SINTEF REPORT

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TITLE

COIN P5 Energy efficiency and Comfort of Concrete Structures
SP 5.2 Comfortable buildings and constructions

State of the art

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CLIENT(S)

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ABSTRACT

This report is the first delivery to the subtask 5.2. *Comfortable Buildings and construction* of the main project COIN (Concrete Innovation Centre). It gives a State-of-the-art review (STAR) about the consequences for the indoor environment when concrete is chosen as the main building material in buildings and especially when large exposed concrete surfaces are used to take advantage of concrete's thermal mass. This report is articulated around 4 themes:

- acoustics
- thermal comfort
- emissions
- visual comfort

Need for future research is summarized on next page and organised in relation to:

- direct interaction systems
- indirect interaction systems
- ground-coupled systems
- built examples
- tunnels

Areas of special interest are highlighted.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1		
GROUP 2		
SELECTED BY AUTHOR	Concrete, sound, heat capacity	Betong, lyd, varmekapasitet

Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.sintef.no/coin

1 Summarized need for future research

	Acoustics	Thermal comfort	Particle emissions	Chemical emission
Direct interaction systems (e.g. exposed ceilings)	**Sound and acoustics is a challenge related to free exposed concrete surfaces. Further studies are needed for mapping out different acoustic solutions for effective use of passive thermal mass (PTM)**	• **Evaluation of indoor climate associated with different design solutions that utilise thermal mass which eliminate the need for mechanical cooling (in conjunction with other passive cooling measures)** • • Methods for improving opportunities for behavioural adaptation of the thermal environment in buildings, maximising exploitation of thermal mass.	-Development of methods to examine particle release from different concrete qualities -Small-chamber studies on particle release from different concrete surfaces uncoated and coated **-Field survey investigations in existing Norwegian buildings to evaluate exposed concrete surfaces and the effect on indoor air quality** -Field survey investigations during the building process and the clean and dry building philosophy. The use of concrete and the amount of concrete/cement particles on surfaces and the effect on indoor air quality	-Laboratory studies of chemical emissions from different concrete qualities (not exposes to alkaline moisture) -Develop methods to evaluate alkali resistance **Laboratory studies of parameters determining the corrosive potential of concrete toward materials in direct contact with concrete. The studies will focus on the relationship between moisture level at the concrete surface, capillary size and corrosiveness.**
Indirect interaction systems (e.g. TABS: Thermo-Active-Building Systems)		Evaluation of why Termodeck has become so popular abroad but not in Norway. Can the "duct cleanliness" issue be convincingly solved?	Studies on particle release from TABS to the indoor air	
Ground coupled systems (e.g. underground ventilation ducts)		Built examples		Evaluation and promotion of the best control systems for night time cooling. This must involve close collaboration with controls manufacturers (e.g. Johnson Controls).

Contents

1 Introduction

Concrete is the most used manmade material on the planet. In buildings, it is used for foundations and structure elements but also as partition walls, floor slabs and ceiling slabs.

This report aims at presenting existing knowledge about the consequences for the indoor environment when concrete is chosen as the main building material in buildings and especially when large exposed concrete surfaces are used to take advantage of concrete's thermal mass. This report is articulated around 4 themes:

- acoustics
- thermal comfort
- emissions
- visual comfort

The following gives a view of project 5 of the main project COIN (Concrete Innovation Centre) with subprojects and subtasks including objectives and contents.

- **Project 5**

  Energy efficiency and Comfort of Concrete Structures

- **Sub-project 5.2** ***Comfortable buildings and constructions***

  The objective is to establish and document methods that permit to take advantage of the using of concrete in buildings without negative consequences for the indoor environment.

- **Deliveries**

  State-of-the-art review (STAR) on concrete as building material and its influence on the indoor environment. Research need have to be1 identified in the STAR.

- **Description**

  The first step of the sub-project is a State-of-the-art review (STAR) about the consequences for the indoor environment when concrete is chosen as the main building material. The state-of-the-art review shall focus on the following themes: acoustics, thermal comfort, emission and day lightening

- **Purpose and scope**

  The STAR shall make the basis for the future planning of the subtask in COIN. It should be as compact as possible and with the objective of the current sub-project in focus. It means that discussion of details and issues outside the focus / objective should be avoided. It shall include the list of references and where they are archived.

2 Acoustics

2.1 Background

This report gives a State-of-the-art review (STAR) about the consequences for the acoustic environment when concrete is chosen as the main building material. Acoustic environment is one of four themes that are handled in the subtask 5.2.1 of the main project COIN (Concrete Innovation Centre).

2.2 Review and analysis on acoustic properties

2.2.1 General

We have in this part of the State-of-the-Art Review (STAR) concerning acoustics focused on sound reverberation within room due to concrete walls and/or ceilings. The review point at importance on possible design for sound absorption combined with exposed concrete (primary in office buildings and schools).

This review is based upon general knowledge on acoustics, SINTEF Building and Infrastructure Knowledge Systems (Building Research Design Sheets), search at the internet and a limited literature survey (see section 4).

Sound properties of materials and construction are divided into three parts: sound reduction (sound insulation between rooms) and sound absorption / reflection (sound propagation in rooms), see explanation of terms in figure 1.In this report we only focus on sound absorption / reflection, i.e. properties that have influence on the sound environment in a room (reverberation time, sound attenuation, noise levels, sound perception, speech comprehension etc.). The sound absorption properties are first of all attached to the surface of the materials facing the inner walls, ceiling and floor.

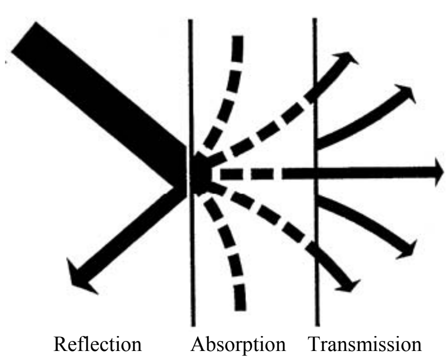

Figure 1. Explanation of terms

1.1 2.3 The current problem

Exposed concrete indoor surfaces are normally highly sound reflective. For many room categories there is a need for a certain amount of sound absorptive surfaces to secure a moderate reverberation time to give a satisfactory indoor sound environment. The amount of needed sound absorption is depending of the type of rooms and the area of utilization. For room categories that need to be highly attenuated, the ceiling and/or walls are often covered with special sound absorptive materials or elements. The sound absorption is often highly frequency depending.

Figure 1 and 2 illustrates the situation. To fully utilize the advantages of massif concrete construction with high heat capacity (thermal mass as a stabilizer of room temperatures at fluctuating heat input), all the insulation should be placed on the outside. In addition the concrete structure should be fully exposed inside to interact with the variations in temperature (figure 1).

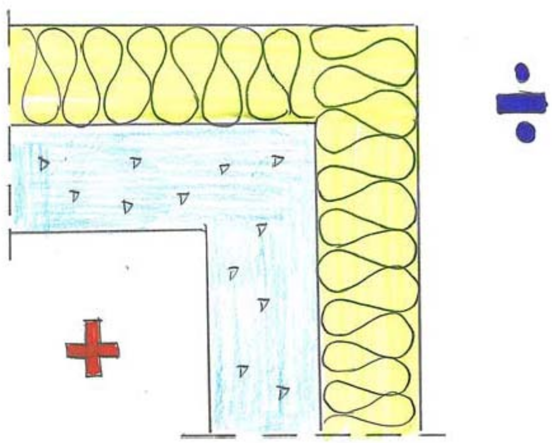

Figure 2. Massif concrete construction with high heat capacity and all insulation on the outside

Exposed concrete surfaces that normally are highly reflective leads to long reverberation time and again to reduced quality as to sound environment (strong reflections from all the surfaces, higher noise levels, poorer speech perception etc.). Normally there is a need for a certain amount of sound absorptive surfaces, see figure 2. In some cases additional sound absorption from furniture can be sufficient.

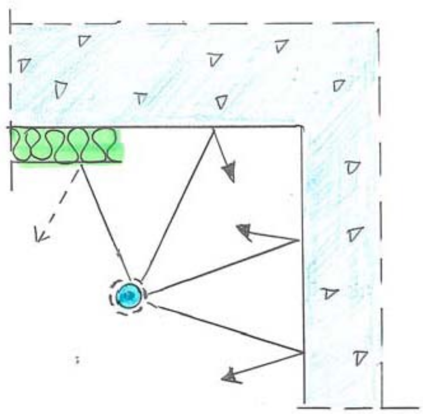

Figure 3. Exposed concrete surfaces are highly reflective and leads to long reverberation time

The challenge is to find solutions that can combine exposed concrete inner surfaces with the need for sound absorption in the room. The sound within a room is partly absorbed and partly reflected from the surfaces and the furniture of a room. The reverberation time is therefore depending of both. Although the concrete surfaces are highly reflective and contribute badly to lower the reverberation time, this can be compensated by sound absorptive furniture and by additional sound absorption elements partly covering the surfaces (e.g. suspended highly sound absorptive ceilings).

Sound absorptive elements on the surfaces (inner and outer) may come in conflict with safety against condensation, fire safety, mechanical strength, cleaning, etc. To reduce danger of condense on climate walls and ceilings it is possible to use mounting with a ventilated open air gap behind. Such a solution may also make the combination with heat interaction possible.

2.4 What we know about it (consensus)

2.4.1 Sound absorption of concrete surfaces

The sound absorption of concrete surfaces are normally low, see table 1. (ref. SINTEF Building and Infrastructure Knowledge Systems, Building Research Design Sheets no. 543.414). Use of direct exposed concrete surfaces on the main part of the room will lead to great challenges as to long reverberation time

Table 1. Sound aborsorption coefficient of concrete surfaces
Ref.: SINTEF Building and Infrastructure design sheet 543.414.

Frequency Hz	Material / surface		
	Concrete, rough	Concrete, smooth unpainted	Concrete, smooth, painted or spackled [1)]
125	0,02	0,01	0,01
250	0,03	0,01	0,01
500	0,03	0,02	0,01
1 000	0,03	0,02	0,01
2 000	0,04	0,02	0,02
4 000	0,07	0,05	0,02
α_w [2)]	0,05	0,05	0,00

1)These values may also be used for ceramic tiles with smooth surface etc.
2) Weighted value according to EN ISO 11654

As table 1 shows the sound absorption of smooth concrete surfaces are very low at all frequencies. The sound absorption coefficient of 0,01 means that 99% of the incoming sound energy are reflected and only 1 % is absorbed.

2.4.2 Possibilities for increasing the sound absorption of the concrete

2.4.2.1 Porous concrete surface

The sound absorption may be increased by making the surface more porous. In practice this means that there must be an open structure for air transportation between the cement grain and the aggregate and/or voids in the structure. Such concrete may improve the sound absorption coefficient.

We have found references to such a study of porous concrete based on the content of recycled aggregate and target void ratio (Cement and Concrete Research , Volume 35, Issue 9 , September 2005, Pages 1846-1854 /www.sciencedirect.com). The sound absorption characteristics of the porous concrete using recycled waste concrete aggregate showed that the rating of the sound absorption coefficient (NRC) was optimum at the void ratio of 25% but the percent content of the recycled aggregate had very little influence on the NRC. Therefore, the optimum void ratio is 25% and the recycled aggregate is 50%. Be aware of that focus was turned toward the development of multi-functional porous concrete having water and air permeability, good sound absorption ability, etc., by artificially forming continuous porosity using coarse aggregate of single size rather than the more traditional fine aggregate.

2.4.2.2 Acoustic, porous rendering

Another possibility for improving the sound absorption coefficient is to add a porous rendering directly on the concrete. This is a well known technique. However, the rendering must be both relatively thick and extremely porous to get good results. Diagram 1 shows laboratory measurements according to EN ISO 354 of 3 mm spatter added Alpha acoustic rendering (ref. www.fellert.com) on 13 mm chipboard. The sound absorption coefficient is relatively good in the high frequency range, but has great limitations in the lower frequency range. The results with the rendering directly on concrete will be poorer in mid- and low frequency due to lack of the resonator effect of the board.

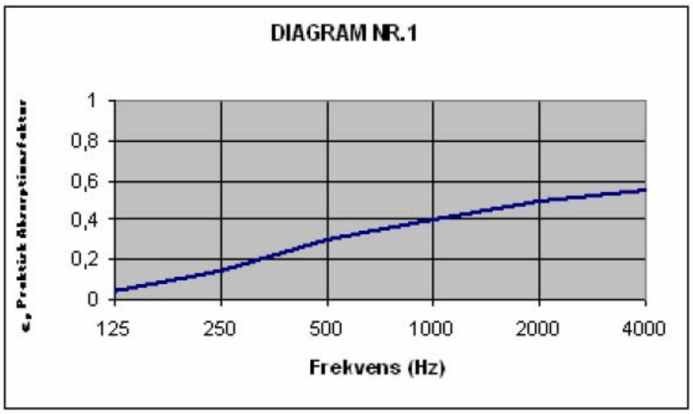

Figure 4. Sound absorption coefficient of 3 mm spatter added Alpha acoustic rendering on 13 mm chipboard

With thicker porous rendering it should be possible to get better results. However this will probably lead to other problems, for instance rough surfaces hard to clean. In any case it will be a problem to achieve sound absorptions properties that can compete with special sound absorbers of mineral wool. Yet, acoustic rendering can absolutely lead to a substantial improvement of the sound absorption compared to smooth concrete surfaces.

The term “acoustic rendering” is also much used for rendering on mineral wool slab. In this context combination with mineral wool is out of the question.

2.4.3 Other possibilities for increasing the sound absorption

2.4.3.1 Sufficient absorption by furniture

In some room categories additional sound absorption is not needed at all. The absorption by furniture are often sufficient in smaller rooms, see section 3. In such cases there is no conflict with a large amount of exposed concrete in walls and ceiling.

1.1.1.1

2.4.3.2 Partly exposed concrete

In some room categories with moderate need for additional sound absorption, parts of the surface may be absorptive by adding sound absorbers. Here we can look upon the possibility of finding a reasonable distribution between exposed concrete surfaces and surfaces with added sound absorbers. The possibilities for such a distribution must be calculated in each case or more general for typical cases.

1.1.1.2

2.4.3.3 Ventilated sound absorbers

In some cases where the indoor climate may cause problems of condensation inside outer walls and ceiling (for instance in public baths / indoor swimming pools), ventilated sound absorbers are recommended. The design principle is to direct the indoor air behind the sound absorbing elements to contact with the surface of the main construction (for instance over suspended ceilings). When the sound absorbers are divided into separate elements with limited dimensions with free openings on all four sides, the air exchange should be secured. Such a principle should be possible to use for the purpose of using thermal mass of a concrete structure as a stabilizer. However, there are challenges attached to dust, cleaning etc.

2.4.3.4 Interaction systems

Subproject 5.1.f "Energy efficient buildings and construction" with the aim of analyzing and develop new building concepts with thermal mass activation shall study direct interaction systems (e.g. exposed ceilings) and indirect interaction systems. Such systems should also include studies for possible integration of sound absorption.

2.4.4 Main types of sound absorbers

There are three different main types of sound absorbers listed below. However, all of them are to be placed under or in front of the main reflective construction. In this sentence this will come in conflict with the temperature exchange to utilize the heat capacity properties of the massif construction part.
Any way they are described here in case it still is possible to utilize those absorbers in alternative solutions.

1.1.1.3

2.4.4.1 Porous absorbers

Porous absorbers are materials with open pores where the sound energy first of all reduces by penetrating into the porous structure and very little are reflected. Examples are mineral wool (ordinary quality and in pressed form), light expanded concrete aggregate (none rendered) etc. Due to low mechanical strength the porous absorbers are often must be covered by perforated boards or slot panels with an open area of about 20 %. The surface of porous absorbers must out of consideration for indoor climate and maintenance in addition be covered by thin plastic foils or fibre cloths. The absorption coefficient is normally very good at medium and high frequencies. It may also be good at low frequencies for relatively thick absorbers.

2.4.4.2 Membrane absorbers

Membrane absorbers are boards and panels with cavity behind. The absorption increases when filling the cavity with a porous material, i.e. mineral wool. The absorption coefficient seldom exceeds 0,5 at low frequencies and is normally very low at high frequencies.

1.1.1.4
2.4.4.3 Resonator absorbers

Resonator absorbers are panels with slots or perforated panels with a cavity behind. The absorption effect is friction in the holes or slots. The cavity is normally filled with mineral wool to increase the absorption effect at low and medium frequencies.

1.1.1.5
2.4.4.4 Micro perforated absorbers

Micro perforated absorbers are a special type of resonator absorbers with extreme small hole or slot dimensions. A good absorption characteristic is depending of interaction with a cavity behind and often two panels and two cavities are used to get good properties in a broad frequency range. The absorbers may be produced of metal boards / panels or by transparent polycarbonate. The price is relatively high and they are normally only used in special cases. See www.deamp.com

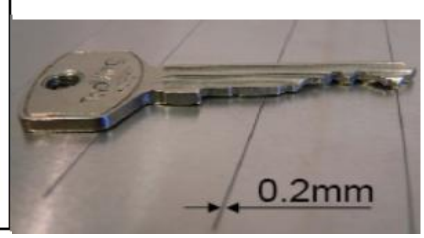

Figure 5. Microperforated materials

2.4.4.5 Typical frequency characteristic

Typical frequency characteristic for the different main types are given in diagram 1.

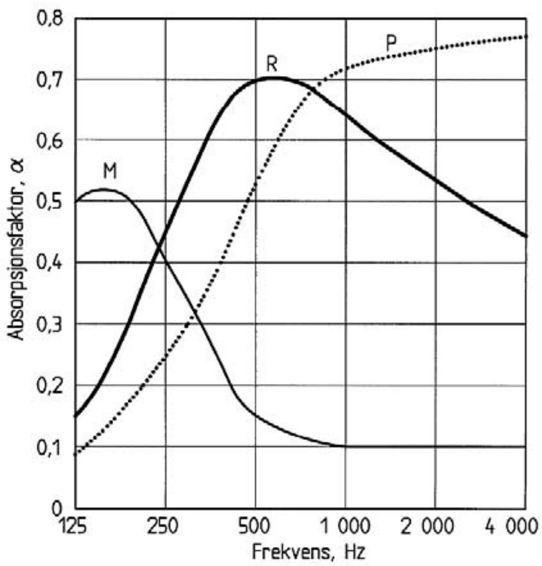

Diagram 1. Typical frequency characteristic for the different main types of sound absorbers (M = membrane absorbers. R = resonator absorbers. P= porous absorbers)

2.5 Any divergent hypothesis / views

Preliminary no divergent hypothesis / views at the moment

2.6 Combination of heat capacity and sound absorption

2.6.1 Possibilities in different room categories

Exposed concrete surfaces may be desirable to utilize the heat capacity of the concrete structure. The ceiling is in practice often the surface of most current interest. We have therefore in table 2 worked out a general view for the possibilities of combination of exposed concrete ceiling without additional sound absorbing ceiling depending of different room categories / area of utilization. The table also indicates in which room categories it will be difficult to avoid a sound absorbing ceiling because of the great need for room attenuation (short reverberation time). Typical evaluation is that this combination will be difficult for open-plan office and open-plan school, but is possible for smaller rooms in offices, hospitals, hotels and dwellings.

Table 2. Combination of heat capacity and sound absoroption. Possible room categories

Building category	**Exposed concrete in ceiling possible**	**Need for additional sound absorption in ceiling**
Offices - single offices - open-plan offices	Yes No	No Yes
Schools – room for teaching Kindergarten - day room etc.	No No	Yes Yes
Hospitals - day rooms **Hotels** - guest room **Dwellings** - living room etc.	Yes Yes Yes	No No No
All categories - staircases, common room, common corridor, meeting room etc.	No	Yes

This means that in many room categories it is possible to utilize exposed concrete without any additional sound absorbers. The reason for this is that for smaller room the reverberation time will be satisfactory only with the absorption from furniture. However, for open-plan offices and schools it is not possible to use for instance exposed concrete in the ceiling alone.

2.7 Literature survey

2.7.1 Internet search

The result of internet search is of limited interest. Search has been performed using search word like concrete, sound, acoustic, absorption coefficient, attenuation, acoustic render, porous concrete. Some results are given in the reference list.

2.7.2 Literature search

2.7.2.1 General

The literature search has been carried out by the Documentation Centre at SINTEF Building and Infrastructure (Elin Maria Fiane). The search queries for this subtask have been suggested by the project manager.

2.7.2.2 Search queries

The following search queries (both in English and in Nordic languages) have been given priority:

• Concrete (exposed concrete, porous concrete, concrete surfaces, indoor surfaces)

• Sound (sound absorption, sound absorption factor/coefficient, sound reflection, reverberation time)

• Acoustic (acoustics, acoustical properties)
• Render (rendering, plastering)

In combination with:
• heat (heat capacity, indoor environment and thermal comfort)

2.7.2.3 Databases and results

Use of the three main search queries: concrete, sound and heat has been carried out towards the following databases listed below. In some extend expanded search queries as given in section 4.2.2 have been used. The results (number of hits) and comments are linked to each database.

1.1.1.6

1.1.1.7 ISI web of science (reference database for scientific articles)

Results: No hits on all three search queries no matter what combinations. However hits on ”sound absorption factor” and “sound absorption and concrete”.

1.1.1.8

1.1.1.9 Broader search from ISI web of science in different foreign databases

These databases are: Agricola; AIAA Meeting Papers American Institute of Aeronautics and Astronautics; All arXiv ePrint Archives; arXiv Computer Science; arXiv Mathematics; arXiv Nonlinear Sciences; arXiv Physics; arXiv Quantitative Biology; Civil Engineering Database; Education Resources Information Center; NASA Astrophysics Data System; NTIS Library Documents published since 1990; Popline Reproductive Health Literature; PubMed. Timespan = Latest 5 years…
Results: Mostly without hits and the hits are not relevant

1.1.1.10 SpringerLink (fulltext database, articles etc.)

Results: No hits on all three terms, no matter what combinations

1.1.1.11 BIBSYS

Results: No hits, neither in database for bibliotecs nor the research database. Nor on ”sound absorption” and ”concrete” including Norwegian terms. Two hits on ”acoustic render”

1.1.1.12 KTH/BYGGDOK (referance database for Nordic building construction litterature)

Results: No hits on all three terms. Some hits on sound and concrete, but not relevant for our subject.

1.1.1.13 ScienceDirect (fulltext base articles).

Results: Temporary no hits that is not included in ISI.

1.1.1.14 Engineering Village (EI)

Results: One hit on all terms, but is not relevant

2.7.3 Results of literature survey

The result of the search combining heat and sound gave, as expected, no relevant references. The acoustical properties including sound absorption are well known and documented. Some references concerning acoustic rendering and porous concrete with increased sound absorption was found and may be relevant to some extend.

2.8 Conclusions and the need are for further research ("white spots")

This review concludes that it is difficult to use exposed concrete in buildings without negative consequences for the indoor acoustic environment. Especially is this primary a problem in open plans, like open plan offices and schools which have been pointed out as of special interest for this evaluation. For many other room categories the problem is limited.

However, we have pointed out some possibilities for an improvement of the sound absorption of concrete surfaces or development of alternatively designed elements. We suggest further investigation on the following topics:

- Interaction systems (integrated elements covering the needed thermal properties, sound absorptions, light emission etc.)

- Porous rendering (documentation of effect and necessary thickness by laboratory measurements, evaluation of problems in use etc.)

- Concrete surface or elements with special design for sound absorptions (further study of test of concrete with cavities for increasing the sound attenuation)

- *Ventilated, suspended or withdrawned sound absorbers (practical issues combined with analysis of the consequences for thermal mass effect)*

2.9 References

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3 Thermal comfort

3.1 The current problem

For thermal comfort the review will focus on:

- Indoor temperature variations in buildings with exposed concrete
- Effectiveness of ventilation by hollow core slab
- Effectiveness of mass and night ventilation for indoor temperature control
- Reduction of cooling load and possibility to avoid cooling in buildings with high thermal mass
- What do we know about exposed concrete and thermal comfort?

3.2 What we know about it (consensus)

One of the most interesting properties of concrete is its high thermal capacity and its influence on the thermal comfort of building occupants. This has direct financial consequences in terms of occupant productivity and for energy consumption associated with climatising the building (both heating and cooling). Optimal use of thermal mass usually involves periodic cooling/heating of the building structure (e.g. night ventilation).

3.2.1 Thermal comfort fundamentals **(bibl.ref. M.Satnamouris; Wikipedia)**

Human thermal comfort is the state of mind that expresses satisfaction with the surrounding environment.

Seminal modern research on thermal comfort, such as acceptable ranges of dry-bulb temperatures, relative humidities, and activity levels, was conducted in the 1970s by P.O.Fanger and others. The findings showed that not everyone can be satisfied at the same time, under the same particular set of static indoor environmental conditions. If very good conditions are in place, a maximum of 95% of all persons might be satisfied. Statistical methods were used to evaluate the steady-state thermal comfort opinions of the many test subjects to yield what are known as the comfort conditions; the predicted mean vote (PMV) was one of the measures used. The most well known and widely accepted methods still in use today are the "Comfort Equation" proposed by Fanger, (Fanger, 1972), and the J.B. Pierce two node model of human thermoregulation, (Gagge, 1973, and Gagge et al, 1986). Based on these models, several steady state thermal comfort standards have been established. (ISO 7730:1994, ASHRAE Standard 55: 1992, Jokl, 1987). Most building regulations today refer to this seminal research on thermal comfort conditions under steady state conditions.

Thermal comfort is also linked with the perception on indoor air quality in a building and productivity, (Humphreys et al, 2002, McCartney and Humphreys, 2002).

Most important for thermal comfort is the so called operative temperature. This is the average of the air dry-bulb temperature and of the mean radiant temperature at the given place in a room. In addition, there should be low air velocities and no 'drafts', little variation in the radiant temperatures from different directions in the room, the humidity has to be in a comfortable range, and the air temperatures in a height of 0.1 m above the floor should not be more than 2°C lower than the temperature at the place of the occupant's head. Also the temperatures should not change too rapidly - neither across the space nor with time.

In addition to environmental conditions, thermal comfort depends on the clothing and activity level of a person. The amount of clothing is measured against a standard amount that is roughly equivalent to a typical business suit, shirt, and undergarments. Activity level is compared to being seated quietly, such as in a classroom.

Because of the thermal interaction between the building's envelope, the occupants and the auxiliary system, in practice steady state conditions are rarely encountered in buildings, especially in "free floating" naturally ventilated buildings. Monitoring of passive solar buildings with constant set point, has shown that there are important indoor fluctuations raising between 0.5 and 3.9 C, as an effect of the control system, (Madsen, 1987). Thus, knowledge of thermal comfort under transient conditions is necessary.

Field studies and basic thermal comfort research, (Humphreys, 1975), has shown that there is a slight discrepancy of the steady state models especially for the zones where no mechanical conditioning is applied. This is mainly due to the temporal and spatial variation of the physical parameters in the building, (Baker, 1993). In fact, occupants living in a permanent basis in air-conditioned spaces develop expectations for low temperature variations and homogeneity and are critical when indoor conditions deviate from the comfort zone they are used to. On the contrary, people in buildings that allow a degree of user control (e.g. naturally ventilated buildings) do so and become used to climate variability and thermal variation. Thus, their thermal preferences extend to a wider range of temperatures or air speeds. Moreover, it can be argued that closely-controlled thermal environment is unnecessary since humans can derive pleasure from the opportunity of responding to a stimulating, dynamic environment (Baker & Standeven 1996). Therefore, having strict requirements for thermal comfort is merely self-fulfilling, as they constrain the adaptive opportunities for occupants. This is one of the many possible confounding causes of sick building syndrome (SBS). Such adaptation to the thermal environment has been extensively studied and documented, (Nicol et al, 1995, Brager and De Dear, 1998, 2000, De Dear, 1998, De Dear and Brager, 1998, Rijal et al, 2002). A further consequence of strict adherence to traditional criteria for thermal comfort under static conditions is that it leads to buildings with expensive air-conditioning.

Field surveys have verified that the comfort temperature is very closely related to the mean indoor temperature, (Nicol et al, 1999), (McCartney and Nicol, 2002). Nicol and Humphreys suggested that such an effect could be the result of the feedback between the thermal sensation of subjects and their behaviour, such as clothing and window-airing according to weather conditions.

The principle of behavioural adaptation has been also verified through the PASCOOL research project. Based on the previous works, the comfort group of the European research project PASCOOL, (Baker, 1993, Baker and Standeven, 94, Standeven and Baker, 1994), has carried out field measurements to understand the mechanisms by which people make themselves comfortable at higher temperatures. It is found that people are comfortable at much higher temperatures than expected, while it is observed that people make a number of adaptive actions to make themselves comfortable including moving to cooler parts of the room. It is characteristic that here were 273 adjustments to building controls and 62 alterations to clothing, out of 864 monitored hours.
Various other research studies have verified the adaptive comfort approach. Klitsikas and all, (1995), have perform comfort studies in office buildings in Athens, Greece during the summer period. It has been found that almost always the theoretical PMV value is higher or equal than the measured thermal sensation vote, and the subjects felt more comfortable than predicted by the PMV theory. Lin Borong et al, (2003), has performed comfort studies in Chinese naturally ventilated buildings. It is concluded that the thermal sensation of people has a larger range than that at a stable environment. Comparisons have been performed against the PMV scale and it is concluded that the PMV model when applied to unstable or natural thermal environment to evaluate people's thermal sensation needs correction. Similar results have been found during a comfort survey under hot and arid conditions in Israel, (Becker et al, 2003), in Singapore, (Hien and Tanamas, 2002), in Indonesia, (Feriadi, 2002), in Algeria, (Belayat et al, 2002), and in Bangladesh, (Mallick, 1994).

Humpherys and Nicol, (2002), and Parsons et al, (1997), have provided some explanations for the errors in the PMV theory. According to the authors, as PMV is a steady state model there is a theoretical contradiction between the basic assumptions of the model and the imbalance assumed if the body is not comfortable. An other reason is related to the uncertainty and the fuzziness to calculate exactly the metabolic heat and the clothing insulation.

Important research has been carried out in order to develop an adaptive comfort standard. Analysis of the data included in the ASHRAE RP-884 database involving data of comfort surveys around the world, (De Dear and Brager, 2002), has shown that while PMV predictions fit very well with the preference of occupants in HVAC buildings, while 'occupants of NV buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns'. The same conclusions have been reported from various comfort field studies, (Webb, 1959, Nicol, 1973, Humphreys 1975, Busch 1992, Nicol and Roaf, 1994, Matthews and Nicol, 1995, Sharma et al, 1999, Taki et, 1999, Nicol et al, 1999, Bouden & Ghrab, 2001) As a result of the field studies, It was proposed that the optimum comfort temperature is a function of the outdoor temperature, and may be predicted by simple linear-regression equations of the following form, (Humphreys 1978, Auliciems and deDear 1986, Nicol and Raja, 1995) :

$T_{comfort} = a * T_{out} + b$, where T_{out} is the mean outdoor dry-bulb air temperature.

Based on these results a new adaptive thermal comfort for naturally ventilated buildings was proposed to be integrated in the ASHRAE – 55 Standard, and CEN standard EN 15251:2007.

Adaptive and variable indoor temperature comfort standards for air conditioned buildings may result in remarkable energy savings for cooling. (Auliciems, 1990, Milne, 1995; Wilkins, 1995; Hensen and Centrenova, 2001). Estimated energy savings of more than 18 % over that from using a constant indoor temperature are reported by (Stoops et al. 2000), while the corresponding energy savings for UK conditions have been estimated close to 10 %.

3.2.2 Annotated bibliography of selected evaluations of specific applications of thermal mass

- **A performance of hollow clay tile (HCT) laid reinforced cement concrete (RCC) roof for tropical summer climates**, K.C.K. Vijaykumar a,*, P.S.S. Srinivasan b, S. Dhandapani (2007): "Most of the Indian concrete buildings have 150 mm thick reinforced cement concrete (RCC) with weathering course (WC) having 75–100 mm thick lime brick mortar. Such roofs account for about 40–75% of total heat transmitted into the occupant zone depending upon the location and also account for the major portion of electricity bill in air-conditioned buildings. A new concept wherein hollow clay tiles (HCT) are laid over RCC instead of WC, has been proposed. The transient heat transmission across various types of roof structures for typical Indian climatic conditions has been studied. The energy savings obtained with the use of HCTroof is found to be 38–63% when compared with conventionalWCroof. When air is allowed to flow through the hollow passages, the air flow is found to take care of all variations in the outside climate and solar radiation, thus providing almost uniform roof bottom surface temperature."

- **A new type of vented concrete block for zero cooling energy** J. Khedari∗, M. Rungsiyopas, R. Sarachitti, J. Hirunlabh (2004): "This paper reports on the performance of a new prototype of horizontal hollow concrete block. Its innovation is that it can prevent the sight from outside and inside as well while permitting natural ventilation and increasing daylighting without inducing overheating. Investigation included compressive strength testing, indoor temperature, natural ventilation and daylight contribution. Performance were compared using two small houses (W × L × H: 1:2 × 1:2 × 2 m) one of them included two rows of the new prototype located near the ceiling and the floor. The experimental observations indicated that with closed window and when the prototype of concrete block was in use in all facades, the temperature di7erence between non-ventilated and ventilated houses was about 2–3◦C. This difference is less important (0.5–1◦C) when the window was open due to the small volume of house considered. The average air change is about 30–70 that demonstrates the good ability of the new prototype of concrete block to improve indoor conditions. The performance of the prototype of concrete block decreased when the number of walls equipped with vented blocks decreased. The contribution of daylight admitted through the block vents is about 20–500 lux. Finally, the compressive strength is twice that of commercial blocks available in the local market."

- **The Role Of Integrated Landscape Design In Energy Conservation In Detached Dwellings In The Arabian Gulf Region**, Mohammad Maqsood Bajwa (1994): "This paper presents an overview of the landscape design considerations, rationale for the selection of specific hard and soft landscape elements and initial observations of their influence in controlling the microclimate in detached residential buildings in the Arabian Gulf region. This experiment is part of a wider research programme in the field of passive solar cooling strategies at the King Faisal University, sponsored by the Joint United States Saudi Arabian Programme for Cooperation in the field of Solar Energy (SOLERAS). The objective is to identify the comfort enhancement potential of a carefully planned and executed integrated landscape design in a full-scale prototype passive solar cooling test house. Conventional concrete-block load-bearing construction with external insulation and heavy internal thermal mass was used. Fanger Predicted Mean Vote, as a function of dry bulb temperature, wet bulb temperature, air velocity and mean radiant temperature, was calculated and recorded continuously. These values have been averaged to evaluate hourly comfort conditions in various zones of the test house. Outdoor solar radiation and heat transferred through walls, openings and roof were similarly recorded before landscape layout and during the initial growth process of the plant material. The full potential of an integrated landscape design towards comfort enhancement can only be assessed after several years of continuous monitoring during the growth period of the plant material. Initial observations, nevertheless, tend to confirm results obtained by other researchers in their studies of the effects of specific individual landscape elements."

• **Comparative study on reduction of cooling loads by roof gravel cover**. A.M. Al-Turki, H.N. Gari, G.M. Zaki (1997): "The increase in demand for power to meet the ascending energy used for air conditioning in arid areas calls for new techniques to lower the cooling loads. In this paper a simple inexpensive method is suggested, where the thermal resistance of the building roof is increased by adding a layer of loose gravel. The gravel properties as well as the intergranular trapped air reduces the heat transfer through the roof. This technique is investigated experimentally for actual outdoor weather conditions. The results show that the effect of the gravel mass intensity is more pronounced than the size of the gravel. A factor that relates the heat transfer through the gravel covered layer to that of blackened concrete roofs is suggested on the basis of the present experimental results."

• **Comparison of DOE-2 with temperature measurements in the Pala test houses**, Rene Meldem, Frederick Winkelmann (1998): "The predictions of version 2. IE of the DOE-2 program for building energy analysis have been compared with measurements in the Pala test houses near San Diego, CA. This work was part of the California Institute for Energy Efficiency 'Alternatives to Compressor Cooling in California Transition Zones' project in which DOE-Z was used for parametric analysis of cooling strategies that reduce peak electrical demand. To establish the validity of DOE-2 for this kind of analysis the program was compared with room air temperature measurements in a 'lowmass' house with conventional insulated stud wall construction and a 'high-mass' house with insulated concrete walls. To test different aspects of the DOE-2 calculation, four different unoccupied, unconditioned thermal configurations of these houses were considered: unshaded windows. shAded windows, white exterior surfaces, and forced night ventilation. In all cases DOE-2 agreed well with the air temperature measuremems, with a mean deviation between simulation and measurement ranging from 0.2 to I .O K depending on configuration and type of house. Comparisons with inside surface temperature measurements also showed good agreement. Agreement between predictions and measuremenrs improved when a more accurate calculation of foundation heat transfer was used, the ground surface temperature was calculated. and the normal 7-day 'warm-up' period in DOE-2 was extended to I I da) s for the high-mass house."

• **Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods**. Baruch Givoni (1997). "Buildings with different mass levels were monitored in the summer of 1993 in Pala, South California, under different ventilation and shading conditions. The effect of mass in lowering the daytime (maximum) indoor temperatures, in closed and in night ventilated buildings, was thus evaluated. Night ventilation had only a very small effect on the indoor maxima of the low-mass building. However, it was very effective in lowering the indoor maximum temperatures for the high mass building below the outdoor maxima, especially during the 'heat wave' periods. On an extremely hot day, with outdoor maximum of 38°C (l00°F), the indoor maximum temperature of the high-mass building was only 24.5°C (76°F)) namely within the comfort zone for the humidity level of California. Comment: In 1994 the monitoring has been continued, first with the original dark color of the envelope and then with the buildings painted white, as well as under natural, all-day ventilation with open windows. The results of the 1994 experiments will be reported in Part II."

• **Predicting indoor temperatures in closed buildings with high thermal mass**. David Mwale Ogoli (2003): "This is an architectural science inquiry in which temperatures were simultaneously observed in buildings with low and high thermal mass at the equator. Four environmental test chambers with different thermal mass levels were monitored under different ceiling types in Nairobi, Kenya, during the warm period between January and March 1997. Walling for two test chambers was natural stone while for the other two was timber paneling. Further to this, roofing for two test chambers was heavy concrete tile while for the other two was lightweight galvanized corrugated iron (GCI) sheets. The effect of thermal mass in lowering the maximum indoor daytime temperatures was evaluated. The low mass test chambers closely followed outdoor conditions and did not offer any significant thermal storage. All the light-mass test chambers without ceilings recorded small effect on the indoor maxima. However, high thermal mass was very effective in lowering indoor maximum temperatures below the high outdoor maxima. On a hot day in February, when maximum outdoor temperature was over 33 ◦C (91 ◦F), the indoor maximum temperature in high mass building was 25.4 ◦C (77.7 ◦F), which is within the comfort zone."

• **A Ventilated Slab Thermal Storage System Model**. M. J. REN and J. A. WRIGHT (1998): "A simplified dynamic thermal model of a hollow core concrete slab thermal storage system and associated room is described. The model is based on a thermal network that can address the heat exchange between the slab cores and the ventilation air, the thermal storage in the building fabric, and the effect of the heat disturbances on the room. The increase in convective heat transfer at the corners of the ventilation cores is also discussed. For normal cyclic operation, the simulated mass and zone temperatures are both in phase with measured performance data. The model root mean square error between the simulated and measured performance is no more than 0.5"C for the average slab mass temperature and 1.O"C for the zone air temperature."

- **Thermal mass activation by hollow core slab coupled with night ventilation to reduce summer cooling loads**. Stefano Paolo Corgnati, Andrea Kindinis (2007): "This study deals with the analysis of the effectiveness of free cooling ventilation strategies coupled with thermal mass activation to reduce peak cooling loads. A numerical simulation of the temperatures distribution of an office placed in Milan, Italy, during the month of July, is conducted on a Simulinks dynamical model. No air-conditioned system is present but two different free cooling systems are analysed and compared. Both systems act a primary ventilation during the day and a night ventilation during the non-occupancy period but the first is a traditional mixing ventilation system, the other is a thermal mass activation system, i.e. the outdoor ventilation air, before entering the room, flows through the ducts of the hollow core concrete ceiling slab. The performances of the two systems are investigated by means of time profile analyses of indoor operative temperatures and by means of frequency temperature distributions during the occupancy period. The cooling performances are measured by two different discomfort indexes: one represents the discomfort time percentage during occupation period, the other the discomfort weighted on the distance of calculated operative temperature from the acceptable temperature interval. This paper, in last analysis, tries to highlight the possibilities on cooling loads reduction and on thermal comfort increase in Mediterranean climate, connected to new strategies for thermal mass activation and night ventilation."

- **A theoretical study of the thermal performance of the TermoDeck hollow core slab system**. P. Barton, C.B. Beggs, P.A. Sleigh. (2002) "The TermoDeck hollow core slab system is a versatile energy storage technique for controlling the environment within large and medium sized buildings. It utilises the hollow cores within pre-cast concrete floor slabs as ventilation ducts to produce an environment which is thermally stable. Although many TermoDeck systems have successfully been installed in Scandinavia, the United Kingdom and in other northern European countries, the thermal performance of the system is not fully understood. This paper presents the results of a theoretical study, using a numerical model, into the thermal performance of the TermoDeck system. In particular, the role of the bends in the system is investigated and the conclusion reached that their impact on overall heat transfer is minimal. It is also concluded that greater thermal attenuation is achieved by using a five-core pass system in comparison with a three-core system."

3.3 Challenges related to use of thermal mass and thermal comfort

Tunge materialer som betong og tegl leder varme bedre enn for eksempel tre. Når disse benyttes konstruktivt, eksempelvis i dekker, brannskillere og utkragede balkongdekker og svalganger, er det viktig med detaljløsninger som minimerer eller aller helst eliminerer kuldebroer. Dersom dette ikke taes hensyn til vil kuldebroer stå for en stor del av transmisjonsvarmetapet (20-40 %). En tommelfingerregel sier at det bør være en kuldebrobryter på minimum 100mm isolasjonsmateriale, se detaljtegningen til høyre.

Styring og kontroll for å samkjøre passive og aktive systemer for å unngå unødig kjøle- og oppvarmingsbehov er en utfordring i dimensjonering av varme-, kjøle- og ventilasjonsanlegg. God styring og samkjøring av systemene i driftsfasen er essensielt for at de aktive og passive tiltakene skal jobbe med hverandre og ikke mot hverandre. Dette er primært en utfordring for RIV og driftspersonalet som har ansvar for den daglige drift gjennom byggets levetid.

3.4 Needs for further research

- Evaluation of indoor climate associated with different design solutions that utilise thermal mass which eliminate the need for mechanical cooling (in conjunction with other passive cooling measures)
- Evaluation of why Termodeck has become so popular abroad but not in Norway. Can the "duct cleanliness" issue be convincingly solved?
- Evaluation and promotion of the best control systems for night time cooling. This must involve close collaboration with controls manufacturers/suppliers (e.g. Johnson Controls).
- Methods for improving opportunities for behavioural adaptation of the thermal environment in buildings, maximising exploitation of thermal mass.

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Heften "Termisk masse og klimatisering av bygninger – en oversikt tilrettelagt for byggherrer, arkitekter og rådgivende ingeniører", utarbeidet av SINTEF Byggforsk for byggutengrenser.no

4 Emissions

4.1 The current problem

In the developed world, most people spend most of their time indoors, and the quality of indoor air is of prime importance for occupant health and well-being. The quality of indoor air is affected by several factors, such as outdoor air, occupant activity, indoor installations and building materials. Gases or particles emitted from building materials into the air may cause effects ranging from irritation to increased risk of serious disease or death.

Building materials deteriorate over time. Deterioration is inevitable, but is accelerated under some conditions and can be retarded if care and knowledge about the behaviour of materials are put into the process of developing and using materials in building structures. Important environmental conditions that add to the stress that is put on a material include temperature, moisture, aggressive substances, ultraviolet radiation and microbes.

The ageing processes of the materials used in a building are not only of importance to those who are concerned with service-life and maintenance intervals, but may also be of immediate relevance to the health and feeling of comfort that its inhabitants experiences. Particularly moisture contributes to health related problems, and several studies have shown that dampness in buildings is a risk factor for health effects such as cough, wheeze and asthma (Bornehag et al. 2004, Bornehag et al. 2005). Some people experience inexplicable feelings of tiredness or headaches in some buildings (Sjögren 2001). These buildings are said to be sick. The reasons for specific health problems as well as more general feelings of discomfort are unknown, but probably related to the quality of the indoor air.

The quality of indoor air is highly dependent on the type and amount of emissions of volatile organic and inorganic compounds from building materials. As the number of materials used in buildings increase and the composition of products become ever more complex concerns for health effects and environmental effects have increased. Legislative measures are being introduced to lower emissions and standards for measuring and evaluating building materials have been developed.
Indoor air is affected by building materials in a number of ways. The most obvious mechanism is perhaps primary emission; i.e. the release of particles or volatile compounds from the components in the material itself. Common examples are release of terpenes from wood and plasticizers from soft plastics. Examples of primary emission of particles are less obvious.

Secondary emissions occur when materials are subjected to degradation mediated by environmental factors. A well-known example is emission of alcohols following alkaline hydrolysis of plasticizers in contact with moist concrete. Particle emission from materials normally requires some mechanical forces, e.g. from air currents, and are thus classified as secondary emissions. Strong forces during construction or maintenance work may generate large amounts of particles.
A proportion of volatile compounds and particles released into indoor air are deposited on surfaces or within materials, from where they or their degradation products may be released in tertiary emission processes.

Concrete is a highly alkaline building material. The alkalinity, in combination with moisture, will sometimes cause degradation followed by secondary emissions from materials in contact with the concrete.

4.2 What we know about it (Consensus)

4.2.1 Particle emission

Airborne particles and settled dust are generated from a variety of natural and anthropogenic sources, both indoors and outdoors, and therefore vary considerably in size and nature. Human health risks resulting from indoor exposure can be linked to the physical properties of particles.
Particles in the atmospheric environment constitute a major class of pollutants. Of significance in the indoor environment are both airborne and settled particles. The occupants inhale airborne particles, while the settled dust can either be inhaled, if it becomes resuspended, via ingestion or skin contact. The nature and size of the particles, duration of exposure time and particle concentration in the breathing zone of the exposed person are of importance.

There are three basic size categories for particulates, inhalable, thoracic and respirable (AIHA 1996, ISO 7708 1995). Respirable particles penetrates to the unciliated airways, thoracic particles penetrates beyond the larynx and inhalable particles are particles that is inhaled through the nose and mouth. Particles suspended in the air range from about 1 nm to about 100 µm. The former is molecular size and the latter is the size which particles sediment rapidly due to gravitation forces.

Cement particles range from about 3 – 100 µm (Owen et al. 1992). Most of the bigger particles are caught in the mucous of the nose and pharynx and are prevented from travelling deeper into the lungs. However, they often cause immediate symptoms and discomfort. The presence of particles in the air may produce ocular and nasal discomfort, or allergic responses affecting comfort and worker productivity (Kosonen et al.2004, Bejan et al. 2004).

Portland cement is corrosive, and workers may be exposed to dust during manufacture and packing of cement, and during mixing of concrete. Health and Safety Executive (2005) has prepared a hazard assessment document based on available scientific literature, the main conclusions being:
Cement causes irritation in skin, eyes and respiratory organs due to its alkalinity.
Hexavalent chromium (Cr(VI)) in cement causes elevated risk of allergic skin reactions in construction workers.
Reduced respiratory capacity is seen by workers exposed to high levels of cement dust for a long time, but dose-response relationship is not established.
There is a possible causal association between cement work and increased risk of certain cancers, but the evidence is insufficient. This report concentrates on effects of long term exposure of cement dust in work environments.

Quartz dust of respirable size is a risk factor for silicosis and chronic obstructive lung disease (COLD). Aggregates commonly contain quarts, and respirable dusts may be formed during quarrying of aggregates, or during e.g. drilling in the concrete or demolition of buildings.

Hygienic standards for total dust and quartz dust are established in several countries. “Administrative norms” from Norway are given in table below. OSHA standards give an identical PEL of 5 mg/m³ for Portland cement dust and “particles not otherwise regulated”

Table1. Administrative norms

CAS-nr.		[mg/m³]
14808-60-7	α-quartz, total dust	0,3 *
14808-60-7	α-quartz, respirable dust	0,1
	Total dust	10
	Respirable dust	5

* Sum of α-quartz, tridynite and christobalite.

4.2.2 Particle emission and indoor air quality

Since the 1980s, several studies have investigated the relationship between dust in buildings and the effect on occupants in the indoor environment (Skov et al., 1987). There has been conducted several studies to investigate the settled dust in dwellings and in commercial buildings. It has previously been shown that qualitative properties of settled dust are important to the development of the sick building syndrome (Gyntelberg et. al., 1994). The sick building syndrome is characterized (not standardised) by irritative symptoms from eyes, nose and pharynx, dry and irritated skin, and general symptoms such as headache, heavy-headedness, fatigue and general malaise (Skov 1992; Wilkoff and Kjærgaard 1992).
Office workers in modern buildings frequently report mucosal complaints from the upper airways. The symptoms may be due to inhalation of particles suspended in the indoor air (Skov et. al., 1993 and Skyberg et.al., 2001).

In 2002, six office buildings in the Oslo region in Norway with no reported “sick building” problems, were investigated for particle types in the indoor air (Kruse et al, 2002). The following particle types were found: concrete, gypsum, other mineral particles, metallic, iron oxide, other inorganic particles, skin scales, organic fibres, other organic particles and aggregates of small particles (probably exhaust and soot). Se figure 1, 2 and 3. Similar particle types have been found in settles dust in sick buildings (Gyntelberg et.al., 1994).

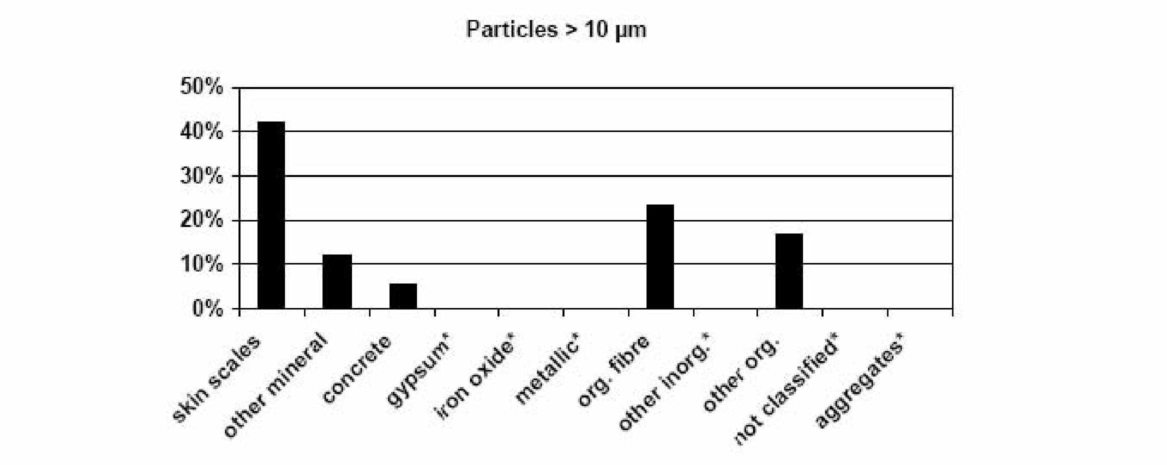


Figure 1. Particles >10µm in office buildings

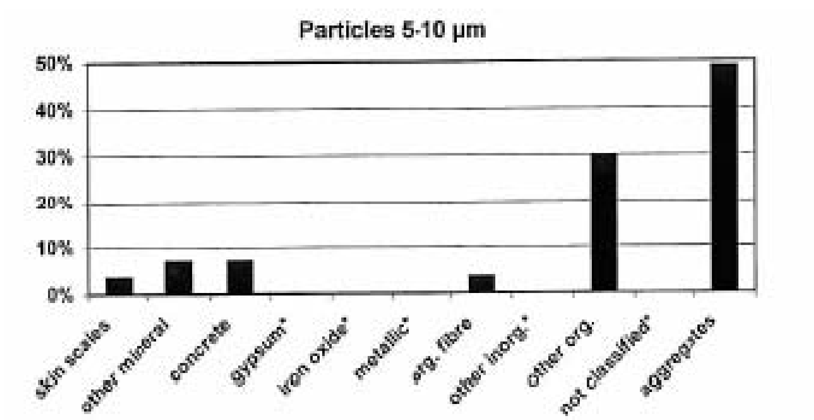


Figure 2. Particles 5 - 10µm in office buildings

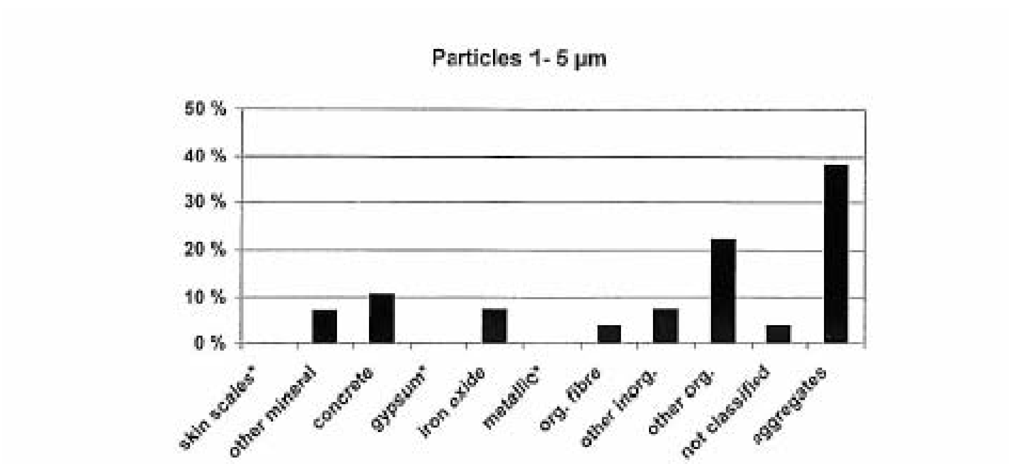


Figure 3. Particles 1 – 5 µm in office buildings

1.1.2 4.2.3 Radon risk

Concrete is produced by mixing cement with fine aggregates (sand), coarse aggregate (gravel or crushed stone), water, and small amounts of various chemicals (admixtures). The properties of concrete are determined by the type of cement, aggregate and water. Some aggregates that have been used in concrete production have turned out to be a source of radon gas, for example some natural stone.

4.2.4 Chemical emission

The sources of moisture in concrete are construction errors, accidents, moisture remaining after pouring the concrete or moisture being introduced as a part of some normal step in the building process (e.g. the use of a water based surface treatment). Concrete contains calcium hydroxide and alkali oxides and as a result the pore water can reach a pH of up to 13.5. Carbonisation of concrete leads to a lowering of the pH to a level between 8 and 9. The extent of the damage to an alkali sensitive material depends on the material composition, the pH in the water, contact time and temperature as well as the microstructure and the relative humidity in the concrete.

4.2.4.1 Critical relative humidity

Concrete is a porous material with a continuous system of pores and capillaries (Geving and Thue 2002). Porosity, i.e. the ratio between pore volume and total volume, and the sizes of the pores depend on the water to cement ratio (w/c). Both porosity as well as the pore sizes increases with increasing water to cement ratio.

The water in concrete is either chemically or physically bonded. Chemically bonded concrete is sufficiently inert that it will not easily be released and does not contribute to the humidity levels. Physically bonded water normally is of one of two different types:

• Adsorbed on the outer surface or pore surface of the material
• Condensed in the material capillaries.

If the material is in equilibrium with the surrounding air at a given temperature and air humidity all pores up to a certain size will be filled with water. At low relative humidity water is condensed only in the submicro pores. At higher relative humidity larger pores are filled as well. Dissolved salts in the pore water causes water to condense at a lower relative humidity.

Since water condenses in small concrete pores at low relative humidity and only condenses in larger pores at higher relative humidity, it follows that concretes dominated by small pores or with small pores at the concrete surface can cause problems at lower relative humidity than concretes with larger pores. The critical relative humidity is the level at which a material in contact with concrete will sustain damages due to alkaline moisture. The critical relative humidity is usually thought to be 85-95 % RH, although materials can sustain damages at lower relative humidities if the concrete is dominated by small pores (Geving and Thue 2002). In response to the realization that concrete floors with smaller pore size (lower w/c ratio) create a more aggressive environment, the Swedish Adhesive and Sealants Association has recommended that alkali resistant adhesives are used when bonding floor coverings to concretes with low w/c ratios (w/c = 0.38-0.50), whereas normal adhesives may be used at concretes with higher w/c-ratios (Swedish Adhesive and Sealants Association 2006).

4.2.4.2 Alkaline hydrolysis of building materials

The reaction between a material and the hydroxide ion in an aqueous solution is called alkaline or basic hydrolysis. Alkaline hydrolysis is responsible for the degradation of materials due to contact with moisture in concrete.

Adhesives containing ester-based linkages are particularly sensitive to hydrolysis, while urethane-, amide- and urea-linkages also show some hydrolytic instability (SpecialChem 2006). Ester linkages can be present in some polyurethane as well as some epoxy adhesives (SpecialChem 2006). Alkaline hydrolysis of an ester-linkage leads to the formation of an alcohol and the salt of a carboxylic acid (Roberts 1981, p. 821), see figure 1. This process is called saponification. Alkaline hydrolysis of an amide-linkage leads to the formation of ammonia or amine and the salt of a carboxylic acid (Roberts 1981, p. 1183).Acrylate-, ethylene vinyl acetate (EVA)- or polyvinyl acetate (PVAc)-based adhesives all containing ester linkages that are susceptible to alkaline hydrolysis as shown in figure 1. However, only the hydrolysis of acrylates will lead to the formation of volatile alcohols, typically 2-ethyl hexanol or 1-butanol. In the case of EVA and PVAc a non-volatile alcohol and the salt of an acetic acid will be formed. In this case there may still be loss of adhesion (Blom et al. 1996).

Alkyd paints are also known to react with alkaline moisture, e.g. in contact with concrete (Weldon 2001). This process is called saponification and involves decomposition of the ester-linkage to form alcohol and the salt of a carboxylic acid. The reaction is essentially the same as when adhesives containing an ester-linkage come in contact with moist concrete. The alcohol is non-volatile, but the paint will debond and loose its protective properties.

Paints based on acrylates and styrene-acrylate copolymers generally have good alkali resistance, but should not be used on a new concrete. It is recommended that the concrete is allowed to cure for at least one month prior to applications, otherwise the coating may fail to perform as intended (Stadelmann 2002).

In the Nordic countries much attention has been given to flooring systems (adhesive and covering) in contact with moist concrete, see Table 1. Adhesives for floor are usually used on large areas, and the damages due to alkaline hydrolysis can be extensive. These studies have concentrated on flooring products commonly used on concrete substrates in Norway and Sweden. Typical reaction products are 2- ethyl hexanol, 1-butanol, heptanol,

C_9- and C_{10}-alcohols. Persson (2003) also found 2-(2-butoxyethoxy) ethanol and 2-phenoxyethanol. 2-(2-Butoxyethoxy)ethanol and 2-phenoxyethanol are most likely not degradation products but rather components in the adhesive that are released when the adhesive decomposes.

Volatile degradation products are not only emitted to the air. A substantial amount of volatile degradation products is also absorbed into the pore system of the concrete and can be released long after the damaged adhesive has been removed, see figure 2.

Björk (2003) and Sjöberg (2001a) found that a number of the materials used in a flooring system were stable towards alkaline hydrolysis at pH 11, but not at pH 13. One would therefore expect that materials in contact with old concrete that has a lower surface pH due to carbonatation will not degrade because of alkaline hydrolysis.

Outside of the Nordic countries the effect of moist concrete on the degradation of building materials and the possible effect on indoor air quality has received little attention in the scientific literature.

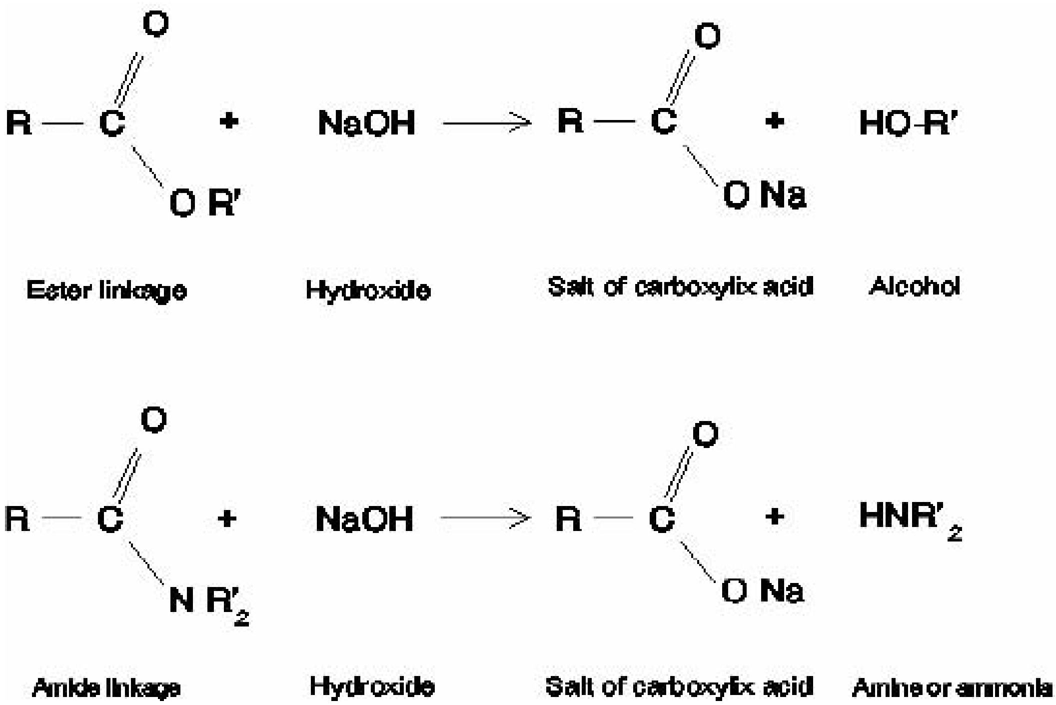
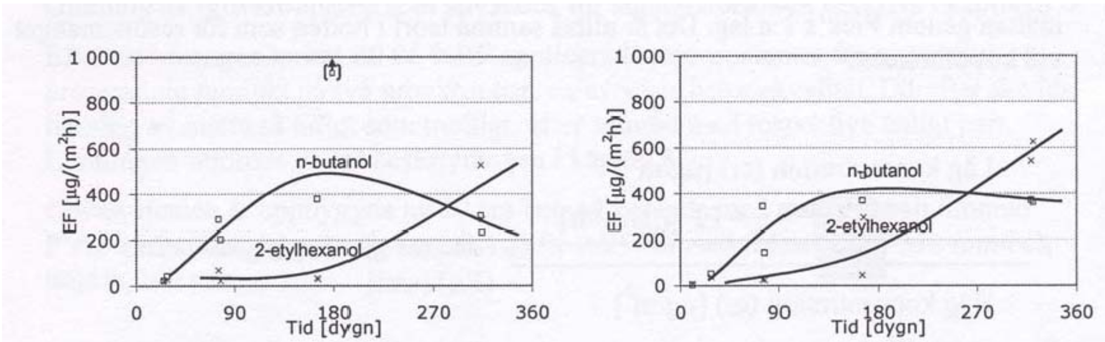
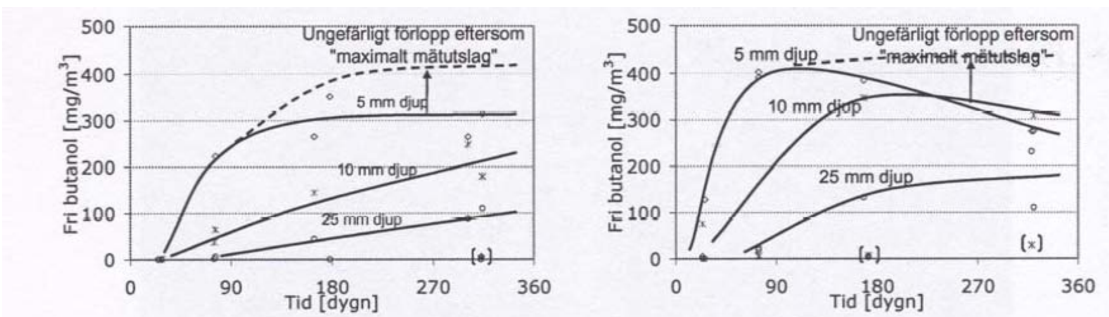


Figure 4. Alkaline hydrolysis of ester and amide linkages.



(a) (c)



(b) (d)

Figure 5. Alkaline decomposition of flooring materials (PVC floor covering and butylacrylate-ethylhexyl acrylate copolymer based flooring adhesive) in contact with moist concrete. The decomposition products are part emitted to the air and part stored in the concrete pore system. a) Emissions of n-butanol and 2-ethyl hexanol from the concrete surface (concrete w/c = 0,66). b) Absorption of butanol into the concrete pores (concrete w/c = 0,66). c) Emissions of n-butanol and 2-ethyl hexanol from the concrete surface (concrete w/c = 0,39). d) Absorption of butanol into the concrete pores (concrete w/c = 0,39). Figures from Sjöberg 2001b.

Table 2: Components that are part of flooring systems. Resistance to alkali moisture.

Product	**Reaction with alkaline moisture**	**Reference**
Components in flooring adhesives:		
Acrylate based flooring adhesives	Hydrolysis of the acrylate polymer in the adhesive leads to formation of alcohols and loss of adhesion. Volatile alcohols can have a detrimental effect on the indoor climate.	Blom et al. 1996, Alexanderson 2004
Acrylate polymer dispersion - component in flooring adhesives	Hydrolysis of the ester group in some acrylate polymers can lead to formation of C_8 hydrocarbons. The amount of hydrocarbon increases with pH. Some acrylates are stable even at pH 13.	Björk et al. 2003
Acrylate copolymer and acrylate-acetate copolymer based flooring adhesives	2-Ethyl hexanol and 1-butanol is formed when the adhesive comes in contact with synthetic concrete pore solution of pH 13. At pH 11 the adhesives are stable. The stability of different adhesives shows large variations. The flooring materials were not affected.	Sjöberg 2001a
Acrylate-based adhesive	2-Ethyl hexanol, 2-(2-butoxyethoxy)ethanol and phenoxyethanol.	Persson 2003
Components in PVC flooring:		

PVC floor covering	Hydrolysis of the plasticizer (normally phthalates) leads to the formation of alcohols such as 2-ethyl hexanol, nonanol isomers and decanol isomers.	Blom et al. 1996, Alexanderson 2004, Persson 2006
DOP - dioctyl phthalate (plasticizer in PVC flooring)	Hydrolysis of the ester group leads to the formation of 2-ethyl hexanol. Some 2-ethyl hexanol can be observed at pH 11 and 70 % RH.	Björk et al. 2003
Jayflex DINA - diiso nonyl adiapate (plasticizer in PVC flooring)	Hydrolysis of the ester group leads to the formation of branched C_9 alcohols. Some alcohols can be observed at pH 11 and 70 % RH.	Björk et al. 2003
Jayflex DINP - diiso nonyl phthalate (plasticizer in PVC flooring)	Hydrolysis of the ester group leads to the formation of branced C_9 alcohols. Some alcohols can be observed at pH 11 and 70 % RH.	Björk et al. 2003
Jayflex 77 - diiso heptyl phthalate	Hydrolysis of the ester group leads to the formation of heptanol. Heptanol is observed at pH 11 and 70 % RH.	Björk et al. 2003
DIDP - diisodecyl phthalate (plasticizer in PVC flooring)	Hydrolysis of the ester group leads to the formation of C_{10} alcohols. Some alcohols are observed at pH 11 and 70 % RH.	Björk et al. 2003

4.2.4.3 Adhesives as a source of moisture

Water based dispersions (latexes) based on acrylate, vinyl acetate or ethylene vinyl acetate copolymers typically contain 25-30 % water by weight, meaning that 55-60 g of water will be added to the substrate as part of the adhesive pr square meter, see table 2. Water from the adhesive that cannot evaporate to the air will be absorbed into the concrete and cause the relative humidity of the concrete to increase. Experiments performed by Sjöberg (2001a) show that the relative humidity increases sharply at the concrete surface shortly after bonding the flooring material; see one example in figure 3. The relative humidity in the top 3-5 mm of the concrete in figure 3 rose well into the range that is considered to be critical for alkaline hydrolysis (85-95 % RH). In an unlucky case the relative humidity under a tight flooring material that prevents evaporation (e.g. PVC) may rise above the critical relative humidity for alkaline hydrolysis of a particular adhesive or floor covering.

There are two principally different methods for bonding: wet- and dry-bonding. In the first case the adhesive is applied to the substrate and the flooring is applied directly onto the wet adhesive. Dry-bonding means that the adhesive is applied to the substrate and allowed to dry until it feels dry when touched lightly. The latter method allows some moisture to evaporate before the flooring is put in place. Dry-bonding is used for non-absorbing substrates with a tight covering. Examinations performed by SINTEF Building and Infrastructure (Blom 2007) of damaged floors indicate that erroneous use of the wet-bonding technique on concrete with decreased ability to absorb the water from the adhesive is suspected to cause alkaline hydrolysis of the adhesive and subsequent debonding of the floor covering.

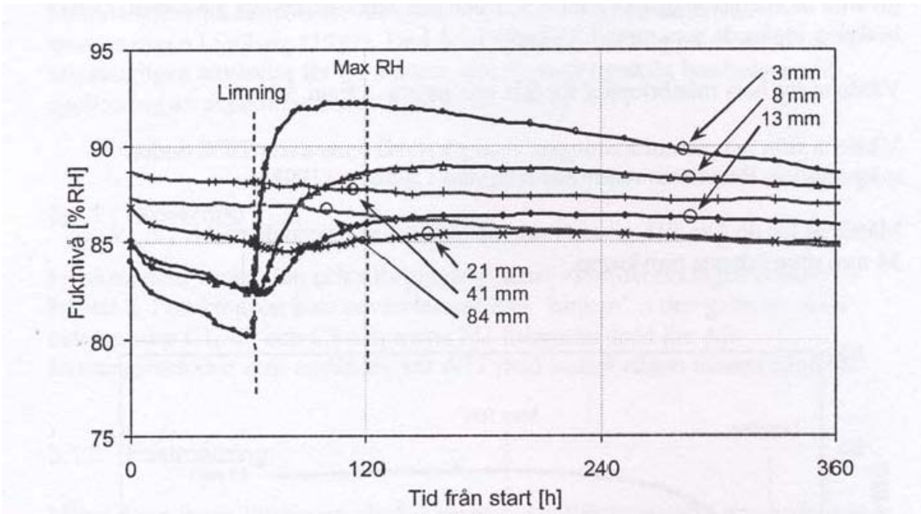


Figure 6. Relative humidity (Fuktnivå) in a concrete sample as a function of time in hours (Tid från start). The concrete (w/c ratio = 0.42) was poured into polyethene buckets (diameter = 205 mm and height = 200 mm). The top surface was levelled and the concrete was allowed to harden for 30 days before the PVC floor covering was applied to the top surface. The adhesive contained 90 g/m^2 water. The relative humidity was measured at 6 depths: 3, 8, 13, 21, 41 and 84 mm. The adhesive was introduced approximately 60 hours into the test (Limning) and the PVC floor covering was applied immediately after the adhesive, i.e. wet-bonding.

Table 3 Adhesives that are used in Norway and Sweden for gluing PVC, linoleum and other floor coverings. The data is according to the specifications of the manufacturers.

Name	**Binder** [1)]	**Dry solids content [%]**	**Density [kg/m^3]**	**Surface covered [m^2/l]**	**Moisture from the adhesive** [2)] **[g/m^2]**
Cascoproff Extra 3444	Acrylate/EVA copolymer latex	72	1260	4-6	59
Cascoproff 3448	Acrylate copolymer latex	70	1300	3-6	65
Cascolin 3449	Acrylate/EVA copolymer latex	74	1400	3-5	73
MultiTac MT Golv och vägglim	Latex	71	1270	3-6	61
Attack golv och vägglim	Latex	71	1270	4-6	61
Linotack linoleumlim	Vinyl acetate copolymer	75	1380	3-6	58

1) EVA - Ethylene vinyl acetate polymers.
2) Calculated from the maximum consumption.

4.3 Views/Hypothesis

4.3.1 Primary emissions from concrete

In Denmark, a study was conducted regarding chemical and sensory evaluation of different concrete qualities (Arbejdsrapport, Miljøstyrelsen, 2006). Four of the most used concrete qualities in Denmark without surface treatment were measured for chemical and sensory emission in a laboratory. These qualities were not exposed to alkaline moisture. The results showed that the chemical components emitted from the surfaces were low. The test panel for the sensory evaluation concluded with "acceptable" odour emission, and reduced odour emission over time. Particle emissions from these surfaces were not examined.
Concrete production has become more higher-tech and a number of chemicals are now commonly added to concrete to control setting time, plasticity etc. Because of these chemical admixtures, concrete could conceivably offgas small amounts of formaldehydes and other chemicals into the indoor air. For instance, use of fly ash in concrete will contribute to a higher amount of ammonia emission to the indoor air.

The clean and dry building philosophy during the building process is intended to provide a secure and healthy work environment and a satisfactory indoor climate to future occupants. How well the procedures function during the building process varies. Particle and dust from the building process can therefore be spread. Experiences from previous assignments conducted by SINTEF Building and Infrastructure, have indicated strong connections between the amount of building dust on high surfaces and indoor air complaints among occupants. A more rigorous study of the effects of coating concrete surfaces and a clean building process is recommendable.

Radon gas emitted from building materials to the indoor air are usually not a problem in Norway compared to the radon gas emitted from the soil. In Denmark in 2001, different qualities of concrete were tested in a laboratory to study the radon gas emission. Only small amounts of radon gas were emitted from the tested concrete qualities, but the study does not describe what kind of aggregates that had been used. In Sweden, the use of "blue concrete" in buildings have had a very negative effect on the indoor air quality.
Future concrete qualities, for example porous concrete, and more exposed concrete surfaces (with aggregates from natural stone) in future buildings might cause a higher radon emission to the indoor air.
Another aspect is underground ventilation ducts where the supply air can contain high radon concentrations because of penetration of radon gas from the ground. In general, underground ventilation ducts are not recommended in areas with high radium content in the ground.

4.3.2 Secondary emissions from concrete

Many commercial buildings in Norway have exposed surfaces such as ceilings, wall etc. The Norwegian laws and regulations recommend that exposed concrete surfaces should be coated because of the possible suspension of concrete particles to the indoor environment over time.

Some individuals suffer non-specific complaints such as headache, nausea, cough or skin problems after exposure to certain indoor environments. This is known as "Sick-building syndrome". It is difficult to link the complaints to specific causes, but 2-ethyl hexanol, a common component in secondary emissions due to alkaline degradation, is suspected to contribute.

In a study of indoor air quality and asthma symptoms in daytime personnel at hospitals, 2-ethyl hexanol has been linked to asthma symptoms in adults (Norbäck et al. 2000). 2-Ethyl hexanol was only observed in the buildings with signs of dampness in the floor construction. The floors had PVC floor coverings and it was assumed that the 2-ethyl hexanol originated from alkaline degradation of the flooring materials. The concentration of 2-ethyl hexanol was found to be on the average 12 µg/m3 (min-max concentrations: 2-32 µg/m3).

A Japanese study of a particularly sensitive individual linked respiratory symptoms with 2-ethyl hexanol in the work environment (Kondo et al. 2007). The concentration of 2-ethyl hexanol was found to be 13-44 µg/m3.

2-(2-Butoxyethoxy)ethanol is commonly used in detergents and paints. The acute toxicity of 2-(2-butoxyethoxy)ethanol due to a single instance of inhalation is low but the liquid substance is classified as an eye irritant, and may cause respiratory irritation at high vapour concentrations (European Union Risk Assessment Report 2000).

4.4 Focus areas for further work

4.4.1 Particle emission to the indoor air

There is little available information on exposures to cement and concrete dust outside cement and construction industry, and no published studies of potential health effects were found.
Dust samples from indoor environments commonly contain a significant amount of inorganic particles and particles derived form building materials (Schneider, 2001), but attempts to differentiate between sources are rarely made.
Exposed concrete surfaces in buildings and ducts may have properties that are desired to obtain a comfortable thermal environment. To assess how this affects indoor air quality and user health and comfort, it is necessary to know more about the amount and properties of particles released, how people are exposed to these particles, and if any effects of such exposure can be seen. Small-chamber studies may be well suited to

examine basic particle release, "source strength", from different qualities of concrete. It is likely that chemical composition, surface structure, setting conditions and age is important determining factors, and these are probably best studied under carefully controlled laboratory conditions. The effect of environmental parameters like temperature, moisture and air speed should be examined. Of particular interest is the effect of surface cleaning and coating. Such measures are more or less standard practice in some countries, while uncommon elsewhere and reasons for this difference are not obvious.
To further understand exposure, it would be desirable to examine the amount and characteristics of air-borne and settled particles in buildings with different use of concrete, preferentially with simultaneous examination of IAQ-related symptoms.

Tasks:

- Develop methods to examine particle release from different concrete qualities in laboratory
- Small-chamber studies on particle release from different concrete qualities, coated or un-coated.
- Field survey investigations in existing buildings in Norway to evaluate exposed concrete surfaces and the effects on indoor air quality.
- Field survey investigations in built examples in Norway to evaluate exposed concrete surfaces and the effects on indoor air quality.
- Field survey investigations during the building process and evaluation of the clean and dry building philosophy and how the use of cement/concrete during the building process affect surface dust load and future indoor air quality.

4.4.2 Chemical emission to the indoor air

Radon emission to the indoor air from concrete surfaces has not been a prioritized area because the main radon source in Norway is from the soil. In Sweden, radon gas from "blue concrete" have been a serious problem. Radon gas causes lung cancer and is a direct threat to occupants. Even though a study in Denmark concluded with low radon emission from different concrete qualities, further knowledge about radon gas emission from concrete surfaces and future concrete surfaces would be of great importance.

Even though chemical emission from concrete surfaces not exposed to alkaline moisture have been low, more chemicals are now commonly added to concrete.
Adhesives, floor coverings and paints in contact with moist concrete may undergo alkaline hydrolysis. Some decomposition products, such as 2-ethyl hexanol and butanol are volatile and are emitted to the air. The occurrence of 2-ethyl hexanol in indoor air is linked to respiratory problems. Substances that are part of an adhesive formulation, such as 2-(2-butoxyethoxy)ethanol and phenoxyethanol, may also be released to the air when an adhesive decomposes. Substances that are released upon decomposition are also absorbed into the concrete and can be released to the air at later point of time. To create a

comfortable and healthy indoor climate, further knowledge of the parameters determining secondary emissions from organic materials in contact with concrete would be of great practical value.

The corrosive potential of a specific concrete, i.e. how damaging it is to a material in contact with the concrete, depends on the relative humidity and the pore size distribution in the concrete. It is thought that concretes with smaller diameter capillaries are more damaging at lower relative humidities because the moisture condenses at lower relative humidity in small capillaries than in large capillaries. More work is needed to establish the relationship between moisture level, capillary size and corrosive potential of a concrete.

Several methods exist for testing alkali resistance. Choosing a test method requires knowledge about the conditions under which the product will be used, possible deterioration mechanisms in this environment as well as the limitations of the test method. Accelerated methods often give unrealistic results, underestimating the durability of a material, while non-accelerated methods are too slow. The GBR method is a useful real-time method for testing the alkali resistance of floor systems that can be extended to other parts of a building. Care must, however, be taken in the planning process.

Tasks:

- Field studies of the amount of radon gas in supply air from underground ventilation ducts.
- Laboratory and field studies on the amount of radon gas emitted from common concrete surfaces in Norwegian buildings and from future concrete surfaces.
- Laboratory studies of parameters determining secondary emissions from organic materials in contact with moist concrete
- Laboratory studies of chemical emissions from concrete surfaces (not exposed to alkaline moisture)
- Studies on the relationship between moisture level, capillary size and corrosive potential of a concrete
- Studies on testing alkali resistance

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5Visual comfort

5.1 The current problem

The goal of this subtask is to look at concrete as a potential material for achieving visual comfort. Can concrete surfaces influence daylight and lighting distribution in a beneficial way? The possible improvement of visual comfort by using concrete applies both to indoor environment (buildings) and to tunnels (motorways), road surfacing and noise-deflection walls etc..

From a visual point of view, lighting can be defined as a set of criteria that enables the luminous environment to satisfy visual needs (Berrutto et al., 1997). Lighting is of primary importance for office occupants and for drivers, whose vision is the sense which contributes the most to the perception of information. In the indoor environment, lighting (due to artificial lighting and/or daylight) is an essential need for the well-being and the capacity of concentration of the occupants. In tunnels, driving safety is highly depending on visual comfort. Recommendations for lighting have historically been issued with visual acuity and security reasons in focus (physiological need). Recent research works in the field of lighting take also in consideration psychological well-being. The physiological approach has been replaced by an approach focusing on visual comfort (Fontoynont, 2002).

5.2 What we know about it (consensus)

Visual comfort is a subjective feeling due to light quantity, quality and distribution. The visual environment procures a comfortable feeling when we are able to see clearly, without strain, in a pleasant coloured atmosphere. Visual comfort depends of a combination of physical parameters: illuminance level, luminance, contrast and glare. But it depends also of the surroundings, the type of visual task to accomplish, the available time for the subject to adapt his vision and the visual sharpness of the subject. (Bodart)

5.2.1 How to define visual comfort

The science of photometry refers to a particular vocabulary and photometric measurements use many different units of measure. One needs to have the following concepts in mind to understand the parameters that influence visual comfort (definitions from wikipedia).

Luminous flux or **luminous power:** measure of the perceived power of light. Expressed in lumen, lm.

Luminous intensity: measure of the wavelength-weighted power emitted by a light source in a particular direction, based on the luminosity function, a standardized model of the sensitivity of the human eye. Expressed in candela, cd (1 cd = 1 lm/sr)

Illuminance: total luminous flux incident on a surface, per unit area. It is a measure of the intensity of the incident light, wavelength-weighted by the luminosity function to correlate with human brightness perception. Expressed in lux, lx (1 lx = 1 lm/m²)

Luminance: density of luminous intensity in a given direction. It describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle. Expressed in candela per square metre, cd/m².

Reflectivity or **reflectance factor**: fraction of incident radiation reflected by a surface. Unitless or expressed in percentage, %.

5.2.2 Architectural design

The architectural design influences the following parameters:

a. illuminance adapted to the visual task
b. correct reproduction of colours
c. uniformity of light and well-balanced luminance ratios in the room
d. absence of cumbersome shadow
e. enhancement of object's shapes and contours
f. daylight penetration in the room
g. agreeable light
h. absence of glare

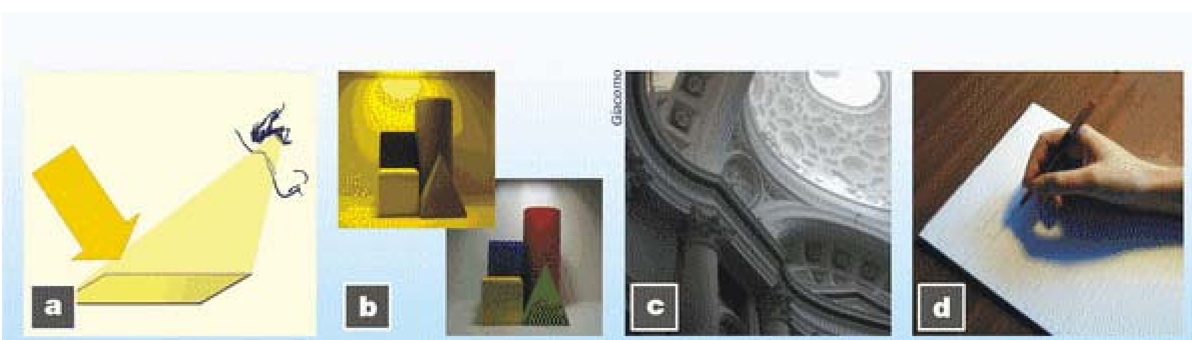

Figure 7. Visual comfort parameters depending of architectural design (Illustration; Bodart)

A surface is characterized by a reflectance factor which influences the luminance of the surface when it is exposed to light. The material choice will commonly have a significant effect on the uniformity of light and the luminance ratios in the room. It could also reduce or create glare.

5.2.3 Buildings

5.2.3.1 Relevant legislation

- NS-EN 12464-1 (2003) Light and lighting - Lighting of work places - Part 1: Indoor work places.
- Norwegian guidance to NS-EN 12464-1: "Luxtabell og planlegging av innendørs belysningsanlegg", Lyskultur 2007.
- NS-EN 12665 (2002) Light and lighting - Basic terms and criteria for specifying lighting requirements
- Planning and Building act 1986
- Technical regulation under the Planning and Building Act 1997.
- Guidance to Technical regulation under the Planning and Building Act 2007.

5.2.3.2 Importance of luminance ratios

The look is attracted by areas with highest luminance. This is the reason why it is important to have a higher luminance on the work plan than on the surroundings. Current recommendations specify luminance ratio limits between visual tasks, immediate surround and remote surface to be like 10:3:1. (Rea M., 1993).

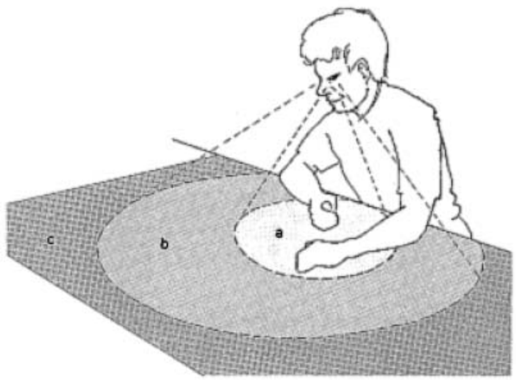

Figure 8. Recommended luminance ratio limits. Relation a:b:c should near 10:3:1 (Illustration: SINTEF Building and Infrastructure Knowledge Systems, "Building Research Design Sheets no. 421.610")

Luminance ratio limits should be lower than 10:3:1 when the eye is exposed to rough luminance changes. By smooth changes in luminance levels, the eye can tolerate higher variation of luminances. Luminance changes in a room shall not be too important and the transition from a luminance to another luminance shall be smooth. At the same time it is necessary to have different luminances in a room to create contrasts that allow perception and orientation in the room. (SINTEF Building and Infrastructure Knowledge Systems, "Building Research Design Sheets no. 421.610").

Luminance ratio depends on the lighting design and on the reflectance factors of the surfaces.

1.1.3

5.2.3.3 CIE recommendations

The CIE recommends a maintained illuminance of 500 lux for general offices (e.g. writing, typing, reading, data processing, etc.), for CAD work stations and for conference or meetings rooms. Where the main task is less demanding, e.g. filing, a lower level of 300 lux is recommended (NS-EN 12464-1).

The following recommendations about designing with direct lighting (Addendum to CIBSE Lighting Guide 3 issued 23 October 2001) have to be noticed.

The wall illuminance needs to be considered to ensure that the walls do not appear dark in relation to the working plane. With pure downlighting, there is a danger of the upper walls, especially, appearing dark. In certain spaces wall washing may be needed. To achieve a good luminance balance in a space, the average wall illuminance above the working plane, from both the direct and reflected components, should be at least 50% of the average horizontal illuminance on the working plane. Where these walls may be seen reflected in any display screens, then care must be taken to avoid bright scallops or patches appearing on the walls, i.e. gradual changes in illuminance will be necessary on these walls. To avoid the ceiling appearing dark, the ceiling average illuminance from both the direct and reflected component should be at least 30% of the average horizontal illuminance. This could be from the sides of surface mounted downlights; from uplighting elements of suspended luminaires; from dropped elements of recessed downlights or from supplementary uplights. In large spaces with unusually low ceilings this may be difficult to achieve and in such circumstances the proportion of light on the ceiling should be as high as is practicable. The following figure, reprinted from Fig 2.1 of the 1994 edition of the CIBSE *Code for interior lighting* indicates recommended surface characteristics.

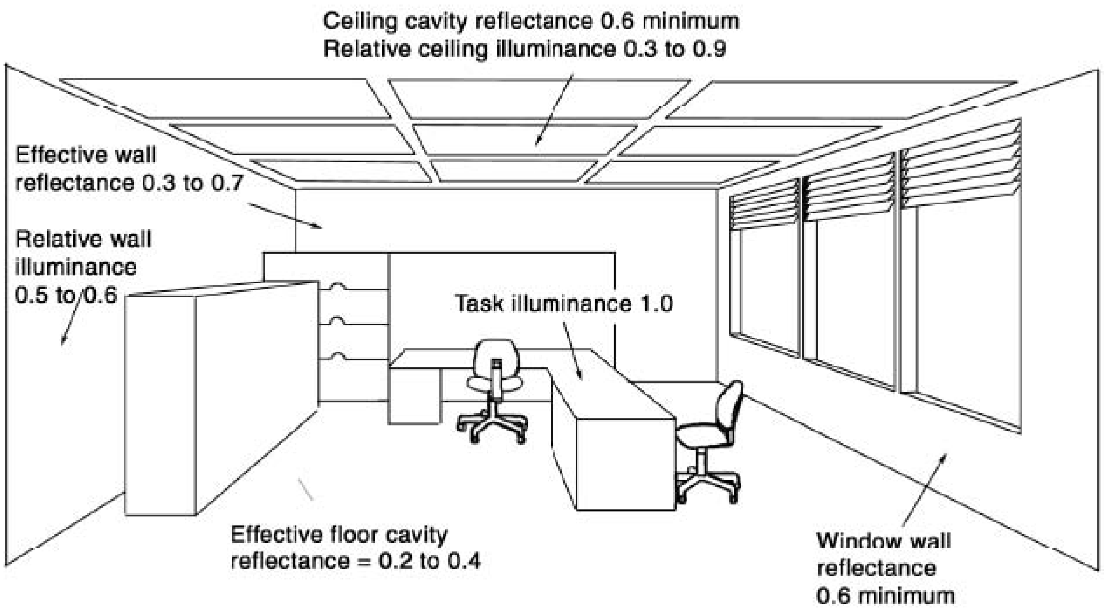

Figure 9. Recommended surface characteristics (reprinted from Fig 2.1 of the 1994 edition of the CIBSE Code for interior lighting)

As shown on figure 3, CISBE have a set of criteria for walls reflectance. To appreciate concrete qualities on visual comfort, it is of major concern to find out if concrete reflectance can match CISBEs recommendations.

CIBSE publications are intended as guidance only and do not have legal standing. Since they are emitted by an authoritative body they are nevertheless considered as a reference tool.

5.2.4 Tunnels

5.2.4.1 Relevant legislation

- CIE 115-1995, Recommendations for the lighting of roads for motor and pedestrian traffic.
- CIE 88-2004, Guide for the lighting of road tunnels and underpasses.
- CIE 66-1984 Road surfaces and lighting (joint technical report CIE/PIARC)
- CIE 61-1984 Tunnel entrance lighting: A survey of fundamentals for determining the luminance in the threshold zone
- NS-EN 13201-2 (2004) Road lighting - Part 2: Performance requirements
- NS-EN 13201-3 (2004) Road lighting - Part 3: Calculation of performance
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- CEN TC 169/WG 6, Tunnel lighting.
- Håndbok 021 Tunneler (under revisjon). Statens vegvesen.
- Håndbok 237 Vei og gatebelysning. Statens vegvesen.
- TØI 1997. Trafikksikkerhetshåndboka.

5.2.4.2 Tunnel lighting criteria

CIE guidance (CIE 88-2004), and UK standard (BS5489-2:2003) state that the amount of light required within a tunnel is dependent on the level of light outside and on the point inside the tunnel at which visual adaptation of the user must occur. When planning the lighting of a tunnel, there are 5 key areas to consider:
1. Access zone

Not within the tunnel itself, this is the stretch of road leading to its entrance. From this zone, drivers must be able to see into the tunnel in order to detect possible obstacles and to drive into the tunnel without reducing speed. The driver's capacity to adapt in the access zone governs the lighting level in the next part of the tunnel. One of the methods used by CIE to calculate visual adaptation is the L20 method, which considers the average luminance from environment, sky and road in a visual cone of 20°, centred on the line of sight of the driver from the beginning of the access zone.

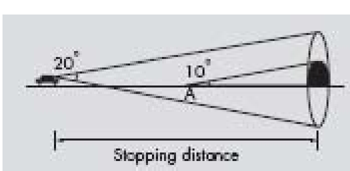

Figure 10. Visual adaptation in the access zone of a tunnel

2. Threshold zone

This zone is equal in length to the 'stopping distance'. In the first part of this zone, the required luminance must remain constant and is linked to the outside luminance (L20) and traffic conditions. At the end of the zone, the luminance level provided can be quickly reduced to 40% of the initial value.

3. Transition zone

Over the distance of the transition zone, luminance is reduced progressively to reach the level required in the interior zone. The reduction stages must not exceed a ratio of 1:3 as they are linked to the capacity of the human eye to adapt to the environment and, thus, time related. The end of the transition zone is reached when the luminance is equal to 3 times the interior level.

4. Interior zone

This is the area between transition and exit zones, often the longest stretch of tunnel. Lighting levels are linked to the speed and density of traffic.

5. Exit zone (one-way traffic)

The exit zone is the part of the tunnel between the interior zone and the portal. In this zone, during the day time, the vision of a driver approaching the exit is influenced by brightness outside the tunnel. The human eye can adapt itself almost instantly from low to high light levels, thus the processes mentioned when entering the tunnel are not reversed. However, reinforced lighting may be required in some cases where contrast is needed in front of or behind the driver when the exit is not visible, or when the exit acts as entrance in case of emergency or maintenance works where part of a twin tunnel may be closed. The length is a maximum 50m and the light level 5 times the interior zone level.

5.2.4.3 Visual adjustment

The visual adjustment from high luminance to low luminance while driving is not instantaneous. This is because of two disability phenomena:

- Spatial adaptation: the large difference in luminance between the outside and the inside of the tunnel will impede the vision of the driver when he is at the adaptation point (‘A’, opposite). The “Black Hole” phenomenon engenders a feeling of discomfort and insecurity.
- Temporal adaptation: human eyes need more time to adapt from brightness to darkness than the reverse. During this period of adaptation, the distance travelled is a critical factor.

The lighting design in tunnels shall include the following parameters: luminance level, type of lighting, shape of the portal, contrast between the floor and the walls, contribution of wall luminance, orientation of tunnel, type and density of traffic, traffic signage…

Glare is difficult to avoid at the end of a tunnel but it could be attenuated by a proper choice of reflectance factors for tunnel walls, an appropriate architectural design and a correct conception of lighting. Designing the exit with a small fall directed on the ground will reduce glare (the ground will generally give a low luminance level, contrary to the sky which is the source of daylight).

5.3 Any divergent hypothesis / views

No divergent hypothesis / views have been registered.

5.4 Needs for further research

Surfaces influence only some of the parameters that define visual comfort: the uniformity of light, the luminance ratios and the glare. All those parameters are related to reflectance factors. In the field of visual comfort, extensive work has been carried out to determine performance indices in artificial lighting and daylighting (Fontoynont, 2002), i.e. defining visual comfort according to the kind of light source. Research studies with focus on materials reflectance, and particularly on concrete reflectance are rare.

5.4.1 Reflectance factors

Reflectance factors for concrete surfaces are poorly documented.

Figure 11. Reflectance factors for concrete

Baker (1993)	0,40
Aschehoug (1979)	0,20 to 0,45
NBN L 13-001, Belgian lighting standard (2002)	0,55 (cement)

RAL is a color space system used to describe paint colors (developed in 1927 by **R**eichs**a**usschuß für **L**ieferbedingungen). Table with reflectance factors corresponding to RAL codes have been developed. (Nersveen J., 2007)

5.4.2 Photometric and colorimetric parameters

Recently, Bodart et al (2006) achieved a web tool for the choice of daylight scale model materials. The tool has been developed in order to help architects or lighting designers to choose materials for the building of daylight scale models. The essential photometric and colorimetric parameters that influence the light reflection and transmission of building materials were identified and several methods, for the qualitative and the quantitative evaluation of these parameters were studied. The tool contains a database with some building materials but concrete is not included.

Bodart et al (2006) identify the following parameters to compare the scale model material and the full-size material:

- the colour and the lightness
- the hemispherical reflectance and/or transmittance
- the reflectance and/or transmittance mode
- the visual aspect

5.4.3 Assessing both thermal and visual comfort

Simulations have shown that thermal and/or energy modelling of a building can result in satisfactory results on thermal comfort without noticing extreme visual discomfort (Greenup, 2001). Daylighting/lighting simulations are computationally-intensive and for this reason are not often incorporated into energy modelling of building. Such integration of daylighting calculation has been into the DOE-2 building energy analysis computer program have been proposed (Winkelmann, 1985). Greenup underlines the necessity of detailed interior daylight distribution calculations in assessing the thermal and visual comfort of a building, and in developing energy performance ratings for buildings.
As a conclusion of this review, recommendations for further areas to be investigated are listed below:

- Documentation of reflectance factors for different concrete categories, with different types of adjuvant. Monitoring procedure as described by Heidi Arnesen in her Ph-D thesis.
- Documentation of photometric and colorimetric parameters described by Bodart et al. for different concrete categories, with different types of adjuvant.
- Comparison of concrete with competitive building materials (concrete / rock / textile in tunnels, concrete / gypsum / painting in buildings).
- Scale models for some building types (typical office building, school, house) using large surfaces of exposed concrete on walls and ceiling (laboratory facilities in Trondheim).
- Modelling different forms of entrances and exits for tunnels, with different reflectance factors for the walls under definite lighting conditions, simulations (by using Radiance or Superlite computer tool) and scale models (laboratory facilities in Trondheim)
- Documentation of reflectance factors for concrete surfaces in tunnels at different moments of the service life. Dirty surfaces have lower reflectance factor than clean surfaces. When will the reflectance factor of the concrete change? Is concrete more porous than competitive building materials and attract easier dust from the motorway?
- Documentation of maintenance and cleaning costs for concrete surfaces in tunnels to maintain a constant reflectance factor, comparison with competitive building materials
- Comparison of concrete with asfalt as roadway covering. Which material have the lowest rate of dust emissions? Which influence of the dust emissions for the tunnel surfaces?

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