility of energy storage and outtake with no time dependent losses.

### 3. Energy storage capacity

#### 3.1 Storage in pure cement gel

The maximum possible energy storage capacity in cement paste can be estimated approximately by using the gel sorption isotherm in Fig 1. The internal specific surface area in cement gel available for adsorption of water vapour is about  $1,8 \cdot 10^5$  m<sup>2</sup>/kg of dry cement gel. The covering area of one water molecule is  $10,9 \cdot 10^{-20}$  m<sup>2</sup>. Thus, the total number of adsorbed water molecules in one monolayer per kg of cement gel is:

$$N = 1,8 \cdot 10^5 / 10,9 \cdot 10^{-20} = 1,65 \cdot 10^{24} \quad (4)$$

The number of molecules in 1 mole is given by Avagadro's number;  $6,02 \cdot 10^{26}$ . Therefore, the adsorbed water in one complete monolayer is:

$$V_m = 1,65 \cdot 10^{24} / 6,02 \cdot 10^{26} = 2,74 \cdot 10^{-3} \text{ kmole per kg of dry cement gel} \quad (5a)$$

Or:

$$V_m = 0,05 \text{ kg per kg of dry cement gel}^1 \quad (5b)$$

#### 3.2 Storage in cement paste

There is a linear relation between the monolayer capacity  $V_m$  and the chemically bound water  $w_n$  in a cement paste. The relation is somewhat depending on the chemical composition of the cement. In /5/ the following relation is given for typical portland cements:

$$V_m' = 0,26 \cdot w_n \quad (6)$$

Where

$V_m'$  the monolayer capacity (kg)  
 $w_n$  the chemically bound water (kg)

The chemically bound water is linearly depending on the degree of hydration. The relation depends somewhat on the chemical composition of the cement. An average relation is:

$$w_n = 0,25 \cdot \alpha \cdot c \quad (7)$$

Where

$\alpha$  the degree of hydration of the cement  
 $c$  the cement content (kg)

<sup>1</sup> Other measurements indicate that the specific surface is as high as  $2,1 \cdot 10^5$  m<sup>2</sup>/kg or even more. This means that the monolayer capacity is 0,057 kg per kg of dry material or more.

The monolayer capacity therefore is proportional to the degree of hydration and the cement content:

$$V_m = 0,26 \cdot 0,25 \cdot \alpha \cdot c = 0,065 \cdot \alpha \cdot c \quad (8)$$

The weight  $Q$  (kg) of a cement paste with cement content  $c$  (kg) is:

$$Q = c + w_n = c(1 + 0,25 \cdot \alpha) \quad (9)$$

Thus, the monolayer capacity in kg per kg of dry cement paste is:

$$V_m = 0,065 \cdot \alpha / (1 + 0,25 \cdot \alpha) \quad (10)$$

The volume  $V$  (m<sup>3</sup>) of a cement paste with cement content  $c$  (kg) is:

$$V = (c/\rho_c + w)/1000 = c \cdot (0,32 + w/c)/1000 \quad (11)$$

Where

$\rho_c$	the true density of cement ( $\approx 3,1$ litres per kg)
$w$	the amount of mixing water (kg)
1000	litres per m <sup>3</sup>

Thus, the monolayer capacity in kg per m<sup>3</sup> of cement paste is:

$$V_m^v = 65 \cdot \alpha / (0,32 + w/c) \quad (12)$$

The maximum adsorption occurs when the degree of hydration is maximum. The maximum degree of hydration is depending on the water/cement ratio. The following values are valid:

$$\alpha_{\max} = 1 \quad \text{for } w/c \geq 0,39 \quad (13a)$$

$$\alpha_{\max} = (w/c)/0,39 \quad \text{for } w/c \leq 0,39 \quad (13b)$$

Thus the following monolayer capacities are valid for the maximum possible hydration:

$$w/c \geq 0,39: \quad V_m = 0,065 / (1 + 0,25) = \mathbf{0,052 \text{ kg per kg}^2}$$

$$V_m^v = \mathbf{65 / (0,32 + w/c) \text{ kg per m}^3}$$

$$w/c \leq 0,39: \quad V_m = \mathbf{0,065 \cdot (w/c) / 0,39 \cdot [1 + 0,25 \cdot (w/c) / 0,39]} \text{ kg per kg}$$

$$V_m^v = \mathbf{65 \cdot (w/c) / 0,39 \cdot (0,32 + w/c) \text{ kg per m}^3}$$

<sup>2</sup> The volume of the adsorbate in one monolayer is  $v_1 = V_m / \rho_w = 0,052 / 1000 \text{ m}^3$  per kg of cement gel ( $\rho_w$  is the density of water). The thickness of one monolayer of water in close-packing is  $2,9 \text{ \AA}$ . Therefore the specific area of cement gel is  $S = v_1 / 2,9 \cdot 10^{-10} = 0,052 / 1000 \cdot 2,9 \cdot 10^{-10} = 1,79 \cdot 10^5 \text{ m}^2/\text{kg}$ .



Examples of the monolayer capacity for different w/c-ratios are shown in Table 1.

Table 1: The monolayer adsorption capacity.

w/c-ratio	$V_m$ in kg per kg	$V_m^v$ in kg per m <sup>3</sup>
0,20	0,030	64
0,30	0,042	81
0,39	0,052	92
0,50	0,052	79
0,60	0,052	71
0,70	0,052	64

The maximum amount in *kg per kg* is obtained when the w/c-ratio is above 0,39. The maximum value 0,052 is very like the one calculated above; 0,050. This is reasonable since a fully hydrated cement paste only contains cement gel.

The maximum amount in kg per m<sup>3</sup> is obtained for the water/cement ratio 0,39. Lower w/c-ratios give lower adsorption since the hydration cannot be complete in such pastes. Higher w/c-ratios give lower adsorption since the amount of cement gel is lower due to the lower cement content in such pastes.

The gel isotherm in Fig 1 corresponds to the cement paste with the water/cement ratio 0,39 and full degree of saturation. Then, the cement paste consists of cement gel only. The gel isotherm in Fig 1 expressed in kg/kg or in kg/m<sup>3</sup> is shown in Fig 2. The data for the monolayer capacity used in Fig 2 are taken from Table 1.

Complete adsorption of water vapour in 1 m<sup>3</sup> of cement gel from 0% RH to 100 % RH corresponds to 92 kg of water in the first layer and  $3 \cdot 92 = 276$  kg in the following 3 layers.

The total potential energy generation at condensation of water in 1 m<sup>3</sup> of cement paste with the water/cement ratio 0,39 at full hydration therefore is:

$$92 \cdot 2690 + 276 \cdot 2280 = 8,77 \cdot 10^5 \text{ kJ}$$

**This corresponds to the burning of 21 kg or 23 litres of fuel oil per m<sup>3</sup> of cement paste.**

1 ton of cement in a cement paste of w/c=0,39 at full hydration produces 1,25 ton of cement gel (see eq (9)). Therefore the monolayer capacity in cement paste produced by 1 ton of cement is  $52 \cdot 1,25 = 65$  kg. The total potential energy generation in a cement paste produced by 1 ton of cement therefore is:

$$65 \cdot 2690 + 3 \cdot 65 \cdot 2280 = 6,19 \cdot 10^5 \text{ kJ}$$

**This corresponds to the burning of 15 kg or 17 litres of fuel oil per ton of cement**

These figures are valid for +20 °C. The adsorption and therefore the amount of heat increases somewhat with lowered temperature.

The sorption energy calculated can be exploited numerous times. The energy requirement for heating a modern well-insulated Swedish one-family house is supposed to correspond to 2 m<sup>3</sup> of fuel oil or 250 litres per month during a heating period of 8 months. Therefore, the required cement paste quantity is about 11 m<sup>3</sup> in order to satisfy the entire energy demand assuming the time between each loading of the "battery" is 1 month. Then, it has been assumed that the entire potential energy storage capacity of the battery can be used at every unloading.

Drying and remoistening of the sorption battery can occur numerous times during many years without the capacity being reduced. Then, it is assumed that the battery does not undergo any ageing. Carbonation of the cement paste might bring about a reduction of the specific surface area. This has to be investigated.

Each change of the moisture condition in the battery requires a flow of air; dry or moist. This causes an energy transport which is however small in comparison with the sorption heat converted. This is shown by the following calculation. The maximum moisture change in 1 m<sup>3</sup> of cement paste is, as shown above, 92+276=368 kg. 1 m<sup>3</sup> of air of temperature +10°C can contain  $9,4 \cdot 10^{-3}$  kg of water vapour at full saturation. Therefore, in order to adsorb or desorb a moisture volume of 368 kg an air volume of  $3,9 \cdot 10^4$  m<sup>3</sup> is needed assuming the air is either completely moist or completely dry. The specific heat of 1 m<sup>3</sup> of air at normal pressure (1 atm) is about 1,2 kJ/degree. Thus, even if the the temperature of the air should be changed by 10°C in connection with the flow of the air through the cement paste battery the corresponding energy change should only be  $4,7 \cdot 10^4$  kJ or 5% of the total sorption heat.

## 4. The design of a sorption heat storage

Moisture transport in a cement paste is a slow process. Therefore, the sorption battery has to be designed as a thin-walled channel system in which moist and dry air is flowing. Other channels with higher flow rates are needed for bringing the sorption energy to the room that shall be heated. A honeycomb structure as that shown in Fig 3 can perhaps be used.

At a w/c-ratio of 0,39 the moisture diffusivity is about  $15 \cdot 10^{-12}$  m<sup>2</sup>/s when moisture content in kg per m<sup>3</sup> of dry cement paste is used as the driving potential for the flow; /3/. Therefore, if a 90% exchange of moisture shall only take 15 days the wall thickness must be limited to about 10 mm.

The size of the channels must be designed according to the required air flow. This can be made small due to the slow moisture transfer. The moisture flow is at its maximum during the first hours after the sorption battery has been reversed. About 20% of the possible moisture change capacity is actually changed during the first 12 hours in a wall of 10 mm assuming the diffusivity is  $15 \cdot 10^{-12}$  m<sup>2</sup>/s. Therefore, if the wall thickness is 10 mm a moisture exchange of about 0,4 kg per m<sup>2</sup> of wall area is

changed during this time assuming the RH-difference between the wall and the air in the channel is 100 % when the water exchange process starts.

In order to bring this amount of moisture to the wall or take it away from the wall an air volume of about  $0,4/9,4 \cdot 10^{-3} = 42 \text{ m}^3$  is needed at  $+10^\circ\text{C}$ . Therefore, in a channel with square cross section with the width  $D$  (m) and the length  $L$  (m) a total air volume of  $42 \cdot 4 \cdot D \cdot L = 168 \cdot D \cdot L \text{ m}^3$  is needed. The required volume flow rate is  $168 \cdot D \cdot L / (12 \cdot 3600) = 0,004 \cdot D \cdot L \text{ m}^3/\text{s}$ . The required flow rate is  $0,004 \cdot D \cdot L / D^2 = 0,004 \cdot L / D \text{ m/s}$ . With a channel length of 1 m and a cross section of  $10 \cdot 10 \text{ mm}^2$  the air flow is 0,4 m/s.

A design of the described type means that the channel volume is 25 %. Thus, for 1  $\text{m}^3$  of effective cement paste volume a battery volume of 1,35  $\text{m}^3$  is needed. At a double channel system -one for loading and one for unloading- a somewhat bigger battery volume is needed. The exact size depends on the geometrical arrangement of the channels.

The adsorption gives an energy release in the sorption battery. This energy is taken care of by letting air from the house pass through a special channel system with impermeable walls. The flow rate is adjusted after normal principles for calculating the heat transfer between air in a channel and the channel walls.

The sorption battery can be designed as a system of modules where each module resembles a steam boiler with its tubes; see Fig 4. The length of the module is determined by the resistance to air that shall flow through the channels. These modules can be cast or extruded which is a great advantage in comparison with sorption batteries made of zeolites.

The exact design of the sorption storage with all its adsorption channels, desorption channels, heat exchange channels, pumps or fans, regulation system etc is not treated in this report due to the author's lacking competence in this field.

The loading of the storage -i.e. the pre-drying or desorption- can be made with outdoor air that has been heated by solar collectors. The unloading -i.e. the adsorption- can be made with outdoor air that is moistened.

The sorption battery can be integrated in the load carrying structure of the building. It can make up the floor and/or the walls. When used as a floor in a villa with the ground area of  $100 \text{ m}^2$  and at 1 m thickness, the effective sorption volume is  $50 \text{ m}^3$  at double channel systems and about  $75 \text{ m}^3$  at single channel system. The potential heat storage capacity at one single loading is  $50 \cdot 8,77 \cdot 10^5 = 4,4 \cdot 10^7 \text{ kJ}$  or  $75 \cdot 8,77 \cdot 10^5 = 6,6 \cdot 10^7 \text{ kJ}$  corresponding to 1,16 or 1,75  $\text{m}^3$  of fuel oil. A considerable amount of energy could evidently be stored considering that numerous loadings and unloadings are possible.

## 5. Solar energy

As said above the loading of the sorption battery can be made with air that is dried and heated by means of a solar collector. The solar energy transmitted to a one-family house in Sweden is more than needed to heat the house. This is shown by the following calculation.

The average global solar radiation per  $m^2$  of ground surface in Sweden is about 1000 kWh/year or 114 W; /4/. Let us assume that 50 % of this can be collected by a solar collector. Then, the average solar energy is 57 W/ $m^2$  or 57 J/ $m^2$ ·s. The solar energy collected during the whole year is  $1,8 \cdot 10^6$  kJ/ $m^2$ .

A solar collector area of 30  $m^2$  collects  $54 \cdot 10^6$  kJ per year. This corresponds to 1,4  $m^3$  of fuel oil.

The solar radiation during the warmest 6 months of the year is considerably higher; about 160 W/ $m^2$ . With the same solar energy collector as above and the same efficiency of this, the total energy collected during half the year is  $37 \cdot 10^6$  kJ corresponding to 1  $m^3$  of fuel oil.

Thus, solar energy gives a large energy contribution under condition that the energy can be saved from the warm season to the cold. This is hardly possible in conventional heat storages based on capacitative heat but can be achieved in a sorption heat storage based on the latent heat when water vapour is adsorbed in a dry material with high internal specific surface. Hydrated portland cement paste is such a material.

## References

- /1/ G Fagerlund: Energy storage by adsorption of water vapour in cement paste. Manuscript in Swedish; dated Vallentuna, June 17, 1985.
- /2/ S.J Gregg, K.S.W Sing: Adsorption, surface area and porosity. Academic Press, London and New York, 1967.
- /3/ G Fagerlund: Moisture mechanics properties of cement paste. Chapter in "Concrete Handbook", part "Material". Stockholm 1980. (In Swedish)
- /4/ G Lundquist, R Persson, J Angbjär, L.O Andersson, E Isfält : Camera Solaris; Architecture for our climate, The Swedish Council for Building Research, Report T28:1980, Stockholm, 1980. (In Swedish)
- /5/ T.C Powers, T.L Brownyard: Studies of the physical properties of hardened portland cement paste. Research Laboratories Portland Cement Association, Bulletin No 22, Chicago 1948.

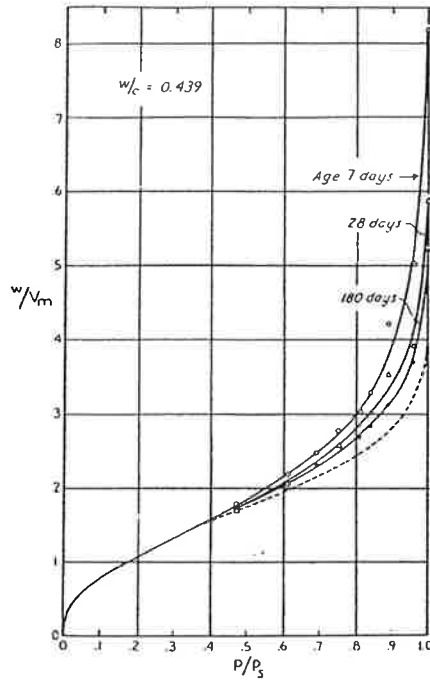


Fig 1: Adsorption isotherms of portland cement paste with the water/cement ratio 0,439; /5/. The sorption expressed in number of monolayers is reduced with increased age of the cement paste. The lowest isotherm -the gel isotherm- is valid at full hydration when the cement paste only contains cement gel. On the other hand, the internal surface area expressed in  $V_m$  is increased with increased age of the cement paste. Therefore the gel isotherm contains the largest amount of adsorbate out of the 4 curves shown in the figure.

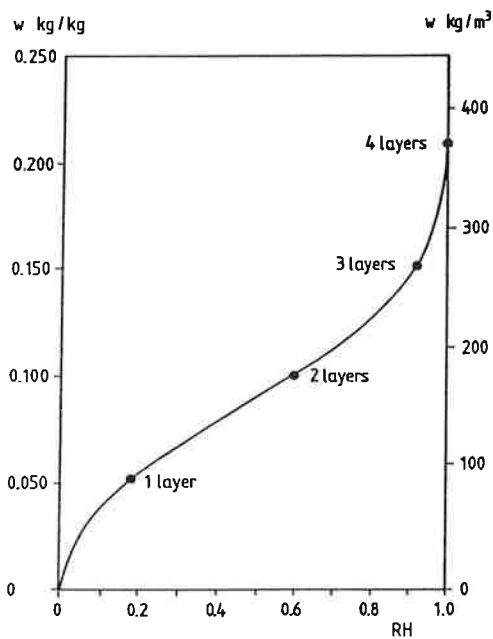


Fig 2: The gel isotherm of fully hydrated cement paste with the water/cement ratio 0,39. The isotherm is expressed in terms of kg of adsorbate per kg of dry cement paste or in kg of adsorbate per  $m^3$  of cement paste

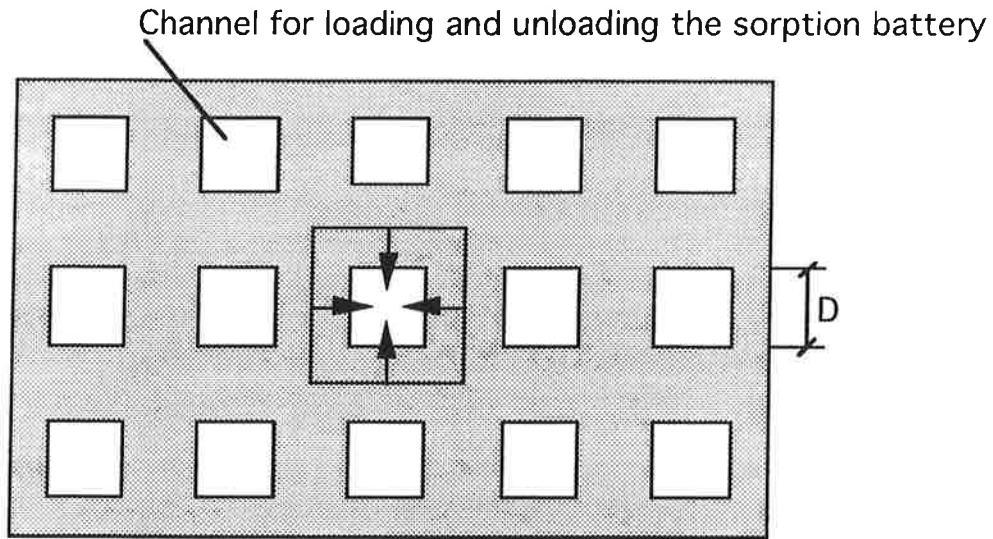


Fig 3: The cross section of a "sorption battery"; principles

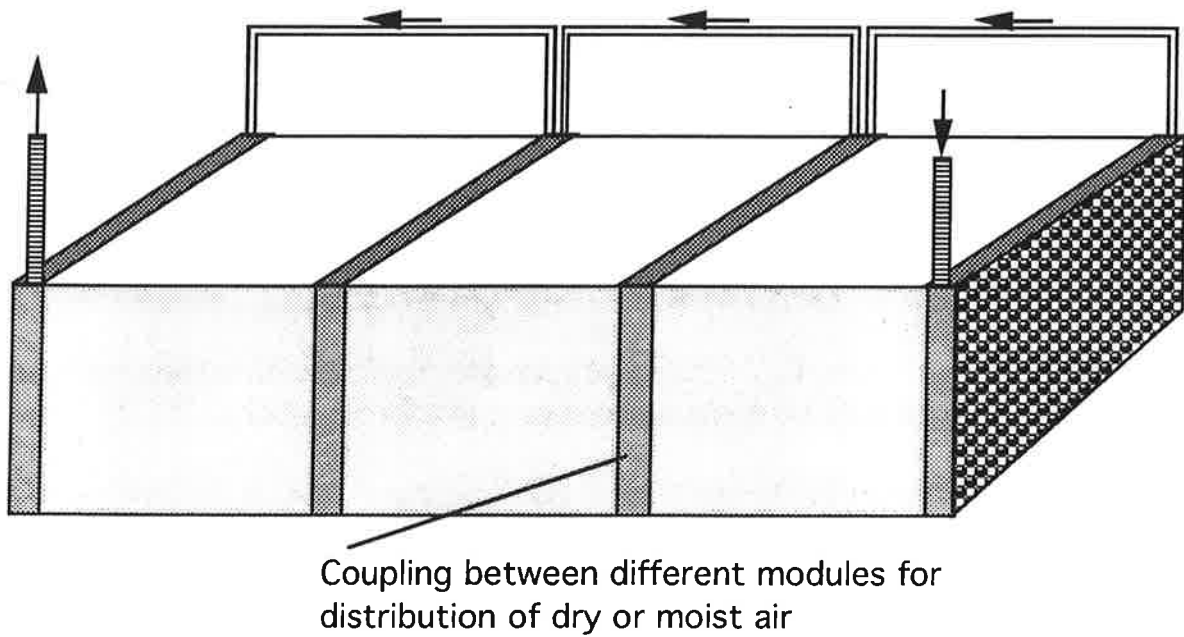


Fig 4: A sorption battery composed of coupled cement paste modules.

## Appendix

### Some comments on economy

Today, it is not possible to make a realistic analysis of the economical potential of the heat storage principles presented in this paper. A simple analysis of the capitalized value of either investing in a heat storage of the type presented in this report or using traditional heating based on oil or electricity, can however be made. The figures are by no means exact. The analysis will only indicate the economical potential of the type of energy storage suggested.

Let us assume that the net investment needed for a heat storage is  $S$ . By the word "net" is meant that the storage can be used as part of the building structure so that a certain investment in the structure can be saved. It is also considered that the investment needed for normal heating can be saved.

Then, the capitalized value of the net investment,  $S_{cap}$ , after  $n$  years at a rate of interest of  $r$  % is:

$$S_{cap} = S(1+r/100)^n \quad (a)$$

The alternative is to use traditional heating. Only the yearly energy cost  $E$  is regarded in the calculation; i.e. the capitalized cost of the installation is omitted. Two different cases are looked upon; (i) the energy price is constant; (ii) the energy price is increased by 3 % each year.

#### **a: The energy cost is assumed not to increase with time**

The capitalized value of the cost of energy  $E_{cap}$  after  $n$  years is:

$$E_{cap} = E(1+r/100) \cdot \{(1+r/100)^n - 1\} / (r/100) \quad (b)$$

The two capitalized values  $S_{cap}$  and  $E_{cap}$  are equal when the following relation between the net investment  $S$  and the yearly energy cost  $E$  is valid:

$$S/E \leq (1+r/100)^{1-n} \cdot \{(1+r/100)^n - 1\} / (r/100) \quad (c)$$

The following relations  $S/E$  is obtained for some values of the rate of interest and the service life.

$r$	10 years	20 years	30 years	50 years
5 %	8,1	13,1	16,1	19,2
7 %	7,5	11,3	13,3	14,8
9 %	7,0	10,0	11,2	12,0

Thus, the lower the rate of interest and the longer the service life of the storage the higher the tolerated investment.

**b: The energy price is assumed to increase by 3 % each year**

The capitalized value after n years is:

$$E_{\text{cap}} = \sum_{i=1}^{i=n} 1,03^{i-1} \cdot E \cdot (1+p/100)^{n+1-i} \quad (\text{c})$$

The relation S/E for equal capitalized value after 30 years at a rate of interest of 7 % is 17,7 with rising energy prices. This shall be compared with the value 13,3 which is valid for constant energy price.

1 m<sup>3</sup> of cement paste can possibly save about 1,8·10<sup>6</sup> kJ each year if the storage can be loaded and reloaded a number of times every year (each total desorption-adsorption cycle corresponds to about 8,8·10<sup>5</sup> kJ; see 3.2). This corresponds to about 50 litres of fuel oil or 500 kWh of electrical energy. Let us assume that the oil price is P<sub>o</sub> per m<sup>3</sup> and the price of electricity is P<sub>e</sub> per kWh. This means that the tolerated investment in 1 m<sup>3</sup> of cement paste storage is the following when the rate of interest is 7 % and the service life of the investment is 30 years:

$$\begin{aligned} \text{Constant energy price:} \quad S &\leq 13,3 \cdot 0,050 \cdot P_o = 0,67 \cdot P_o \\ S &\leq 13,3 \cdot 500 \cdot P_e = 6650 \cdot P_e \end{aligned}$$

$$\begin{aligned} \text{3 \% yearly increase of energy price:} \quad S &\leq 17,7 \cdot 0,050 \cdot P_o = 0,89 \cdot P_o \\ S &\leq 17,7 \cdot 500 \cdot P_e = 8850 \cdot P_e \end{aligned}$$

1 m<sup>3</sup> of cement paste consumes 1,4 tonnes of cement. Let us assume that the present relation between the energy price (P<sub>o</sub> or P<sub>e</sub>) and the cement price per ton (P<sub>c</sub>) will be more or less maintained in the future.

The relation between the cement price per ton and the energy price per m<sup>3</sup> of oil or kWh is defined:

$$P_o/P_c = \pi_o \quad (\text{e})$$

$$P_e/P_c = \pi_e \quad (\text{f})$$

This means that the maximum tolerated relation between the total net investment cost of the storage S and the total cost C of the cement in the storage is:

$$\begin{aligned} \text{Constant energy price:} \quad \text{oil} \quad S/C &\leq (\pi_o \cdot 0,67)/1,4 = 0,48 \cdot \pi_o \\ \text{electricity} \quad S/C &\leq (\pi_e \cdot 6650)/1,4 = 4750 \cdot \pi_e \end{aligned}$$

$$\begin{aligned} \text{3 \% increase of energy price:} \quad \text{oil} \quad S/C &\leq (\pi_o \cdot 0,89)/1,4 = 0,64 \cdot \pi_o \\ \text{electricity} \quad S/C &\leq (\pi_e \cdot 8850)/1,4 = 6320 \cdot \pi_e \end{aligned}$$



Let us assume that typical relations between the energy price and the price of cement are:

$$\pi_o = 7$$

$$\pi_e = 10^{-3}$$

Then, the following maximum cost relations between the cement and the total net investment are valid if the cost of energy storage in a cement paste battery shall be equivalent with ordinary heating:

Constant energy price:	oil	$S/C \leq 3,4$
	electricity	$S/C \leq 4,8$

3 % increase of energy price:	oil	$S/C \leq 4,5$
	electricity	$S/C \leq 6,3$

Thus, the total cost of the energy storage can not be allowed to be higher than a certain multiple of the cement cost. The price can be allowed to be higher if the storage shall compete with heating by electricity than by oil. Changes in the price of different energy sources as well as changes in the relation between the cement price and the energy price will of course change the picture. The method described for estimating the relative costs can however still be used.

It is also possible that the energy storage capacity is higher than what is suggested in the calculation above; viz. 50 litres of fuel oil or 500 kWh per m<sup>3</sup> of cement paste per year. If this is the case, the economy of the storage will of course be improved. More exact information of the economical potential can only be obtained when a full scale test has been made.