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Jointly edited by:

STEVIN-LABORATORY
of the Department of
Civil Engineering of the
Delft University of Technology,
Delft, The Netherlands
and
I.B.B.C. INSTITUTE TNO
for Building Materials
and Building Structures,
Rijswijk (ZH), The Netherlands.

Secretariat:

L. van Zetten
P.O. Box 49
2600 AA Delft, The Netherlands

Contents

THE SPALLING OF NORMALWEIGHT AND LIGHTWEIGHT CONCRETE ON EXPOSURE TO FIRE

Ir. W. J. Copier

Preface

The immediate reason for setting up, CUR Committee C 29 in November 1972 was provided by the results of some fire tests on beams and floors which had been carried out at the request of DSM* by the Institute TNO for Building Materials and Building Structures (IBBC-TNO) in 1971. The beams and floor-elements were made of lightweight concrete. The thermal properties of lightweight concrete suggest that a smaller depth of cover than in the case of normal weight concrete can be applied. The test were set up to establish the possible reduction in cover and still to obtain the required fire resistance. However during the tests destructive spalling occurred resulting in a very disappointing fire resistance. Destructive spalling being explosive dislodging of small or large pieces of concrete from the surface.

Some further research indicated that the moisture content of the hardened concrete play a very important role for destructive spalling to occur or not.

Committee C 29 has theoretical and experimental research undertaken for studying the drying process of concrete in relation to the composition of the concrete, the dimensions of the members concerned, and the climate that can be expected to occur in a building. Furthermore, some fire tests on beams and on slab-type specimens were performed at the Committee's request. The results of these tests are presented in this report.

The research on the moisture content of concrete members was duly completed. The experimental research on spalling conducted with the aid of fire tests remained on a fairly limited scale, however. The main reason for this was that during the investigations it emerged that the cost of the present-day types of lightweight concrete made the application thereof rather unattractive in economic terms. This does not alter the fact that the study which was carried out did indeed contribute to improving our understanding of the factors that play a part in connection with spalling. This is of importance in assessing the merits of new aggregates for concrete in relation to their behaviour under fire conditions.

On completion of the research the constitution of the Committee was as follows:

Ing. A. Gerritse, Chairman
Ir. Th. A. Feijen, Secretary
Ir. A. E. Christiaanse
Ir. Y. Collet
Ir. W. J. B. van Dalfsen
Ir. G. J. Gantvoort
Ir. A. Langhorst
Ir. J. G. Hageman, Mentor
Mr. W. O. Boekwijt, Reporter
Ir. W. J. Copier, Reporter

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* DSM = Dutch State Mines.

Mr. J. Boon (whose death occurred in 1976) and Drs. M. Stolp also participated in the Committee's work from the outset. These gentlemen, however, resigned from the Committee in 1975 and 1977.

The research was carried out under the direction of Ir. W. J. Copier, the author of this report, by IBBC-TNO. The investigation of the moisture content of concrete was undertaken by Mr. W. O. Boekwijt, likewise on the staff of IBBC-TNO.

Thanks are due to the Netherlands Committee for Concrete Research (CUR) for financing this work. Also thanks are due to the firms of Liesbosch Beton and NCH for their help in making some T-beams and in making some trial mixes with a plasticizer respectively.

THE SPALLING OF NORMALWEIGHT AND LIGHTWEIGHT CONCRETE ON EXPOSURE TO FIRE

Summary

It is well known that under certain circumstances concrete can show very violent spalling in fire tests. After a fire in a real building concrete structures show area's which have been effected by spalling. In general however the effected area's are rather limited indeed. It seems therefore obvious that in real buildings the conditions for violent spalling are seldom present. Evaluating the results of fire tests spalling can be subdivided in four catagories:

a. explosive dislodging of a few large pieces of concrete from the surface; it gives rise to serious damage resulting in failure of the member affected (destructive spalling with large pieces).
b. dislodging of small pieces of concrete at a few points of the surface; spalling which occurs at the edges (corners) of members such as beams and columns also comes within this category (local spalling).
c. gradual reduction of a cross-section; this phenomenon occurs mainly at very high temperatures (sloughing off).
d. explosive dislodging of small pieces of concrete from the surface, which occurs continuously; it gives rise to serious damage resulting in failure of the member affected and occurs especially at lightweight concrete (destructive spalling with small pieces.

From tests it appears that both forms of destructive spalling (point a and d) are very close related to the moisture content in the concrete. It appears that for lightweight concrete the destructive spalling with small pieces does not occur when the moisture content is below 5 to 7% (by volume). From the research it is also apparent that the probability of destructive spalling with a few large pieces diminishes if the thickness exceeds 0,2–0,3 m and the moisture content is less than about 7% (by volume) and, preferable, less than 5% (by volume).

Tests have shown that in practice concrete will seldom have a lower moisture content than 5 to 6% (by volume).

This moisture content is indeed very close to the moisture content below which the probability of destructive spalling has decreased very much.

Thus in order to avoid or diminish the probability of spalling one must among others try to reach a moisture content as low as possible. Starting with a moisture content of about 12 to 16% it is obvious that a certain time will elapse before a content of 5 to 7% will be reached. Regarding spalling one has to accept a certain drying time and or try to keep the drying time as short as possible.

The investigations concerning the moisture content occurring in actual practice showed that for members with a thickness of 0,3 m a moisture content of 7–10% must be expected at the end of two years. This period can hardly be reduced by ensuring as low

an initial moisture content as possible, but it can be reduced by artificial drying or by providing an environmental climate having a strong drying action. The study of the drying process revealed that in the first two years after concreting this process, in for example, office buildings, can be determined with reference to a weighted climate of 16 °C/65% RH, on the assumption that the openings in the external walls of the building are all glazed 4½ months after the time of concreting. It can be assumed that after two years the drying process is determined by a weighted climate between 20 °C/55% RH and 25 °C/40% RH. It has proved possible to calculate the material moisture content at any desired point of time [11], [12] and [13]. For this purpose the above-mentioned weighted climatic conditions and the thickness of the member in question are used, while some material properties must also be known, namely:

- the hygroscopic curve; (ψ as a function of φ)
- the diffusion resistance coefficient $\mu = (\delta / \delta_a)$
- the initial moisture content $\overline{\psi}$.

The influence of some parameters, on the drying process can roughly be established using the Boekwijt number B_0 being:

$$B_0 = \frac{(\rho' \delta_a / \rho_l) \cdot t}{\mu r^2 (\psi / \varphi)} = \text{constant}$$

It can readily be seen that:

- doubling the diffusion resistance index μ will entail doubling of the drying time;
- doubling the thickness r will entail quadrupling the drying time.

From calculations it can furtheron be shown that the factor $(\rho' \delta_a / \rho_l)$ halves when the temperature decreases from 25 °C to 15 °C which entails doubling of the drying time.

The effect of the factor ψ / φ is not easy to estimate. To obtain the shortest possible drying time, the hygroscopic curve should descend rapidly from the initial moisture content (at 100% RH). This means that the pores or voids in the concrete should be as coarse as possible. For normal circumstances however one want to achieve a concrete quality as good as possible and thus the factor ψ / φ can mostly hardly be influenced.

From fire tests it is shown that other parameters than the moisture content can contribute to the occurrence of spalling as far as they are bound up with the possibility of the moisture in the material being able to built up pressure in the interior of the member.

Some of the main parameters are mentioned subdivided into two categories I and II.

Category I contains those parameters from which the influence can be shown in fire tests namely:

I-1. the moisture content; as the moisture content increases the probability for formation of a saturated layer increases; the saturated layer is created by vapour, moving from the heated surface to colder interior regions; the saturated layer itself can move from the heated surface where the speed depends among others on the material porosity; when the saturated layer cannot penetrate fast enough into the member the heated zone and the saturated layer will meet causing high internal pressure resulting in spalling;

I-2. heating applied on one or two sides; when heating is applied at two sides the two saturated layers can meet each other so that further movement from the heated zone is prevented; when heating is applied at one side the moisture can escape at the non- heated surface;

I-3. the thickness mainly for heating from two sides; for decreasing thickness the two saturated layers can sooner meet each other;

I-4. compressive stress from prestress or external loads; when non or small compressive stresses are present it is very likely that internal cracking occurs (due to temperature stresses); due to internal cracks moisture can move or escape more easily;

I-5. reinforcement; from this simular effects as from compressive stress can occur.

Category II contains those parameters from which the influence can hardly be recognized from fire tests, using an approach of phenomenological demarcation of processes which, on experimental evidence, can be expected to occur in a fire. The meant parameters which must in spite of this of importance with regard to spalling are:

II-1. Material properties as porosity, permeability, heat conductivity and tensile strength;

II-2. for lightweight concrete, the kind of coarse aggregate (as far as investigated);

II-3. the moisture distribution over a cross-section;

II-4. the magnitude of the compressive stress; the presence of compressive stress seems to be of more importance than the magnitude;

II-5. the amount of reinforcement (provided that the bars are not too close to each other); the distinction "whether or no reinforcement" is more of importance than the amount of it (practical reinforcement ratio's).

Besides the findings described in this report, which are bound up with the causes of spalling related to the moisture content, there are a number of other possible measures that can be taken with a view to ensuring a certain degree of fire resistance. These are applicable both to normalweight and to lightweight concrete and are indicated in Chapter 2.

In spite of the mentioned results from the research carried out one must remember that spalling will be a capricious event. This is caused by the fact that the occurrance depends on many parameters from which, one by one, any influence can be present or from which, more or less, several influences working together simultaneously. Generally speaking the influence of the moisture content is the most important of all.

As the moisture content of concrete structures will be on the long run below a certain level (5 to 7% by volume) the probability of destructive spalling to occur, will be rather low in practice. This in accordance with the impression of real concrete structures after fire.

This report, giving the results of the research carried out, comprises four subdivisions:

- Literature research on the spalling of normalweight and lightweight concrete (Chapter 1, 2 and 3);

- theoretical experimental research on the behaviour of the moisture content in concrete under practical conditions (Sections 4.1, 4.2 and 4.3);
- supplement experimental research on the spalling of lightweight concrete during a fire (Sections 4.4 and 4.5);
- conclusions and recommendations.

Knowing that the last words on spalling have not yet been written it was tought usefull to give an extensive description in this report of all the tests carried out in order to contribute in the discussion.

NOTATIONS

B_0	constant (Boekwijt number)
C	ratio
d	thickness of slab
G	weight
p	vapour pressure
p'	saturation vapour pressure
q	mass flow density or flux
R	gas constant of water vapour
r	distance
ϑ	temperature
T	temperature
t	time
δ	water vapour conduction coefficient in a material
δ_a	water vapour conduction coefficient in air
σ'_b	compressive stress in concrete
ρ_1	specific gravity of water
ρ	vapour concentration
ρ'	saturation vapour concentration at a particular temperature
$\Delta\rho$	difference in vapour concentration
Φ	relative humidity of air
Ψ	moisture content in % by volume
$\overline{\psi}$	average moisture content in a section, measured in % by volume
μ	diffusion resistance index
ζ	ratio

The spalling of normal weight and lightweight concrete on exposure to fire

1 Introduction

1.1 *General*

An analysis of cases of damage or failure affecting structures has shown fire to be one of the most commonly occurring causes [1]. Partly for this reason it is laid down in Chapter 3 of the Netherlands Standard NEN 3850 that the designer must take account of the possible occurrence of fire as a so-called "special influence". In the present report a particular aspect of the behaviour of reinforced concrete and prestressed concrete structures under fire conditions will be examined in more detail.

In general, the behaviour of reinforced concrete structures at high temperatures can be described as favourable. For a structural member of given dimensions and carrying a given load it is possible to predict the length of time during which it can resist the effect of a fire before failing. During a fire the ambient temperature will rise, and so will the temperature of the member under consideration.

With rising temperature the mechanical properties such as the strength and rigidity of the steel and concrete will diminish. A reinforced concrete or prestressed concrete structural member will fail when the temperature of the respective constituent materials (i.e., steel and concrete) is so high that the reduced strength associated with that temperature is no longer able to equilibrate the external forces.

For members loaded mainly in compression (columns) the temperature within the concrete is largely the determining factor with regard to their loadbearing capacity. In the case of members loaded mainly in bending (beams and floors) the temperature attained in the steel plays an important part. The temperature at a particular point of a cross-section at a particular instant after the outbreak of fire is determined by, on the one hand, the intensity of the fire and, on the other, by the thermal resistance of the material and by the distance of that particular point from the heated face of the member. Hence it follows that the thickness of the concrete cover to the steel is of major importance with regard to the temperature that develops in the latter. A greater thickness of cover means that the temperature in the steel at a given point of time after the outbreak of fire will be lower. The instant of failure can therfore be modified by the choice of concrete cover provided. The length of time that elapses between the start of a standardized fire and the failure of a structural member exposed to it is a measure of the resistance of the member to the action of the fire. It is called fire resistance and is expressed in minutes. The fire resistance is determined by the attainment of a particular limit state, more especially the limit state of failure. Other limit states are also possible, as appears from the Netherlands standard NEN 3884. To ensure the safety of human and animal life and to limit the amount of damage and loss sustained in the event of fire, codes of practice and building regulations lay down certain requirements with regard to fire resistance.

The designer should so design and detail a structure as to fulfil these requirements.

From the foregoing it is evident that for members loaded in bending the fire resistance requirement with respect to the limit state of failure can be duly fulfilled by an appropriate choice of concrete cover to the steel, provided that one can be sure that this cover will remain intact during a fire. In practice it sometimes occurs that, because of what is known as "spalling" of the concrete, this last-mentioned condition is not satisfied.

1.2 *Spalling of concrete under fire conditions*

By the spalling of concrete on exposure to fire is to be understood the explosive detachment of large or small pieces of concrete from the concrete surface subjected to heating. Fire tests show this spalling to be an erratic phenomenon. It may occur locally or it may affect the entire surface and it is accompanied by popping noises which may range from faint to loud. In one fire test performed on a lightweight concrete beam the noise emitted by the spalling was so loud that conversation in the vicinity was not possible without raising one's voice. On the basis of a survey of observed forms of spalling in tests performed in various European laboratories [2] it appears that, broadly speaking, there are three forms in which this phenomenon manifests itself:

a. Explosive dislodging of a few large pieces of concrete from the surface (destructive spalling with large pieces). This form of spalling usually occurs in the first 10 to 50 minutes after the commencement of the fire; it gives rise to serious damage, resulting in failure of the member affected (see Fig. 1). It sometimes occurs that the member is entirely shattered without any preliminary spalling of the concrete to give advance warning of this event, which must likewise be assigned to this category of spalling.

b. Dislodging of small pieces of concrete at a few points of the surface (local spalling). In this case only relatively minor portions of the surface of, for example, a beam or slab are dislodged (see Fig. 2). Spalling which occurs at the edges (corners) of members such as beams and columns also comes within this category.

c. Gradual reduction of cross-section (sloughing off). This form of spalling, in which layers of concrete drop away from the surface, occurs chiefly at very high temperatures of the material and slowly continues as time goes by.

   From experimental research it appears that the phenomena described in a, b and c occur both in normalweight concrete and in lightweight concrete. In the latter, however, there additionally exists the possibility of a form of spalling which in character and manifestation cannot be assigned to any of the three above-mentioned categories. It will, to complement the subdivision envisaged in [2], be described separately as a fourth category d.

d. Explosive dislodging of small pieces of concrete from the surface (destructive spalling with small pieces). If this phenomenon does indeed develop, it occurs continuously in the period between 8 and 25 minutes after the commencement of the fire, resulting in removal of concrete to a depth extending far beyond the reinforcement (Fig. 3).

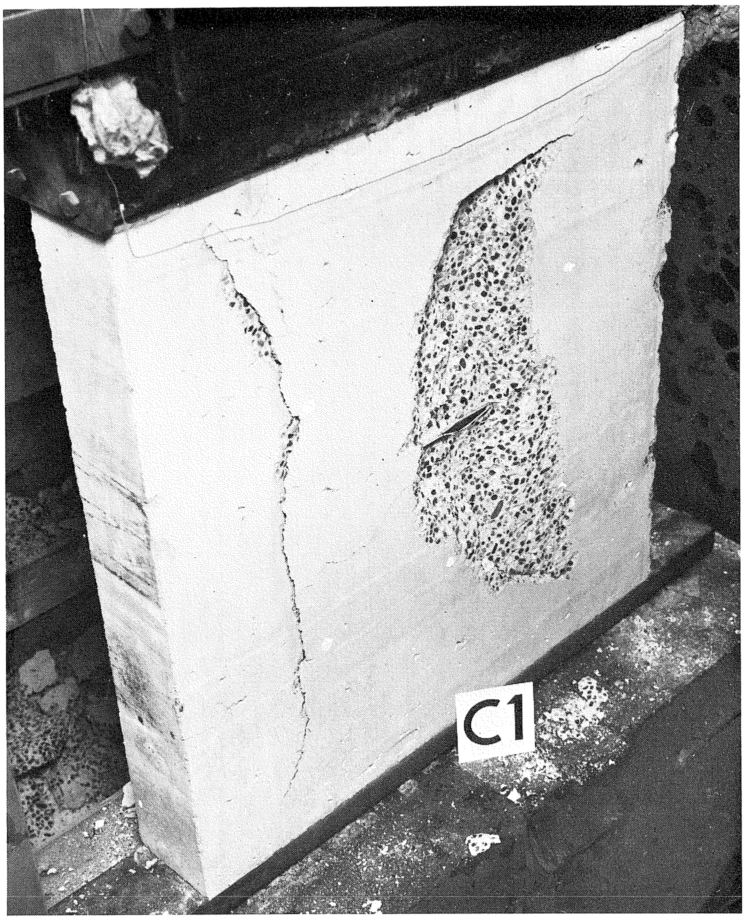

Fig. 1. Slab-type lightweight concrete specimen after a fire test.

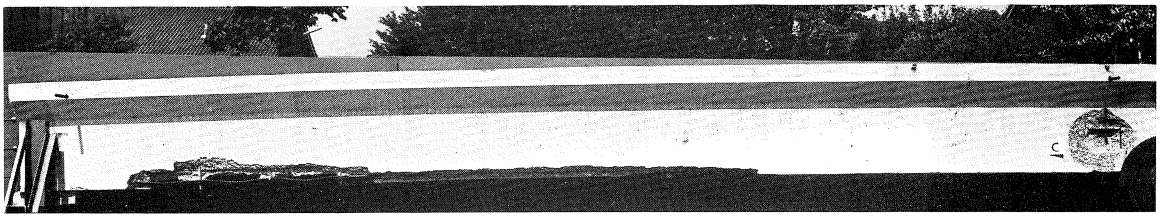

Fig. 2. Prestressed lightweight concrete beam after a fire test.

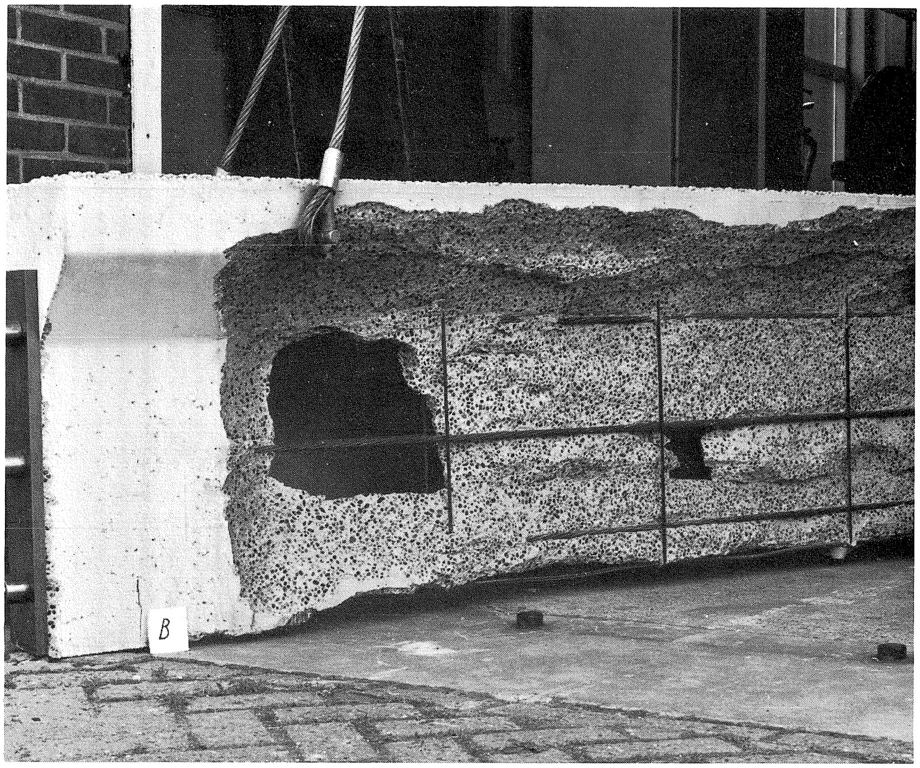

Fig. 3. End portion of a prestressed lightweight concrete beam after a fire test.

From the fire tests it has also emerged that hybrid froms of these several types of spalling may occur. It is apparent from Figs. 1, 2 and 3 that the concrete cover, or indeed more than the cover, may be lost as a result of spalling during a fire. This loss of cover will obviously have an adverse effect on the fire resistance of members which rely in part for their fire resistance upon the protection given to the steel by the concrete cover. The prediction of fire resistance by calculation is complicated by the possibility that spalling will occur. For this reason the causes of this phenomenon have been the subject of research conducted in various laboratories. The results of these investigations, in so far as they are available to the present author, will now be briefly discussed.

2 The spalling of normalweight concrete: information published in the literature

2.1 *Possible causes and associated theories for normalweight concrete*

In general, the following three principal causes of spalling are mentioned in the literature, namely:

a. mineralogical constitution of the aggregates;

b. temperature stresses resulting from:
   - restrained expansion due to non-uniform temperature distribution in the cross-section and to restrained expansion in the longitudinal direction;
   - difference between the coefficients of thermal expansion of steel and concrete;

c. moisture content of the hardened concrete in connection with compressive stress in the concrete due to prestress or external loading.

Re a

As a result of temperature rises, physical and chemical changes may occur in the material of certain aggregates and such changes may be accompanied by an increase in volume. However, in the literature [3] the view is expressed that this phenomenon is seldom so serious as to cause failure of a structural member.

Re b

When a concrete member is exposed to a rise in temperature, the temperature on the surface of the member will be higher than farther inwards. The temperature distribution within the cross-section is not linear, so that expansion restraint of the fibres of the material will give rise to secondary stresses. For materials with linear-elastic behaviour it is possible, for a given temperature distribution and given boundary conditions, to calculate the stresses. With this analysis it can be determined whether the stresses in the outer layer attain the compressive strength of the concrete, thus giving rise to thermal spalling. Both in [3] and in [4] it is concluded, on the basis of tests and calculations, that the occurrence of such spalling cannot be ruled out. The authors consider it unlikely, however, that the serious forms of spalling observed in many tests are due to this cause, and they come to the same conclusion with regard to spalling that may occur as a result of a difference in thermal expansion between steel and concrete.

Re c

The possibility of spalling being bound up with clogging of pores (voids) by carbonation is envisaged in [5]. Water present in the concrete would thus be prevented from escaping and would develop pressure in the voids on undergoing a rise in temperature, thus producing tensile stress which could attain the tensile strength of the concrete. These considerations are, however, concerned with a theoretical model whose consequences have not been experimentally investigated. With regard to this it must be borne in mind that the so-called carbonation front penetrates only at a slow rate into the concrete. If this hypothesis were correct, spalling would not occur in young concrete. This is contradicted by tests performed in West Germany as well as by tests performed in collaboration with CUR Committee C 29 at the Institute TNO for Building Materials and Building Structures (IBBC-TNO). These last-mentioned tests will be further discussed later on in this report.

In [4] and [6] an interesting theory is discussed which merits a fuller description. When a concrete surface is subjected to a rise in temperature, heat will penetrate into the concrete, resulting in desorption of moisture in the outer layer thereof. Most of the water vapour thus formed will flow towards the colder interior of the concrete and be reabsorbed in the voids. Since the thickness of the heated outer layer gradually increases, an accumulation of water and vapour will occur in the voids behind this heated layer. At some distance from the hot face of the concrete this effect will result in the formation of a saturated layer of a certain thickness (moisture clog). At the same time, the thickness of the heated layer will continue to increase. The moisture clog will thus be displaced farther and farther into the interior of the concrete at a rate depending on the internal voids structure. If the saturated layer cannot move fast enough, it will be overtaken by the advancing heat front. At the "interface" there occurs evaporation of water, which consumes heat, so that a steep temperature gradient develops there. The water vapour thus formed at the interface cannot migrate farther inwards, since the layers it encounters there are saturated with water, and it will therefore strive to makes its way into the heated layer. Since the temperature progressively rises from the interior to the exterior, the temperature of the water vapour - and, because of restrained expansion, therefore also the vapour pressure - rises very rapidly. The forces set up by the restraint of expansion which are developed on a front located between the heated layer and the saturated layer will have to be resisted by tensile forces acting in the concrete perpendicularly to that front. If the tensile strength of the concrete (at the temperature attained) is not sufficient to resist the tensile forces thus produced, a layer of approximately the thickness of the heated dried-out outer layer will be dislodged from the surface of the concrete. As conceived in the model envisaged here, the occurrence or non-occurrence of spalling is determined by the material properties such as porosity, permeability, thermal conductivity and tensile strength. With regard to this, Harmathy [4] established a set of equations which have not yet been experimentally verified. A drawback of the model is that it ignores possible influences such as the magnitude of the moisture content, the dimensions of the member, the presence of compressive stresses (due to prestress or external loading), and the occurrence of stresses as a function of the duration of the fire.

Some years ago, research on the spalling of normalweight concrete [3] and of lightweight concrete [7] was carried out in West Germany. More particularly for normalweight concrete it was attempted to find an explanation for the occurrence of spalling on the basis of the results of very comprehensive experimental research. A theory which is based on the model developed by Harmathy and others (as described above) and which tries to remove the above-mentioned shortcomings of that model interpretation is presented in [3]. This theory mainly gives an analysis of the flow of water vapour through the heated outer layer after the formation of a saturated layer. The flow of vapour through the voids will, according to this theory, set up frictional forces at the walls of the voids, and these forces manifest themselves as tensile forces within the concrete skeleton. The theory indirectly leads to a number of inferences.

The highest values of the tensile stresses in the concrete occur in those zones where water is converted into vapour, subject to the condition that the prevailing temperature is 100 °C–105 °C. These stresses will be higher as the initial moisture content of the concrete is higher. For normalweight concrete it appears that for a moisture content of about 7% (by volume) the tensile stresses that develop will be of the order of magnitude of the tensile strength of the concrete.

If the fire develops more rapidly than in accordance with the so-called standard curve, the tensile stresses that then occur in the concrete will be higher. From the theoretical model it follows that in the case of relatively thick members (> 200 mm) made of normalweight concrete the occurrence of spalling diminishes, or even ceases, after about 25 minutes. This is confirmed experimentally. The explanation is that the evaporation front moves farther and farther into the concrete, while at the same time there occurs escape of moisture, to the exterior of the member. After about 25 minutes any moisture still present in the concrete is unable to build up tensile stresses that can reach the tensile strength. Besides, with the rise in temperature, secondary stresses lead to the formation of hair cracks, in the interior of the concrete member, as a result of which the flow resistance encountered by the moisture is reduced. It appears from experiments that in members in which a compressive stress is acting (due to prestress or external loading) the occurrence of spalling has a more violent character. This may be so because there is less hair crack formation within such members. In [8] it is also stated that the expansion of materials is counteracted by prestress. The fibres remain under compression, so that no hair cracking occurs. It is considerd that for this reason the compressive strength at elevated temperatures is higher if the rise in temperature has taken place under load.

If the thickness of a concrete member is less than about 200 mm, the evaporation front can develop much more quickly, and spalling will then occur at an earlier stage after the outbreak of fire. With regard to this, heating applied to the member from two sides is more unfavourable than one-sided heating. In the latter case, the moisture can escape also at the cooler face of such relatively thin members, without being able to build up really high tensile stresses in the concrete. In the case of two-sided heating it follows from the model that spalling will occur after about 15 minutes in an 80 mm thick member, and after about 7 minutes in a 50 mm thick one. Spalling ceases when the temperature at the axis of symmetry attains 110 °C. The intensity of spalling of structural normalweight concrete is virtually unaffected by the quality (strength class) of the concrete. Concrete of higher quality possesses higher density and therefore offers higher resistance to flow phenomena in its interior. However, the tensile strength of such concrete will as a rule also be higher. These two counteracting influences practically cancel each other out. Besides, no appreciable shift in the occurrence of cracking in relation to time is observed.

In conclusion it can be stated that the presence of moisture is to be regarded as the principal cause of spalling and that the manifestations become more serious according as more of the following factors co-operate:
- the moisture content increases;
- a compressive stress (due to prestress or external loading) is present;

- reinforcement is provided;
- heating is applied from two sides;
- the thickness of the member decreases.

On the basis of the theories outlined above and of the experimental research conducted, a number of recommendations for the prevention of spalling of normalweight concrete can be made.

2.2 *Recommendations for the prevention of spalling of normalweight concrete* [3]

In this section a set of preventive measures drawn up by Meyer Ottens [3] will be reviewed. It is to be noted that these recommended measures have not, in so far as might be necessary, been critically examined on their merits by the Committee.

2.2.1 Prevention of spalling of normalweight concrete

According to [3] an important cause of spalling is low tensile strength of the concrete. This is considered to be more particularly relevant in connection with the destructive type of spalling. The following remedial measures are recommended in [3]:
- as far as possible, use aggregate with a rough surface texture;
- as far as possible, reduce the quantity of very fine aggregate and do not use any fractions that are of powder fineness;
- do not use any aggregates which in themselves already have a low tensile strength, such as slate or gneiss.

It is also important to avoid as far as possible the development of secondary stresses. This can be achieved by, for example, choosing the cross-sectional shape and dimensions as favourably as possible (see [3])

2.2.2 Prevention of destructive spalling of normalweight concrete

Destructive spalling refers more particularly to the case where large pieces of concrete are dislodged. In [3] it is reported on experimental evidence that no seriously detrimental forms of spalling will occur if the moisture content of the concrete is below 5% (by volume), a value which can be adopted as a safe upper limit. If the moisture content is above 5% and if heating is applied from two sides, serious spalling can be prevented by designing the member with due regard to the data presented in Fig. 4. This diagram is valid for plain (unreinforced) or lightly reinforced normalweight concrete members. In conformity with the theory outlined earlier on, it appears that for diminishing thickness and increasing compressive stress in the concrete the member may come within the "severe spalling" region. From the steep rise of the curve it is evident that the magnitude of the compressive stress has no considerable effect. We shall revert to this in subsequent chapters.

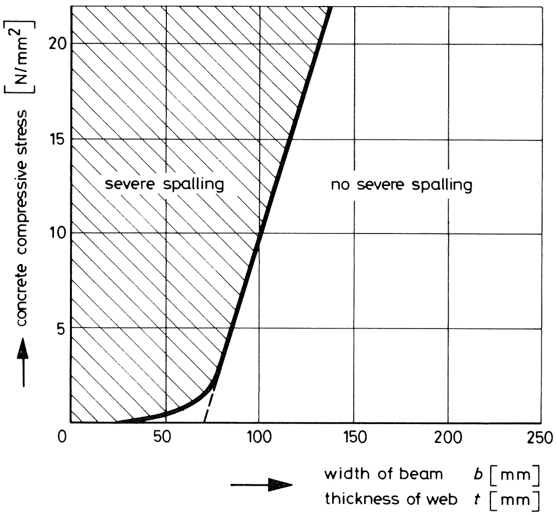

Fig. 4. Occurrence or absence of severe spalling in:
- plain or lightly reinforced normalweight concrete
- moisture content in excess of about 5% (by volume).

2.2.3 Other measures for the prevention of spalling of normalweight concrete

Besides the measures referred to in 2.2.1 and 2.2.2 [3], the application of one or more of the following measures can prevent spalling or reduce the risk of its occurring:

- partial or complete encasement of the concrete, ensuring that the rate of temperature rise in the structural member is slowded down, the consequences of this are, first, that the secondary stresses due to the non-linear temperature distribution are lower and, second, that the drying process during the fire proceeds more slowly, so that no build-up of high tensile stress due to moisture can occur; the casing is assumed to be so constituted as to allow the released moisture to escape;
- taking steps to ensure that the average moisture content is as low as possible; this can be achieved by drying the concrete to a moisture content of less than 5% (by volume), preferably starting from as low as possible an initial moisture content (low water-cement ratio, e.g., by using a plasticizer); in this connection it is to be noted that the research conducted by the Committee showed the drying process generally to proceed very slowly; it also emerged that, in striving to obtain a low initial moisture content, the drying time needed for attaining a certain average moisture content is not proportionally reduced;
- using concrete with a tensile strength which is substantially higher than commonly employed; unfortunately, with the concrete mix compositions in present-day use, this is hardly a practicable measure;

- using a fine-mesh reinforcement (not fly-wire netting) in the concrete cover: so-called skin reinforcement, which is advisable more particularly where large depths of cover (> 40 mm) are provided; this mesh will keep the cover in position (even though perhaps damaged), so that it will continue to protect the main reinforcement; in the Committee's opinion such mesh is meaningful only in cases where high standards of fire resistance have to be met; in such cases fairly high temperatures are liable to occur, causing the concrete to disintegrate and to lose its cohesion more particularly in the parts constituting the cover; a high moisture content will, however, have an adverse affect in such circumstances because it may result in the entire layer of concrete being dislodged.

In conclusion, it can be stated that, if desired for practical reasons, the measures mentioned in 2.2.1 and 2.2.2 do indeed appear quite practicable. Thus, casings or facings are employed in buildings for other reasons (e.g., architectural), and by ensuring that they also meet relevant requirements in connection with fire hazard, complete or partial protective enclosure is possible.

3 The spalling of lightweight concrete: information published in the literature

3.1 *Possible causes and associated theories for lightweight concrete*

Generally speaking, the causes for the spalling of lightweight concrete reported in the literature are the same as those indicated for normalweight concrete (see Section 2.1). In [7] it has been investigated, on the basis of numerous tests, whether a diagram as given in Fig. 4 for normalweight concrete can also be established for lightweight concrete. This has not proved possible on the evidence of the test results obtained, however. It has furthermore been attempted in [7] to apply also to lightweight concrete the moisture flow model adopted for normalweight cncrete in [3] for explaining the results. A number of approximate calculations showed the tensile concrete stress due to vapour pressures in lightweight concrete to be an order of magnitude lower than those in normalweight concrete. The main reason for this difference lies in the greater porosity of lightweight concrete. It is considered unlikely that the occasionally quite violent spalling observed in lightweight concrete can be explained with the moisture flow model. In view of the approximate assumptions made, further research is recommended.

From experimental research as described in [7] and from tests carried out by the Committee it has been found that for lightweight concrete:

- spalling becomes more severe with increasing moisture content;
- if spalling occurs, it generally does not cease and results in failure of the member.

Hence in [7] it is considered possible that spalling in lightweight concrete occurs in consequence of sudden expansion of water vapour and not of outflow of vapour. The lightweight aggregate particles which can absorb water or vapour are surrounded by a relatively impervious skin. A rise in temperature can cause a build-up of pressure due to expansion restraint.

Spalling may occur as a function of the dimensions of the space in which the vapour is enclosed (as determined by the particle dimensions and the voids volume present), the distance to the surface of the member, the tensile strength of the concrete and the vapour pressure. This is experimentally demonstrated in [9]. In [7] this is considered to be the most probable theory to account for the occurrence of spalling in lightweight concrete.

3.2 *Conclusions from the literature with regard to the spalling of lightweight concrete*

From the phenomena described in 2.1 and 3.1 it emerges that as yet no clear-cut theories to account for spalling are available. From tests it does indeed appear that it is essentially an erratic process. Hence any empirical or theoretical consideration of spalling will always contain some element of uncertainty. In the literature the generally accepted opinion is that its principal cause lies in the development of high vapour pressures during heating. The magnitude of these pressures is dependent on the amount of vapour produced and on the transport of vapour that takes place. This means that a realistic analysis must be based on a model in which the transport of heat and moisture are taken into account. Moisture transport may take place both in the liquid and in the vapour phase. Furthermore, it is necessary to have information on material properties such as permeability, diffusivity, porosity (with structure and dimensions of the pores or voids). In combination with the moisture transport mechanism other causes may also affect the occurrence of spalling. Thus, temperature stresses may arise in consequence of a rise in temperature. A proper analysis of these stresses requires information on the multiaxial behaviour of concrete at high temperatures ($T > 300\,°\mathrm{C}$), which information is not at present available. Further research with regard to the above-mentioned aspects is meaningful and is bound to receive the attention of future investigators. Vapour pressure measurements as reported in [9] and [10]* can yield interesting information. In combination with this it is conceivable that measurements will be performed for determining the size and the distance travelled by the spalled-off pieces (large or small) of concrete. From this information it will be possible to deduce the force involved (vapour pressure in combination with the diminished tensile strength as a function of temperature). As appeared from Section 2.2 a few simple precautions for the prevention of spalling can be applied to normalweight concrete. As for lightweight concrete, the information available in the literature is rather less clear-cut. The Committee accordingly conducted research relating more particularly to lightweight concrete; the results obtained are reported in Chapter 4.

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* In the description of the literature on spalling, no mention has been made of [10]. The reason is that the measurements performed had extended over a period of several days, which is not realistic with reference to an outbreak of fire, but is relevant to processes occurring in furnaces and chimneys. The measured vapour pressures were an order of magnitude lower than those reported in [9].

4 Research on lightweight concrete

4.1 *Statement of problem; other considerations*

From the literature and from test results it emerges that the main cause of spalling lies in the moisture contained in the concrete, in conjunction with compressive stress simultaneously acting in the concrete. If the moisture content is high, but the compressive stress is of low magnitude, the probability of spalling will be less (in a case where no reinforcement has been provided). Concrete as a construction material owes its considerable scope for application more particularly to its favourable mechanical properties under compression. Viewed in this light, it is hardly meaningful to aim at designing structures with low compressive stresses in order to reduce the hazard of spalling in the event of fire. For this reason, in further research the emphasis has been laid more particularly on the moisture content occurring in the material of the structures concerned. These considerations led the problem serving as the starting point for such research to be formulated as follows:

a. What moisture content can in actual practice be expected to be present in lightweight concrete in a building after some time? With regard to this it is of course possible to modify the moisture content, e.g.:
    - by trying to install the glazing as early as possible (so as to exclude atmospheric influences from the interior of the building) and by utilizing the time until occupation of the building for drying it as far as possible by heating;
    - by using concrete with the lowest possible initial moisture content, which may be achieved by steam curing, low water-cement ratio or indeed vacuum treatment to extract water after the concrete has hardened.

b. Is it possible, for a given compressive stress, to indicate a particular moisture content at which spalling will no longer, or hardly, occur?

c. What conclusions can be drawn as to fire resistance in relation to spalling, having regard to the moisture content values envisaged in a and b?

It may be asked whether it is indeed necessary to require additional precautions in connection with safety. This question is not being dealt with by the Committee, however, because the formulation thereof comes within the competence of the proper authority. The results of this research can, however, serve as a basis for a decision that may be made with respect to this.

The experiments which were performed with a view to answering question a are described in Section 4.2. These can be subdivided into three categories:

- Measurements of the variation of the moisture content of the material as a function of time in specimens made with various materials. The specimens were stored under various climatic conditions, the moisture content being measured over a period of 1¼ years. The procedure applied is discussed in Section 4.2.1.
- Measurements of the climate in four buildings. The purpose of these measurements is to obtain some idea of the conditions under which the drying of concrete in a building will take place. The procedure applied is described in Section 4.2.2.

- A theoretical experimental determination of the moisture content of the material. For this purpose the climate data recorded in the four buildings are being used. With the aid of a number of experimentally determined material properties the course of variation of the material moisture content as a function of time, as was measured in the test specimens, will also be determined by calculation. The procedure applied is described in Section 4.2.3.

The measured data will be further analysed in Section 4.3. A climate which can be rated as representative of the drying process will be deduced from the recordings of the climatic conditions. With this representative climate it will then, with the aid of the arithmetical determination of the moisture content, be possible to calculate the moisture content of the material at any desired point of time. This is meaningful because time is an especially important factor in this context.

With a view to answering question b a number of fire tests were performed on lightweight concrete members, which will be described in Section 4.4 and further analysed in Section 4.5.

The answer to question c will be dealt with in Chapter 5, where a comparison will moreover be made between the fire resistance of normalweight concrete and lightweight concrete as regards spalling.

Finally, with reference to the above statement of the problem, two points are to be noted in relation to the experimental research carried out:

- The research is subdivided into two parts: on the one hand, the fire tests; on the other, the determination of the moisture content under service conditions, as a function of time.
- The research is not directed at the physical processes which occur in the concrete with regard to spalling during a fire,but constitutes rather more a phenomenological demarcation of processes which, on experimental evidence, can be expected to occur in a fire. This is not to suggest that investigation of the physical processes which cause spalling under fire condition is superfluous. Adequate knowledge of these processes may well provide indications for possible measures to reduce or prevent spalling. These possibilities are left in abeyance in the research within the context of the problem as stated above. This approach has been deliberately adopted for practical reasons.

4.2 *Experiments relating to the moisture content of the material* [12]

Since water is used for making concrete, some moisture will be present in the hardened concrete. As a rule, this amount of moisture will decrease by diffusion and evaporation (drying) as time goes by. The moisture content is an important factor in connection with spalling, and for this reason it is important to know after what period of time a certain moisture content can be expected. It has accordingly been attempted to find the answer to this question both by experimental and by theoretical means. The drying process of concrete is governed by:

- the climate (temperature and relative humidity);
- the type of concrete (pore or voids structure);
- the dimensions.

A number of experiments were performed in order to arrive at a description of the drying process, namely:
- measurements of the moisture content of the material in test specimens; these were subjected to various climatic conditions which were measured;
- recording of the climate in four buildings

The results of these measurements were used for a theoretical verification from which it appeared that it is indeed possible to describe the course of the drying process.

4.2.1 Measurements of the moisture content of test specimens

For the purpose of determining the moisture content that occurs, 15 specimens were made. These were stored under various climatic conditions. Some data relating to these specimens are given in Table 1. As appears from this table, the following variables were adopted:
- The composition of the concrete in five different mix proportions in accordance with Table 2, incorporating the lightweight aggregates Korlin A, Korlin B, Agral 650 and Argex S. Table 3 gives information on these materials. The grading of the coarse aggregate employed is given in Fig. 5.
- The dimensions: the thickness is more particularly of importance with regard to the drying process; the thicknesses of the specimens were 0,22 m, 0,44 m and 0,15 m.
- The climatic conditions. A number of specimens were stored in an air-conditioned room providing a constant climate of 25 °C and 35% relative humidity. Other specimens were stored in a building (Rabo Bank at Doetinchem) in which the temperature

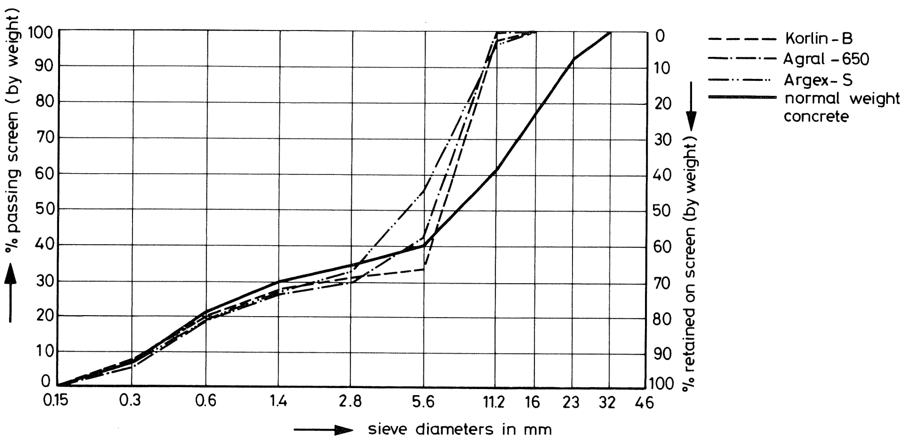

Fig. 5. Grading curves for the aggregates.

Table 1. Data of the test specimens.

specimen	aggregate	dimensions (m^3)	number of evaporation faces not sealed off and area per face	climate
1	Korlin A	0,70 × 0,22 × 0,22	4 × (0,22 × 0,70 m^2)	outdoor
2			2 × (0,22 × 0,70 m^2) diametrical	outdoor
3				25 °C/35%
4		0,70 × 0,44 × 0,44	4 × (0,44 × 0,70 m^2)	outdoor
5			2 × (0,44 × 0,70 m^2) diametrical	outdoor
6				25 °C/35%
7	Korlin B	0,15 × 0,50 × 0,50	1 × (0,50 × 0,50 m^2)	25 °C/35%
8	Argex-S			
9	Agral-650			
10	gravel			
11	Korlin B	0,15 × 0,50 × 0,50	1 × (0,50 × 0,50 m^2)	Rabo Bank
12	Argex-S			
13	Agral-650			
14	gravel			
15	Korlin B			

Table 2. Concrete mix compositions and properties of the fresh concrete

constituents and properties of the fresh concrete		Korlin-A	Korlin-B	Agral-650	Argex-S	normalweight concrete
specimen No.		1 to 6	7 and 11	9 and 13	8 and 12	10 and 14
cement (PC-A-ENCI)	kg/m^3	370	325	335	331	300
coarse aggregate	kg/m^3	634	496	547	599	1204
sand	kg/m^3	631	619	639	630	676
water	kg/m^3	159	202	197	237	159
water-cement ratio	-	0,43	0,62	0,59	0,72	0,53
bulk density	kg/m^3	1794	1642	1718	1797	2339
Walz's compaction index	-	1,41	1,09	1,12	1,13	1,10
air content	% by vol.	-	-	-	-	2,4
compressive strength (0,15 m^3) at 28 days	MPa	about 40	27,5	32,9	31,9	33,3

and relative humidity were ascertained by measurements (see Table 4). A third batch of specimens was stored in the open air on the site of IBBC-TNO at Rijswijk, where the temperature and relative humidity of the atmosphere were recorded, as indicated in Table 4.

The moisture content of the 15 specimens was measured in drilled cores which were obtained with a hollow drill (30 mm internal, 40 mm external diameter) equipped with a Widia alloy (tungsten carbide) bit. The moisture content was defined as the difference between the weight of the core sample in the condition considered and its weight after drying at 105 °C to constant weight.

Table 3. Lightweight aggregates employed.

	raw material	manifacturing process	mass of the particle kg/m^3	application
Korlin A*	selected Brunssum clay	expanded in a heat-treatment process	1100 to 1300	structural lightweight concrete
Korlin B*	selected Brunssum clay	expanded in a heat-treatment process	1100	not for structural lightweight concrete
Argex S**	river clay from the Scheldt	expanded in a heat-treatment process	1300 to 1500	structural lightweight concrete
Agral 650***	slate	expanded in a heat-treatment process	650	structural lightweight concrete

For further information the following brochures should be consulted:
* "Korlin DSM", published by DSM, P.O. Box 65, Heerlen
** "Argex", published by NV Argex, Marnixlaan 19a, Brussels 5
*** "Agral 650", published by NV Agral, P.O. Box 8-6240, Farciennes

For the determination of the moisture content so much hardened cement paste and associated aggregate was used as corresponded to the composition of the concrete, so that the moisture content thus found could justifiably be regarded as a continuum. The cross-sectional distribution of the moisture at any particular time was likewise determined by obtaining drilled core samples at various depths.

The measured average material moisture content $\overline{\psi}$ over the cross-section for the various specimens is indicated in Figs. 6 to 11. The diagrams can be conceived as representing the drying process under the given conditions. The solid lines indicate the measured behaviour of the moisture content in relation to time, while the dotted lines indicated the calculated behaviour, which will be further considered later on.

4.2.2 Recording the climate associated with the specimens in a number of buildings

As appears from Table 1, a number of specimens (see Section 4.2.1) were stored in a building under construction (Rabo Bank), in which the climatic conditions were ascertained by means of thermohygrograph measurements (Table 4). Temperature as well as relative humidity values are recorded with this apparatus. For theoretical analysis of the drying process it is important to know whether the climate recorded in this building is indeed representative of simular buildings. For this reason, climate recordings were

Table 4. Indoor climate in Rabo Bank building, Doetinchem.

week	average temp. $\overline{T}_i$ (°C)	average relative humidity $\overline{\varphi}_i$ (%)	week	average temp. $\overline{T}_i$ (°C)	average relative humidity $\overline{\varphi}_i$ (%)	week	average temp. $\overline{T}_i$ (°C)	average relative humidity $\overline{\varphi}_i$ (%)
73-26	20,6	69	74- 1	10,4	64	74-28	18,6	72
73-27	20,6	65	74- 2	14,2	63	74-29	18,8	68
73-28	23,3	73	74- 3	14,4	68	74-30	18,2	72
73-29	15,6	81	74- 4	13,6	65	74-31	19,2	73
73-30	14,7	82	74- 5	14,6	59	74-32	19,4	70
73-31	17,4	79	74- 6	13,6	62	74-33	20,8	74
73-32	17,7	69	74- 7	14,2	65	74-34	21,2	63
73-33	21,0	55	74- 8	16,2	54	74-35	21,8	65
73-34	15,8	65	74- 9	17,8	43	74-36	20,5	64
73-35	16,5	73	74-10	18,2	42	74-37	20,4	68
73-36	19,6	72	74-11	20,0	45	74-38	20,4	63
73-37	14,0	61	74-12	17,0	59	74-39	20,2	57
73-38	14,0	81	74-13	15,4	69	74-40	20,4	51
73-39	11,4	85	74-14	14,6	63	74-41	19,8	52
73-40	11,4	85	74-15	14,6	57	74-42	20,0	48
73-41	8,0	87	74-16	14,2	57	74-43	19,4	53
73-42	6,8	88	74-17	14,6	50	74-44	20,0	46
73-43	6,8	88	74-18	15,2	62	74-45	20,0	43
73-44	7,6	89	74-19	17,2	54	74-46	18,8	54
74-45	7,6	87	74-20	17,8	57	74-47	19,5	51
73-46	4,6	79	74-21	17,4	59	74-48	18,6	50
73-47	5,0	91	74-22	17,6	59	74-49	18,6	57
73-48	1,8	84	74-23	17,7	62	74,50	18,2	49
73,49	5,2	93	74-24	17,8	65	74,51	18,5	48
glazing installed								
73-50	9,0	81	74-25	19,4	67			
73-51	11,4	67	74-26	19,6	68			
73-52	10,9	65	74-27	19,4	67			

also performed in three other buildings, though without having test specimens stored in them. In connection with the measurements described in Section 4.2.1 the climate recordings can be subdivided into two groups:

a. The climate to which the various specimens were exposed, so that the drying tests were repeatable, namely:
   - climate in the air-conditioned room for the specimens 3 and 6 to 10; this climate was adjusted to 25 °C and 35% relative humidity;
   - outdoor climate (according to Table 5) for the specimens 1, 2, 4 and 5;
   - indoor climat in the Rabo Bank building at Doetinchem (according to Table 4) for the specimens 11 to 15.
b. The climate in three buildings, over a period of 1 to 2 years from the time of construction, namely:

Table 5. Outdoor climate on TNO-site, Rijswijk.

week	average temp. $\overline{T}_e$ (°C)	average relative humidity $\overline{\varphi}_e$ (%)	week	average temp. $\overline{T}_e$ (°C)	average relative humidity $\overline{\varphi}_e$ (%)	week	average temp. $\overline{T}_e$ (°C)	average relative humidity $\overline{\varphi}_e$ (%)
72-51	6,9	85	73-32	20,1	87	74-14	11,3	76
72-52	0,4	88	73-33	15,5	79	74-15	9,7	76
72-53	1,8	76	73-34	16,8	86	74-16	7,2	82
73- 1	3,0	91	73-35	16,8	86	74-17	6,9	81
73- 2	3,2	84	73-36	18,1	90	74-18	9,4	86
73- 3	2,6	92	73-37	14,6	78	74-19	9,4	79
73- 4	3,5	88	73-38	14,2	90	74-20	13,8	76
73- 5	5,6	92	73-39	12,1	90	74-21	11,7	84
73- 6	3,2	82	73-40	12,6	93	74-22	12,6	78
73- 7	4,5	87	73-41	8,9	92	74-23	12,2	78
73- 8	4,1	81	73-42	8,4	90	74-24	14,0	85
73- 9	4,9	85	73-43	8,4	87	74-25	15,6	85
73-10	4,1	80	73-44	8,8	93	74-26	15,7	88
73-11	7,4	76	73-45	9,1	86	74-27	14,5	84
73-12	6,1	82	73-46	6,7	79	74-28	15,8	84
73-13	5,4	82	73-47	6,1	89	74-29	14,6	82
73-14	4,5	81	73-48	-0,5	96	74-30	15,4	83
73-15	6,7	81	73-49	5,2	92	74-31	16,7	82
73-16	8,2	77	73-50	3,7	90	74-32	15,7	82
73-17	10,8	83	73-51	4,6	87	74-33	17,5	87
73-18	9,8	78	73-52	4,8	100	74-34	15,8	81
73-19	12,0	69	74- 1	2,8	94	74-35	15,7	81
73-20	14,4	82	74- 2	6,4	91	74-36	14,3	86
73-21	12,7	84	74- 3	7,9	87	74-37	15,1	90
73-22	13,5	84	74- 4	5,6	90	74-38	13,3	84
73-23	15,4	77	74- 5	6,4	85	74-39	9,8	91
73-24	18,5	76	74- 6	5,8	89	74-40	8,8	88
73-25	20,1	75	74- 7	6,7	86	74-41	7,7	92
73-26	19,0	72	74- 8	4,3	76	74-42	6,9	93
73-27	17,1	78	74- 9	2,0	84	74-43	9,2	91
73-28	16,1	83	74-10	2,4	87	74-44	5,4	92
73-29	14,8	87	74-11	5,2	90	74-45	6,1	89
73-30	17,5	85	74-12	7,9	86	74-46	9,1	90
73-31	17,5	80	74-13	8,7	89			

- indoor climate of a student's flat at Delft;
- indoor climate of an office building of Polydor at Rijswijk;
- indoor climate of a home for old people, "De Vijverhof", at Delft.

It is to be noted that in processing the measured data obtained in the three buildings mentioned in point b the climate data for the Rabo Bank (Table 4), envisaged in point a, will also be included. Furthermore, the time behaviour of the measured outdoor climate (Table 5) will be used for the determination of a representative indoor climate. As

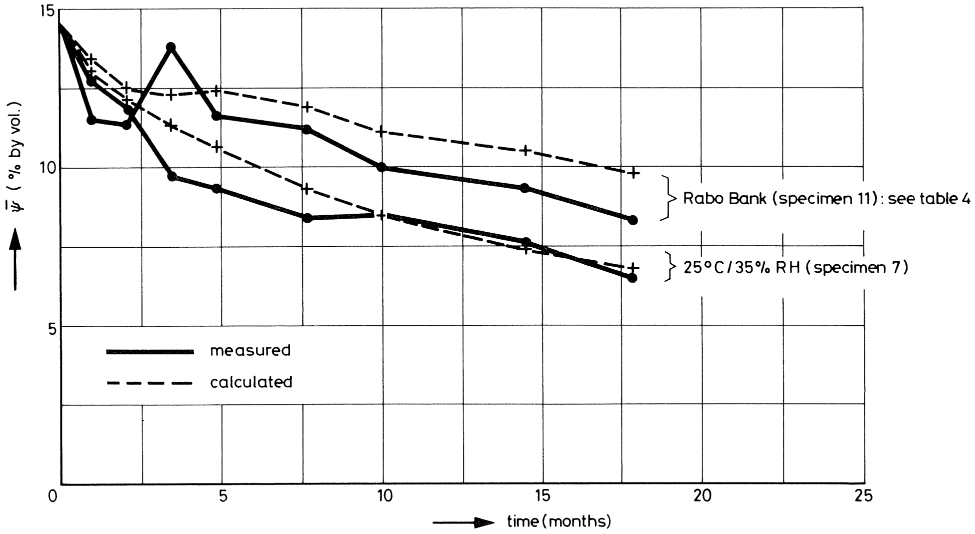

Fig. 6. Average moisture content $\overline{\psi}$ (% by vol.) of specimens 7 and 11 (Korlin B) for one-sided drying (slab thickness 0,15 m).

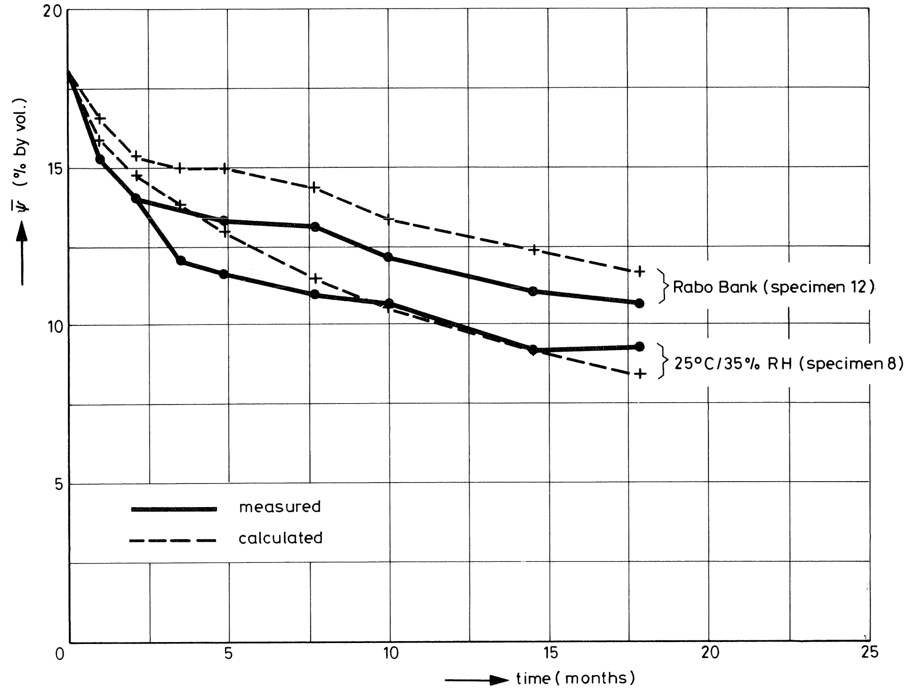

Fig. 7. Average moisture content $\overline{\psi}$ (% by vol.) of specimens 8 and 12 (Argex) for one-sided drying (slab thickness 0,15 m).

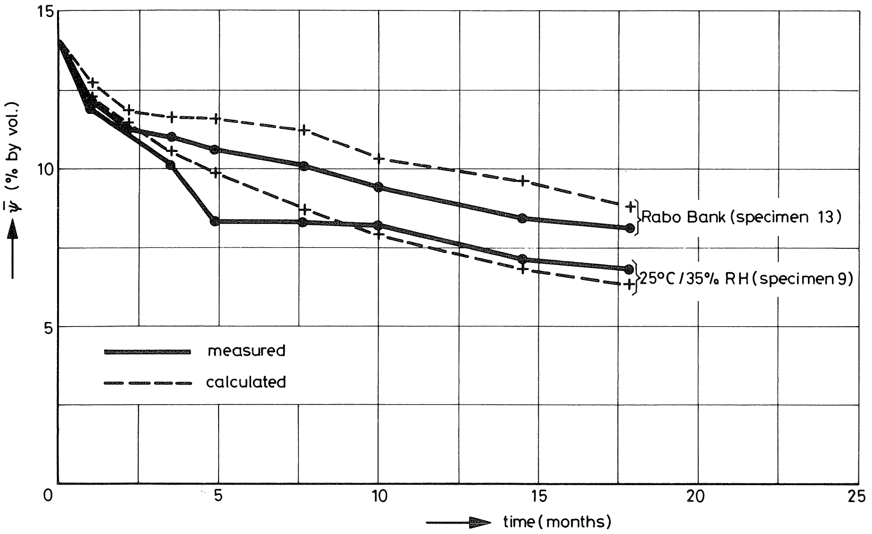

Fig. 8. Average moisture content $\bar{\psi}$ (% by vol.) of specimens 9 and 13 (Agral) for one-sided drying (slab thickness 0,15 m).

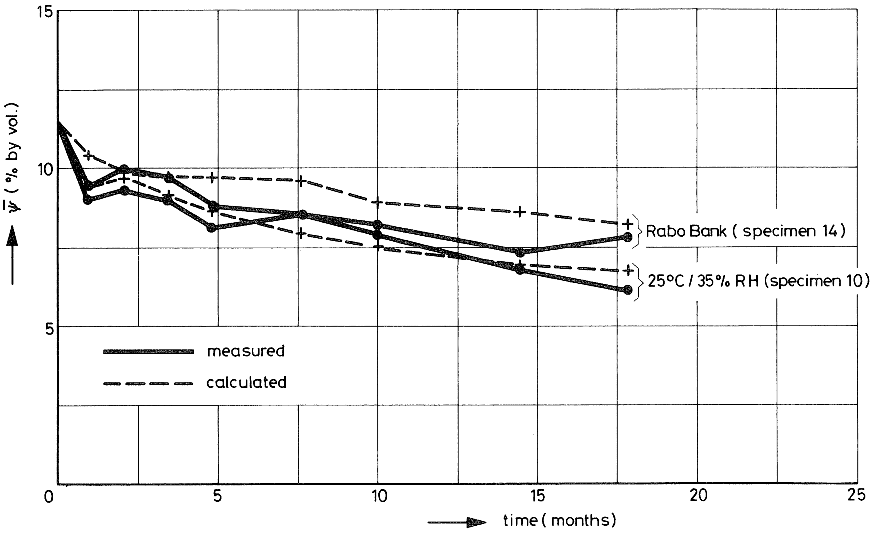

Fig. 9. Average moisture content $\bar{\psi}$ (% by vol.) of specimens 10 and 14 (normalweight gravel concrete) for one-sided drying (slab thickness 0,15 m).

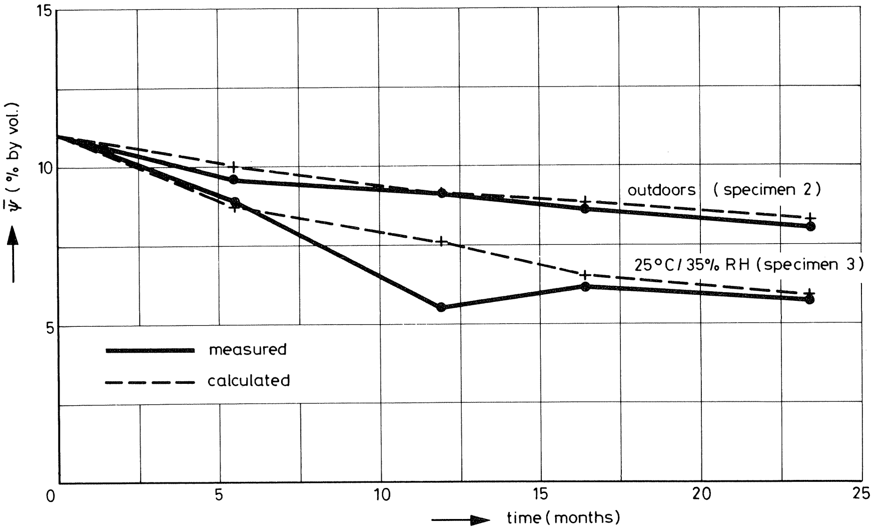

Fig. 10. Average moisture content $\bar{\psi}$ (% by vol.) of specimens 2 and 3 (Korlin A) for two-sided evaporation (slab thickness 0,44 m).

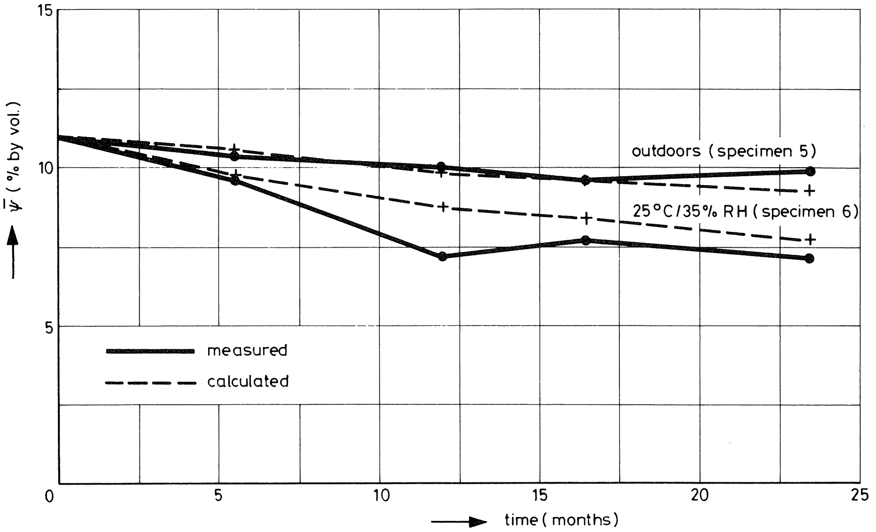

Fig. 11. Average moisture content $\bar{\psi}$ (% by vol.) of specimens 5 and 6 (Korlin A) for two-sided evaporation (slab thickness 0,44 m).

Table 6. Standard outdoors climate at De Bilt (1901-1930).

	De Bilt 1901-1930	
month	$\overline{T}_e$ (°C)	$\overline{\varphi}_e$ (%)
1	2,2	88
2	2,5	85
3	4,8	79
4	7,8	74
5	12,5	72
6	14,7	72
7	16,7	73
8	16,2	75
9	13,7	79
10	9,8	83
11	5,1	86
12	3,0	88

only one outdoor climate was measured, the data relating to the "standard outdoor climate" according to the Royal Netherlands Meteorological Institute at De Bilt (Table 6) will also be used. This last-mentioned climate is an average determined over a long period of time, so that all random influences have been eliminated. In the following, it will be briefly described how the measured data - temperature and relative humidity - have been processed.

Within any given space the temperature will vary from one point to another, as will also the relative humidity. Such variation does not apply to the vapour concentration, i.e., the quantity of water vapour per unit volume of air in the space under consideration. From measurements of the temperature and the relative humidity at any particular point the vapour concentration in that space can be calculated from the following formula:

$$\varphi = \rho / \rho'$$

where:

φ = the measured relative humidity (–);

ρ' = the saturation vapour concentration (kg/m^3 of air): this quantity is known if the temperature is known, and can be looked up in appropriate tables;

ρ = the vapour concentration (kg/m^3 of air).

For determining the vapour concentration ρ the weekly averages of the measured indoor temperatures in the four buildings were plotted as a function of time (Fig. 12).*

In Fig. 13 the measured outdoor temperature at De Bilt, as given in Table 6, has been plotted as a function of time. On comparing this diagram with Fig. 12 it is notable that,

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* In March 1974 the thermohygrograph in the Polydor building was moved from a central position to a sunny hall. The higher temperatures in this new location were associated with unchanged vapour concentrations, which is in accordance with the information given in the literature on this subject.

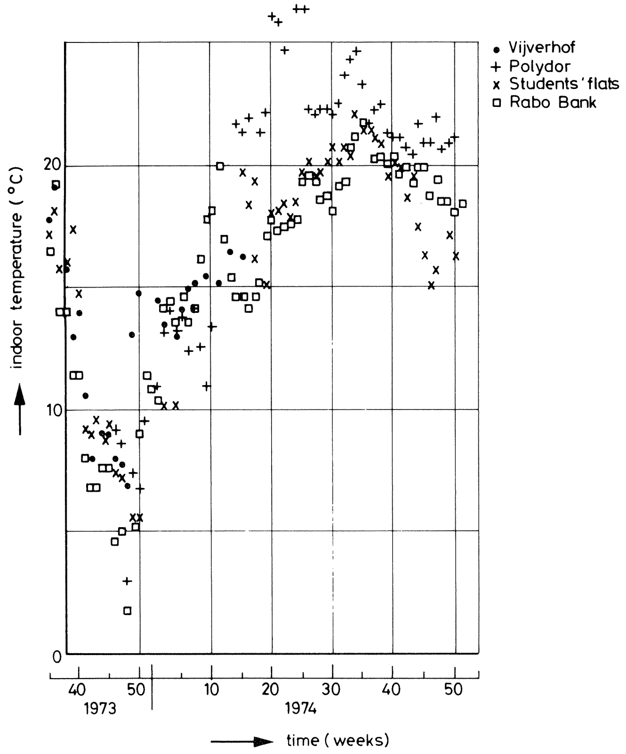

Fig. 12. Measured indoor temperature in four buildings.

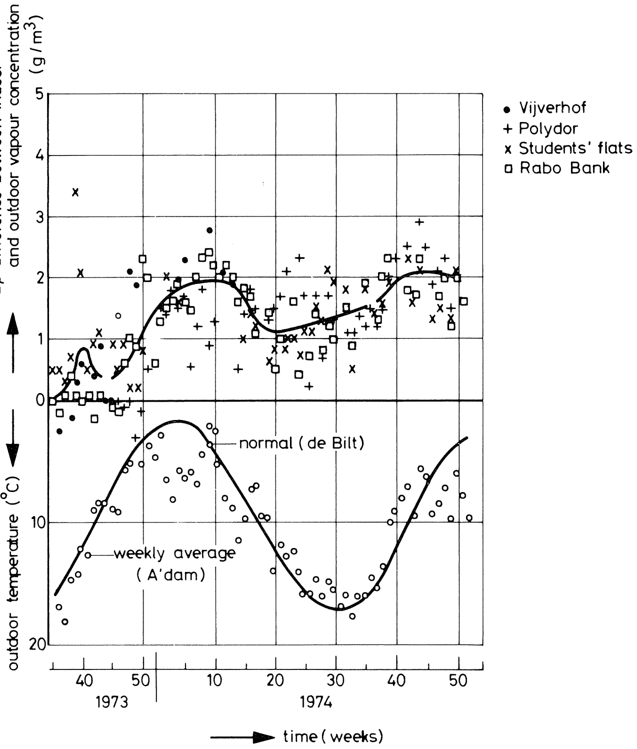

Fig. 13. Δp and outdoor temperature as a function of time.

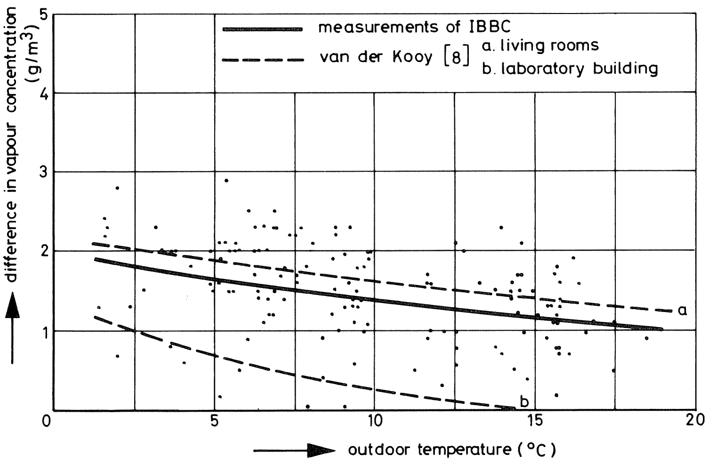

Fig. 14. Average difference in vapour concentration between indoor and outdoor air as a function of the outdoor temperature after installation of glazing in the four buildings.

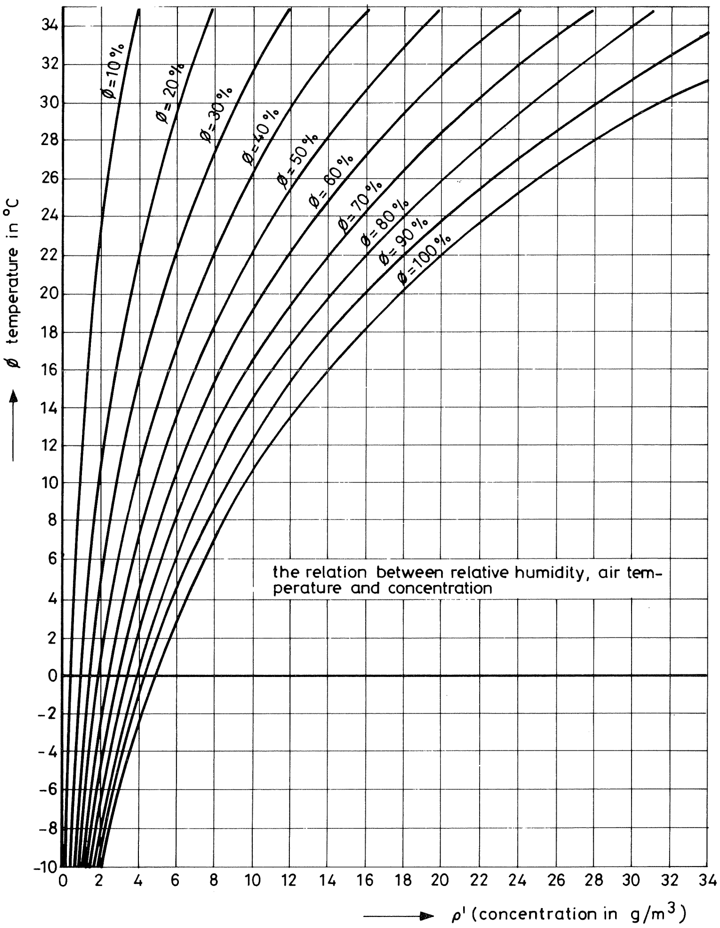

Fig. 14a. Mollier diagram.

Table 6a. Locations of the thermohygrographs for climate recording.

		condition of the building	
building	period of recording	glazing installed	in use
student's flat V. Hasseltlaan, Delft	73-08-27 to 73-12-17 and 74-04-08 to 74-12-16	November 1973	April 1974
Polydor BV Verrijn Stuartlaan, Rijswijk (ZH)	73-11-12 to 74-12-16	December 1973	March 1974
old people's dwellings "Vijverhof" Montgomerylaan, Delft	73-08-27 to 74-12-16	before the measurements	after the measurements
Rabo Bank Terborghseweg, Doetinchem	73-08-28 to 74-12-20	December 1973	May 1974

from the end of 1973 onwards, all the indoor temperatures are above the outdoor air temperatures. The reason is that all four buildings had been fully glazed before the turn of the year (see Table 6a). With the data listed in Tables 5 and 6 it is also possible to determine the vapour concentration in the outdoor air. The difference in vapour concentration $\Delta\rho$ between indoor and outdoor air can now be plotted as a function of time (Fig. 13). With the aid of Figs. 12 and 13 the difference in vapour concentration can be plotted against the outdoor temperature, as has been done in Fig. 14, in which the measured data obtained in the four buildings have been incorporated. From these data the solid line in that diagram is obtained, determined by the method of least squares for an exponential function.

In Fig. 14, besides the average line derived from the IBBC-TNO measurements (the solid line), two dash lines as found by Van der Kooy [14] are included. The upper of these two lines (line "a": measurements in living-rooms) closely corresponds to the IBBC-TNO line, while the lower one (line "b": measurements in a laboratory building) is more than 1 g/m^3 lower down in the diagram. If the IBBC-TNO line were determined at a later stage, when the concrete had dried out more, it would certainly be located lower down, though it is questionable whether, even so, it would coincide with line "b". This would depend on the number of people occupying the premises and on the frequency of ventilation air changes. The advantage of the curve thus determined for the difference in vapour concentration is that it enables the corresponding relative humidity, for a given temperature of the outdoor climate, to be determined quite simply as a function of that particular outdoor climate. This will be further explained with the aid of the following example.

For the outdoor climate:

$$\varphi_e = \rho_e / \rho_e'$$

where the subscript "*e*" denotes external. For the indoor climate:

$$\varphi_i = \rho_i / \rho_i'$$

where the subscript "*i*" denotes internal. Since:

$$\rho_i = \rho_e + \Delta\rho$$

the following relationship can be derived:

$$\varphi_i = \frac{\rho_i}{\rho_i'} = \frac{\rho_e + \Delta\rho}{\rho_i'} = \frac{\varphi_e \rho_e' + \Delta\rho}{\rho_i'}$$

Suppose that at a given instant the outdoor climate is characterized by the temperature $\vartheta = 15\,°C$ and relative humidity RH = 80% and that the indoor temperature is 21 °C.

From a Mollier diagram (Fig. 14a) it can be determined that for $\vartheta = 15\,°C$ the saturation vapour concentration is 12,8 g/m^3; for $\vartheta = 21\,°C$ the saturation vapour concentration is 18,3 g/m^3.

According to Fig. 14: $\Delta\rho = 1{,}2$ g/m^3 for $\vartheta = 15\,°C$.

With these data the following is found for the indoor relative humidity:

$$\varphi_i = \frac{0{,}80 \times 12{,}8 + 1{,}2}{18{,}3} = 0{,}63 \; (63\%)$$

As appears from this example, the relative humidity can be determined for the usual range of indoor temperatures with the aid of Fig. 14. For this purpose the standard values as determined, for example, at De Bilt and the Mollier diagram (Fig. 14a) will have to be used. We shall revert to this later on: see Section 4.3.2.

4.2.3 Theoretical experimental determination of the moisture content of the material

As already stated in 4.2.1, the moisture content of the material is determined by the constitution and structure of the material, the dimensions, and the climate.

In actual practice these factors are likely to vary, so that a large number of different conditions are in fact possible. In view of this, it is desirable to be able to describe the drying process theoretically. At IBBC-TNO this had indeed been realized for some time and prompted the development of an arithmetical approximation. For this purpose an electrical analogy was employed with which any drying process can be simulated [11]. Fig. 15 shows the electronic equipment used. The simulation can be performed if, in addition to the dimensions and the climate, the properties of the concrete which are of importance in connection with the drying process are known. These material properties are characterized by means of:

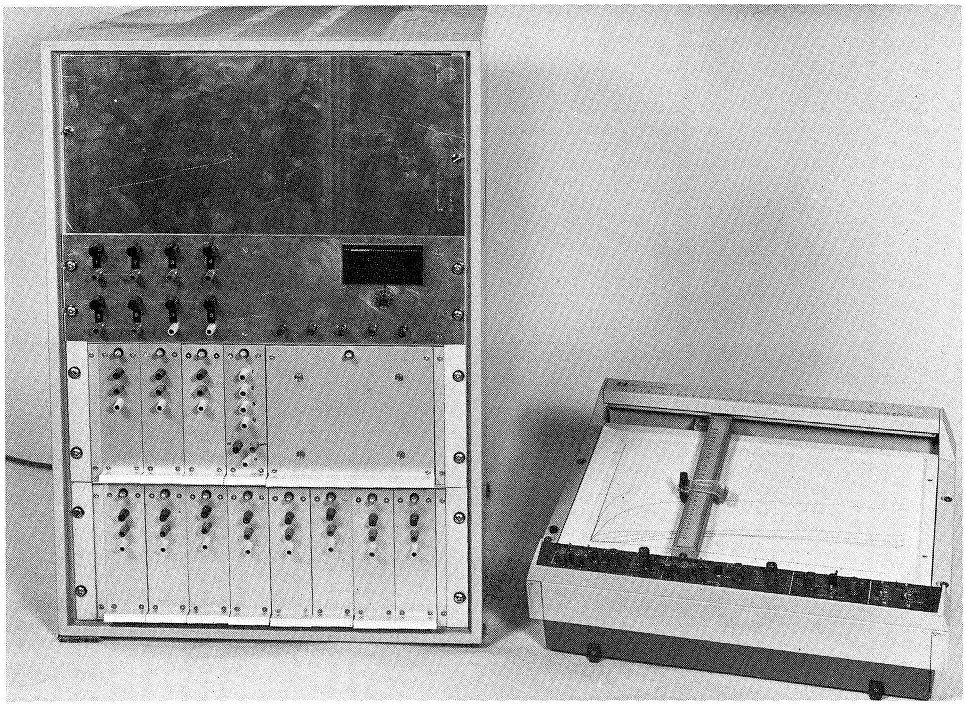

Fig. 15. Electrical equipment for calculating the drying process.

- the hygroscopic curve;
- the diffusion resistance number.

These properties are fairly simple to determine for any type of concrete.

Of these two characterizing data the hygroscopic curve will be explained here. The significance and method of determining the diffusion resistance number are dealt with in Appendix A. A concrete member of a given composition and with certain dimensions will, for constant climate (temperature and relative humidity of the environment), acquire a certain equilibrium moisture content. If the climate changes after this moisture content has been attained, a different equilibrium moisture content will establish itself in course of time. For constant temperature the equilibrium moisture content in the material can be plotted as a function of the relative atmospheric humidity.

The experimentally determined relationship thus obtained is called the hydroscopic curve. Different hygroscopic curves are found for different materials. For the materials within the scope of the present research, these curves are given in Figs. 16 to 20. The hygroscopic curve which is obtained for a completely saturated material (desorption isotherm) differs from that which is obtained for a dry material (absorption isotherm). In principle, each constant temperature is associated with a particular hygroscopic

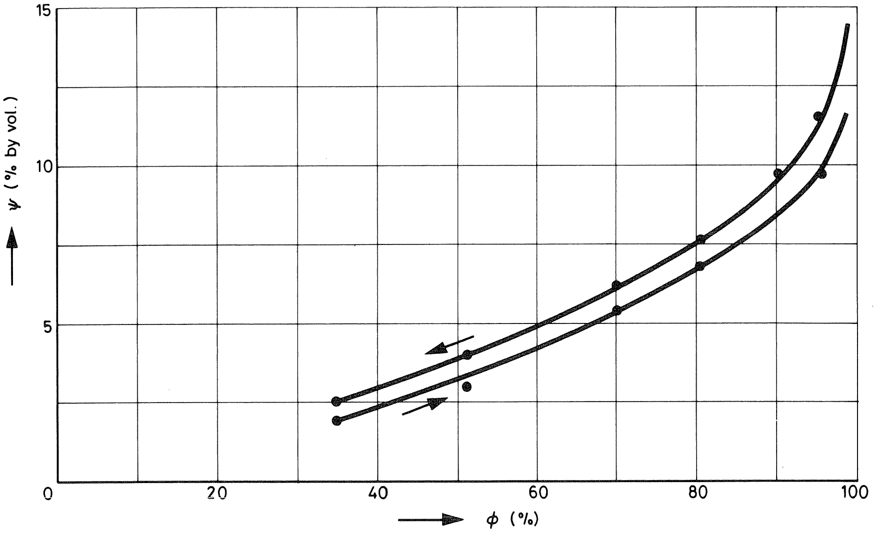

Fig. 16. Hygroscopic moisture content ψ of Korlin B concrete as a function of the relative humidity φ.

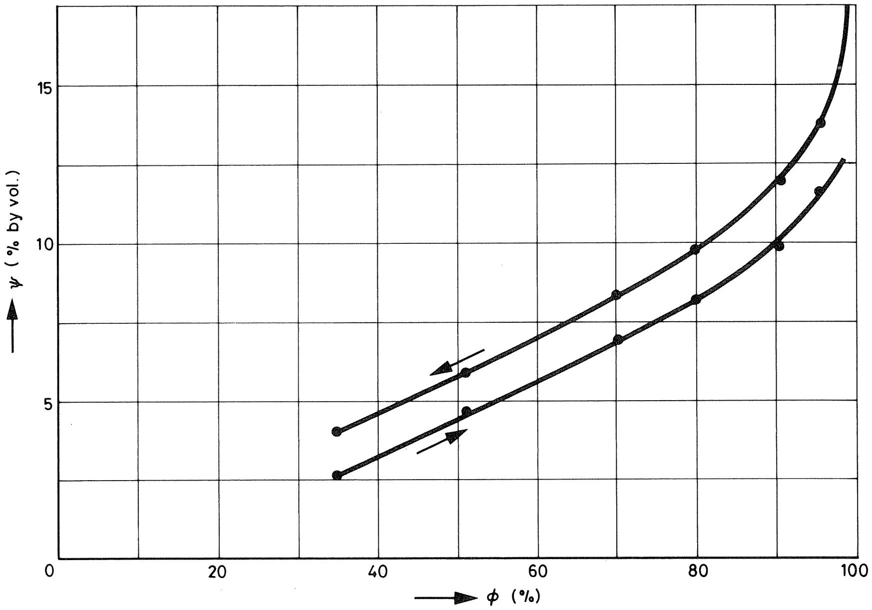

Fig. 17. Hygroscopic moisture content ψ of Argex concrete as a function of the relative humidity φ.

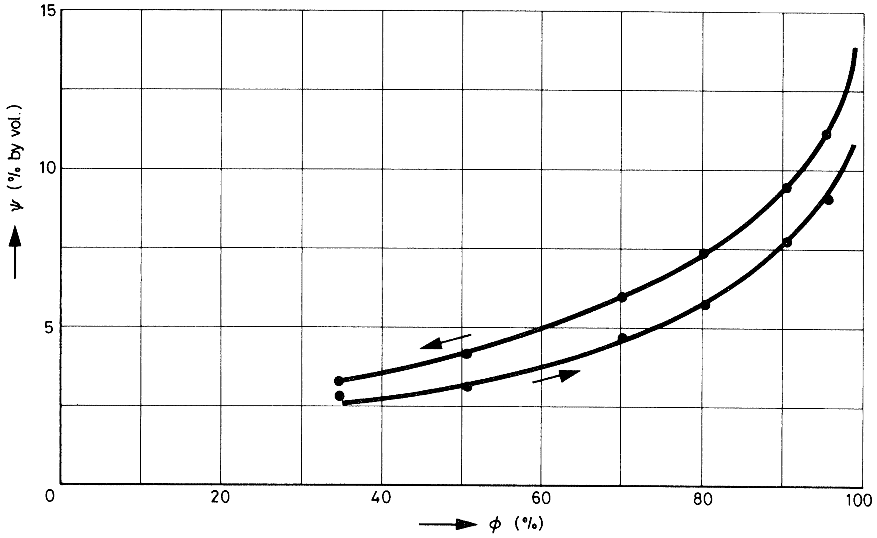

Fig. 18. Hygroscopic moisture content ψ of Agral concrete as a function of the relative humidity φ.

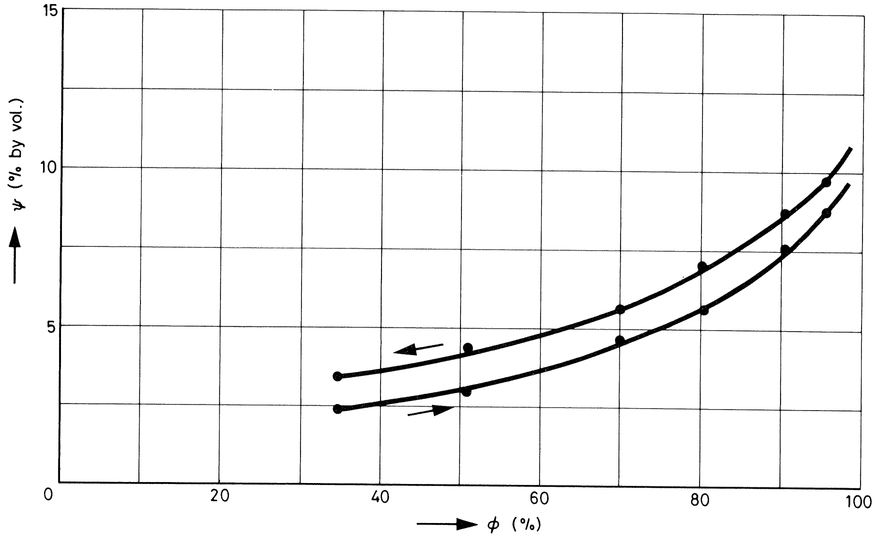

Fig. 19. Hygroscopic moisture content ψ of Korlin A concrete as a function of the relative humidity φ.

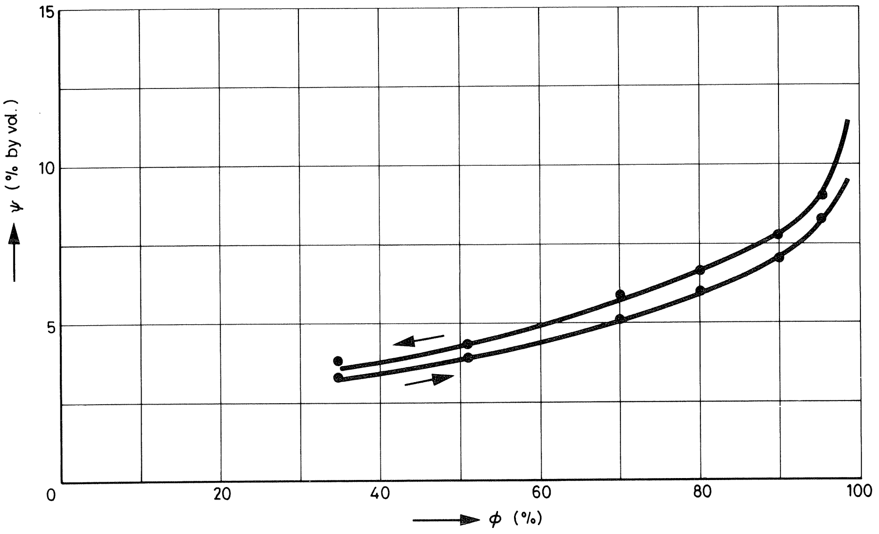

Fig. 20. Hygroscopic moisture content ψ of normalweight gravel concrete as a function of the relative humidity φ.

curve (hence the addition "isotherm"). The curves in Figs. 16 to 20 were determined at $\vartheta = 20\,°C$. The change in equilibrium moisture content occurring in response to temperature changes of the magnitude such as occur in building practice is negligible for any particular value of the relative humidity. For this reason the hygroscopic curves can permissibly be used also for temperatures other than 20 °C. On the other hand, the temperature of the concrete does play an important part in connection with the drying process, as the water vapour conductivity coefficient is highly temperature-dependent. If the climate inside a given building is constant, it is possible with the aid of the hygroscopic curve directly to read the equilibrium moisture content, irrespective of the dimensions of a concrete member.

This is not the case of the climate is not constant, however. Furthermore, the hygroscopic curve does not give any information on the length of time that elapses before a particular moisture content is attained. The hygroscopic curve plays an important part in connection with the description of the drying process with the aid of the electrical analogy.

Just how this operates and what other data (hydration and carbonation) are involved in the calculation procedure are described in Appendix A.

The result of the arithmetically determined pattern of behaviour of the moisture content of the material in the specimens, as described in Section 4.2.1, is indicated in Figs. 6 to 11. A closer analysis of this result in comparison with the measured values will be presented in the next Section, where the recorded climate data will also be further discussed and a prognosis given of the moisture content that concrete can be expected to have in practice.

4.3 *Analysis of the moisture content and climate measurements*

4.3.1 Measurements and calculations of the material moisture content

The hygroscopic curves discussed in 4.2.3, associated with a particular material, can be used for determining the equilibrium moisture content. By way of illustration the equilibrium moisture content for the various lightweight concretes under different climatic conditions is indicated in Table 7. From fire tests performed on normalweight concrete [3] it was inferred that, for a material moisture content below 5% (by volume), the probability of the occurrence of serious forms of spalling is low (see also Section 2.2.2). On the evidence of the hygroscopic curve this value, for the normalweight concrete used in the present research, is attained at approximately 65% relative humidity of the air.

For the lightweight concretes investigated it can be stated that, with the exception of the concrete made with Argex, the material moisture content finally attained at 65% relative humidity is about 5,4% (by volume) (see Table 7). Anticipating the fire tests performed on lightweight concrete, as will be reported in Section 4.4, it can be assumed with regard to spalling that a material moisture content of around 5% (by volume) is a safe value.

This means that in the long run the difference in spalling behaviour between normalweight concrete and lightweight concrete will be slight if the prevailing climate is characteriszed by a relative humidity of 65%. In the period between the time of concreting and the time when a particular equilibrium moisture content has been reached, however, the material moisture content will be above 5% (by volume). With reference to this is must be asked: at what rate does the moisture content decrease before a "safe value" is attained? In this connection the dimensions are, besides the other factors already mentioned, certainly of importance as regards the rate of drying.

If a cement content of, say, 330 kg/m^3 and a water-cement ratio of 0,55 are employed, the material moisture content will initially be about 18% (by volume). Some of this moisture will evaporate and some will be chemically combined by the cement (hydration). Some days after concreting, the effects of hydration and evaporation will thus have resulted in a lower content of evaporable water than the initial 18%. The measured values of the average moisture content at 30 days after concreting are presented in Table 8. These values have been obtained from Figs. 6 to 11.

Table 7. Material moisture content in the equilibrium condition according to the hygroscopic curves of Figs. 16 to 20.

	humidity of the air		
type of aggregate	R.H. = 50%	R.H. = 65%	R.H. = 80%
Korlin B concrete	$\psi = 3{,}9\%$	$\psi = 5{,}5\%$	$\psi = 7{,}6\%$
Agex-S concrete	$\psi = 5{,}7\%$	$\psi = 7{,}6\%$	$\psi = 9{,}8\%$
Argral-650 concrete	$\psi = 4{,}2\%$	$\psi = 5{,}5\%$	$\psi = 7{,}4\%$
Korlin A concrete	$\psi = 4{,}1\%$	$\psi = 5{,}2\%$	$\psi = 6{,}8\%$
normalweight (gravel) concrete	$\psi = 4{,}3\%$	$\psi = 5{,}3\%$	$\psi = 6{,}6\%$

Table 8. Loss of moisture after 30 days

type of aggregate	water-cement ratio	cement kg/m^3	water in % by vol.	specimen No.	$\overline{\psi}$ (% by vol.) after 30 days	average moisture loss in % due to hydration and evaporation	moisture loss in % by vol./100 kg of cement
Korlin B	0,62	325	20,2	7	12,7	40	2,51
				11	11,5		
				15	11,9		
Argex S	0,72	331	23,8	8	15,3	36	2,56
				12	15,3		
Agral-650	0,59	335	19,8	9	11,9	39	2,32
				13	12,1		
gravel	0,53	300	15,9	10	9,0	42	2,23
				14	9,4		
Korlin A	0,43	370	15,9	2	10,8	33	1,41
				3	10,6		
				5	10,8		
				6	10,6		
						average 38	

It was found that after 30 days about 100−38 = 62% of the initially added water was still present as uncombined water. In course of time some of this water is chemically combined in consequence of continuing hydration, while part of the remaining uncombined water evaporates, depending on the existing climatic conditions. In the cross-section of the member the moisture content at first shows an increase from the periphery to the centre. (It is to be noted that on attainment of the equilibrium moisture content there is equal moisture content throughout the section).

In Figs. 6 to 11 the average material moisture content, as measured in the specimens, is shown plotted as a function of time. The moisture content calculated with the electrical analogy is likewise presented in these diagrams. The effects of climate, material properties, continuing hydration and the consequences of carbonation have been allowed for in these results. The manner in which this has been done is explained in Appendix A. From the diagrams it is apparent that the measured and the calculated values are in fair agreement.

A good criterion for the deviations between the calculated and the experimentally determined values is obtained by calculating the standard deviation. The result is given in Table 9. The largest standard deviation is 1,54% and the smallest 0,51% (by volume). The experimental results presented in Figs. 6 to 11 in some cases show fairly large abrupt changes, as distinct from the behaviour of the calculated curves. These variations are due mainly to the comparatively small diameter of the drilled cores (30 mm) in

Table 9. Average difference ($\Delta\psi$) between calculated and measured results, and the standard deviation (sd) of the individual differences.

specimen	aggregate	dimensions (m^3)		$\Delta\overline{\Psi}$ (% by vol.)	sd (% by vol.)
1	Korlin A	0,70 × 0,22 × 0,22	outdoor	-	-
2			outdoor	0,1	0,51
3			25 °C/35%	0,6	1,46
4		0,77 × 0,44 × 0,44	outdoor	-	-
5			outdoor	−0,2	1,01
6			25 °C/35%	0,7	0,85
7	Korlin B	0,15 × 0,50 × 0,50	25 °C/35%	0,5	0,89
8	Argex-S			0,3	1,54
9	Agral-650			0,1	1,13
10	gravel			0,3	0,65
11	Korlin B	0,15 × 0,50 × 0,50	Rabo Bank	0,9	1,16
12	Arges-S			1,3	1,51
13	Agral-650			0,8	0,84
14	gravel			0,6	0,98
15	Korlin B			1,1	1,19
average				0,6	1,06

relation to the distribution of the lightweight aggregate particles and their size (3–10 mm). It emerges from the results that the mean standard deviation in the deviations between the experimental and the theoretical results for all cores is 1,06% (by volume) (see Table 9).

On the assumption that the measured results conform to a normal distribution, it appears that for a 5% two-way probability of being exceeded the accuracy of the material moisture content determined from a single drilled core is approximately ±2% (by volume). For all the cores a mean difference between measured and calculated moisture content of 0,6% (by volume) is found (see Table 9). This means that it is, within the scope of practically attainable accuracies, possible to make a good assessment of the material moisture content as a function of time by calculation. With the experimentally verified method of calculation it is thus possible to obtain some idea of the length of time that elapses before a certain moisture content can be attained as a function of a certain climate.

With regard to the indoor climate measured in the Rabo Bank building (Table 4) it is found, by extrapolation of the data presented in Figs. 6 to 11, that none of the specimens attained a moisture content of less than 7% (by volume) at the end of about 24 months. The results of this extrapolation is given in Table 10. On calculating the average of all the measured temperatures and relative humidity values for the Rabo Bank, a weighted climate of 16 °C/65% RH is found.

The hygroscopic moisture contents for RH = 65% are likewise given in Table 10. It is apparent that these values are lower than the average material moisture contents calculated at 24 months. As Figs. 16 to 20 show, the measured average moisture content can

Table 10. Moisture content after 24 months for the indoor climate of the Rabo Bank building (Table 4).

type of aggregate	specimen No.	climate	$\overline{\psi}$ (% by vol.) after 30 days	$\overline{\psi}$ (% by vol.) after 24 months	$\overline{\psi}$ after 24 months conceived as hygroscopic ψ gives a RH of	hygroscopic ψ at 20 °C/65% RH
Korlin B	11	Rabo Bank	11,5	~ 8,0±0,5	82%	5,5
Argex-S	12	Table A-9	15,3	~10,0±0,5	81%	7,6
Agral-650	13	$\overline{T}$ = 16 °C	12,1	~ 7,5±0,5	82%	5,5
gravel	14	$\overline{RH}$ = 65%	9,4	~ 7,0±0,5	82%	5,3

be in equilibrium with a relative humidity of 80%. A lower average relative humidity is associated with the measured indoor climate. This means that after 24 months the material moisture content will further decrease, the rate of drying being dependent partly also on the temperature that occurs. For thicker members than those employed for the specimens the time needed for attaining a certain moisture content will increase. As is discussed in Appendix A-III, it can be stated that, starting from a temperature of 15 °C, the rate of drying doubles if the temperature rises by 10 °C. It also appears that this rate is quadrupled if the thickness of the member is halved.

The average drying rates (in % by volume/year), as measured for all the specimens during the first 15 months, are assembled in Table 11. The average drying rate is defined as the slope of a straight line connecting the initial moisture content and the moisture content attained after 15 months (see Figs. 6 to 11). In Figs. 21 and 22 the rate of drying has been plotted against the initial moisture content, this being taken as the measured average moisture content at 28 days after commencement. These curves relate only to the first 15 months. It is clearly manifest that the drying rate increases with initial moisture content. Hence it follows that applying a low initial moisture content with the intention of more speedily attaining an average low material moisture content is not an effective measure. This statement, however, is somethat speculative, because measured values relating to various materials are embodied in Figs. 21 and 22. At the request of NCH (Nederlandse Cement Handelmaatschappij) the DSM* carried out some tests for the Committee. In these tests a water-cement ratio of 0,4 was employed and a plasticizer added to the mix, enabling good workability to be obtained despite reduction of the water content of the concrete. However, none of the properties of this concrete were determined which are required for the calculation of the drying process (see Appendix A).

A more detailed investigation showed that the properties (hygroscopic curve and diffusion resistance) hardly change.

For the purpose of drying calculations it is essential to base oneself on a representative climate. What climate can suitably be adopted for the purpose will now be described.

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* DSM = Dutch State Mines.

Table 11. Average rate of drying of the specimens.

material		Korlin-A				Korlin-B		Argex-S		Agral-650		gravel	
water-cement ratio		0,43				0,62		0,72		0,59		0,53	
initial moisture content ψ_i (% by vol.)		11,0				14,5		18,0		14,0		11,5	
thickness (m)		2×0,22		2×0,11		1×0,15							
specimen No.		2	3	5	6	11	7	12	8	13	9	14	10
climate		out-door	25°/ 35%	out-door	25°/ 35%	Rabo Bank	25°/ 35%	Rabo Bank	25°/ 35%	Rabo Bank	25°/ 35%	Rabo Bank	25°/ 35%
average moisture content $\overline{\psi}$ (% by vol.) after 15 months	measured	9,7	8,0	8,9	6,5	9,2	7,4	11,0	9,3	8,3	6,7	7,8	6,9
	calculated	9,7	8,6	8,9	6,8	10,4	7,4	12,6	9,3	9,4	6,7	8,7	6,9
average drying rate $d\overline{\psi}/dt$ (% by vol./year)	measured	1,04	2,40 5,16*	1,68 1.94*	3,60	4,24	5,68	5,60	6,96	4,56	5,84	2,96	3,68
	calculated	1,04	1,92	1,68	3,36	3,28	5,68	4,32	6,96	3,68	5,84	2,24	3,68

* $d\overline{\psi}/dt$ converted to a thickness of 0,15 m according to the quadratic rule in Appendix AI-III.

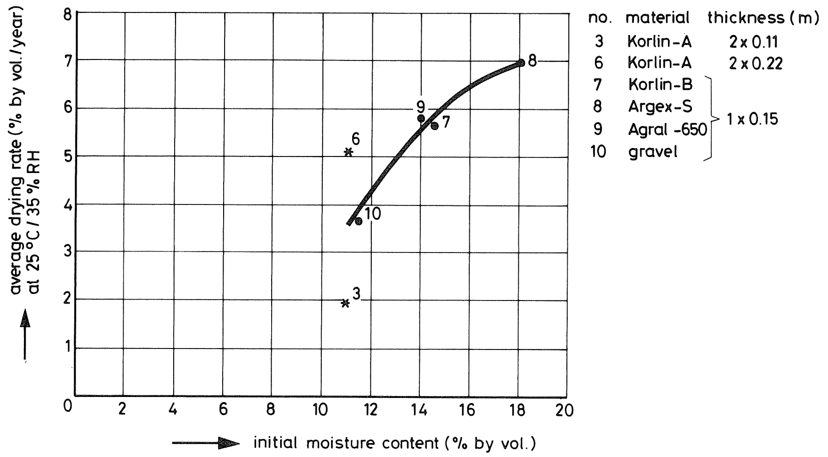


Fig. 21. Relation between drying rate and initial moisture content (measured on drilled cores): figures from Table 11 (for first period only).

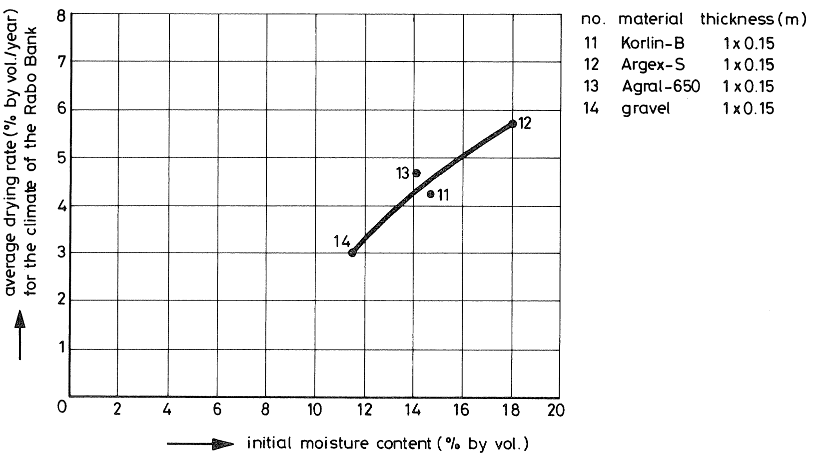


Fig. 22. Relation between drying rate and initial moisture content (measured on drilled cores); figures from Table 11 (for first period only).

4.3.2 Measurements and calculations relating to the climate to be adopted

The indoor climate in four buildings was recorded over a period of 1¼ years. The measurements and the procedure employed have been described in 4.2.2. Among other information, these measurements served to give some idea of the pattern of behaviour of the indoor climate of a building. Thus the indoor temperature was found to vary between 20 °C and 25 °C. With the aid of the procedure described in 4.2.2 it is possible to

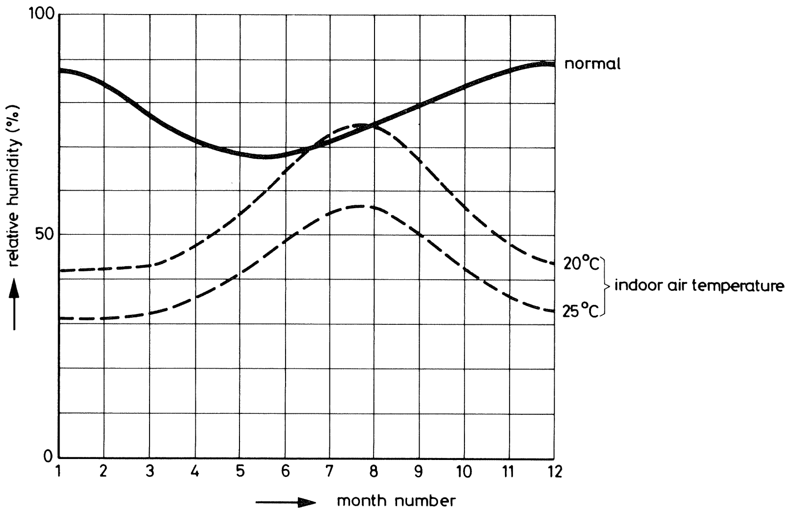


Fig. 23. Relative humidity of indoor air at 20° and 25 °C calculated from Δp (IBBC-TNO line in Fig. 14) and standard climate data at De Bilt (Table 6).

estimate the relative humidity of the air in a building over a period of a year. The results of such a calculation are presented in Fig. 23. It appears that in winter the relative humidity may be below 35% for a temperature of 25 °C. The annual average of the relative humidity for an indoor temperature of 20 °C is 55%, and for an indoor temperature of 25 °C it is 40%. As stated in 4.3.1, the measured average climate in the Rabo Bank building was 16 °C/65%. This average was obtained over a period of 18 months after concreting. It also appears from the measurements that in the initial period after the installation of glazing there occurs a higher relative humidity. Calculations indicate that a good estimate of the drying rate can be made on the basis of the weighted climate of 16 °C/65% in the early part of the building's existence (about 2 years). For a period in excess of about 24 months a calculation based on this weighted climate will no longer be correct, for then the effect of higher values of the relative humidity occurring in the initial period after concreting will be less and less perceptible. In these circumstances the drying process will be increasingly governed by the weighted indoor climate, which may be assumed to range between approximately 20 °C/55% and 25 °C/40%, as appears from Fig. 23. The drying conditions are therefore more favourable. Finally, in this research, it was investigated whether the timing of concreting and of installing the glazing will affect the rate of drying in the initial period. The procedure adopted for this investigation is described in Appendix B. It emerged that the differences in material moisture content due to this in the initial period are negligible. In this approximation the building is assumed always to have been glazed 4½ months after concreting. This means that the drying rate in the initial period can permissibly be determined with a weighted climate of 16 °C/65%, irrespective of the time of concreting.

4.3.3 Expectations as to the moisture content of lightweight concrete in practice

It emerged from the research described in 4.2.2 that the drying process of concrete proceeds at a slow rate. None of the test specimens with a thickness of 0.3 m (2×0,15 m) was found to have a moisture content of less than 7% (by volume) after about 24 months. It was also found that the drying process in this initial period can be described with the aid of the weighted climate 16 °C/65%. With regard to this the glazing is assumed to be installed in the building 4½ months after concreting. Calculations showed the time of concreting (summer, winter, etc.) to have no significant effect upon the drying process in the initial period.

On the basis of hygroscopic curves it can be ascertained that, with the exception of concrete made with Argex S aggregate, the hygroscopic material moisture content is about 5,4% (by volume) if the relative humidity is 65%. For Argex S this moisture content is attained at 48% relative humidity.

In buildings in which there occurs a climate corresponding to the above-mentioned weighted climates (20 °C/55%, 25 °C/40%) it can justifiably be assumed that the ultimate material moisture content will, in so far as the concretes investigated are concerned, be in the region of 5% (by volume).

The period prior to the attainment of a certain equilibrium moisture content will be longer according as the thickness is greater. As a general rule, the rate of drying is slowed down by a factor 4 when the thickness increases by a factor 2. The test results show a higher drying rate to occur with higher initial moisture content.

For a low initial moisture content (low water-cement ratio, possibly achieved by using a plasticizer) a certain average material moisture content will perhaps be attained sooner. The trend that emerges from the test results, however, suggests that this measure is not so effective as might be supposed in view of the reduction in the quantity of moisture to be evaporated.

4.4 *Fire tests*

4.4.1 General

Within the overall context of the Committee's research project it was, inter alia, endeavoured by means of fire tests to find an answer to the question raised already in point b of Section 4.1, namely: Is it possible, for a given compressive stress, to indicate a particular moisture content at which spalling will no longer, or hardly, occur? What gave rise to the question formulated in this way were the results of tests performed on lightweight concrete by IBBC-TNO some time before the CUR Committee was set up. Table 12 reviews all the preliminary fire tests as reported in [19], [20], [21], [22] and [23].

These tests were performed at a time when the causes of spalling were still somewhat obscure. Only a few tests were divised with the specific object of gaining some information on spalling. This being so, the set-up of the tests as a whole is rather arbitrary.

The tests reported in [19], [20] and [21] were undertaken at the request of DSM with the object of investigating to what extent the behaviour of lightweight concrete under fire conditions might be more favourable than that of normalweight concrete. This assumption was based on foreign test results and was supported by the fact that the thermal properties of lightweight concrete suggest that a smaller depth of cover than in the case of normalweight concrete may suffice to protect the reinforcing steel against excessive rise in temperature. These tests showed the behaviour of lightweight concrete to be indeed more favourable if no prestress was applied. An additional fact to emerge was that a reinforced normalweight concrete floor, when subjected to heating on one face, exhibited some spalling whereas a similar floor of lightweight concrete construction was entirely free from spalling [19]. The moisture content was about 8% (by volume). In [19] and [20] some test results are reported which relate to prestressed floor units and columns made of lightweight concrete which did show spalling.

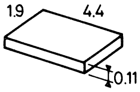
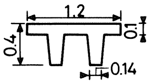
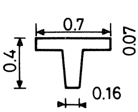
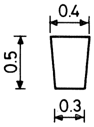
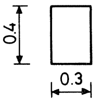
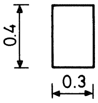
To supplement this experimental research, at the initiative of IBBC-TNO investigations were carried out both on prestressed and on reinforced normalweight concrete beams with the object of studying the spalling behaviour [22], [23]. The results of six fire tests on reinforced normalweight concrete beams are reported in [22]. For two of these beams a fire was simulated whose rate of development was more rapid than in the standard fire test. Unfortunately, in these tests the material moisture content was not determined by measurements, so that there was no clear-cut information on the amount of uncombined water present in the specimens. However, no artificial drying was applied prior to the fire tests, the cross-sectional dimensions of the beams were 0,3 × 0,4 m, and the beams were not older than about 4 months at the time of testing; hence it can be assumed that the material moisture content was rather high.

The results of the fire tests on these non-prestressed beams were such that their spalling behaviour could tentatively be allocated as local spalling as described in point b of Section 1.2. The authors of the report [22] themselves come to the conclusion that "the phenomenon of spalling was not observed in these fire tests".

In [23] the results are reported of fire tests performed on two reinforced and two prestressed beams made of normalweight concrete. The material moisture content of the beams in this case was determined from concrete specimens which were made from the same mix simultaneously with the casting of the beams. The content of uncombined water was determined by weighing in comparison with the weight found after drying at 110 °C. The moisture content thus found was 7,5% (by volume). In the two prestressed beams the compressive stress in the concrete at the more highly compressed face was about 10N/mm^2. From the results of the fire test it appears that spalling did not occur in the reinforced beams, but did occur in the prestressed ones.

In [23] the tentative conclusion was that "a combination of a high moisture content and large compressive stress is liable to cause the explosive spalling of pieces of concrete from the surface". On comparing the results of the tests on the lightweight concrete beams [21] with those of the tests on prestressed normalweight concrete beams [23], the following emerges: if the conditions necessary for the occurrence of spalling

Table 12. Summary of some fire tests performed before Committee C 29 was set up (TNO reports 1

lit. ref.	No.	aggregate	shape	dimensions [m]	heating	reinforcement stirrups	compressive stress [N/mm^2]	moist $\overline{\psi}$ [vol.%
19	1	gravel	floor		1-sided	⌀12-110 ⌀ 6-140	0,0	8,0
	2	Korlin				⌀12-110 ⌀ 6-140	0,0	8,0
20	1	Korlin	floor element		1-sided	no stirrups	average 4,0	8,0
21	1	Korlin	T-beam		2-sided	stirrups at the end	5,4	high
	2		T-beam				5,4	low
	3		T-beam				7,3	low
	4		T-beam				7,3	high
	5		column		4-sided	stirrups ⌀8-250	13,0	high
	6		column			⌀4-32	13,0	low
	7		column				13,0	low
22	1	gravel	beam		3-sided	stirrups ⌀8-300	0,0	7,0*
	2							8,0*
	3							5,0*
	4							6,5*
	5							5,5*
	6							5,0*
23	1	gravel	beam		3-sided	stirrups ⌀8-300	0,0	7,5
	2						0,0	7,5
	3						0,0-10,0	7,5
	4						0,0-10,0	7,5

* Estimated moisture content based on the quantities of water and cement in the mix.

** Heating in all other tests according the ISO-curve.

m- essive rength /mm^2]	no spalling [min.]	destructive spalling with a few large pieces	destructive spalling with small pieces	local spalling	sloughing off	end of test f = failure s = stopped	remarks
	0–60	a few small pieces from heated surface				60 (f)	
,8	0–60						deflection approx. 80% of normal weight concrete floor
,0	0–10	a few small pieces from face (10 min.)				51 (f)	
,4		?	6–30 min.			30 (f)	
		6–28 min. 3 flattish lumps				75 (s)	dried at 100 °C
		13–14 min.				92 (s)	dried at 100 °C
		?	25–50 min.			69 (s)	
2,4		30 min. flattish lump from top	6–90 min.			90 (s)	
		8–30 min. (bottom)					
		18–30 min. (top)				90 (s)	dried at 100 °C
		10–40 min. (ends)			concrete cover detached at 86 min.	90 (s)	dried at 100 °C
8,0				edge		60 (s)	
8,0				edge			
8,0				edge			accelerated heating**
8,0				edges rather serious			accelerated heating**
8,0				edge			
8,0				edge			
7,5						60 (s)	
9,5						60 (s)	
6,0						60 (s)	
3,0			some pieces 8–25 min.			60 (s)	

are satisfied, namely, a high moisture content and some compressive stress, then the phenomenon is more serious in lightweight than in normalweight concrete.

The results of the research reported in [24] can be cited in support of the conclusions stated above. That research comprised fire tests on 18 prestressed I-beams made of normalweight concrete (9 beams) and lightweight concrete (9 beams). They were stored in the open air for some months after being concreted. At the end of this period they were all stored at 22 °C/35% RH for a year or more.

At the time of testing, the material moisture content in all these beams was below 7% (by volume). During the fire tests there was spalling only in a few places on the flange in the vicinity of the ends of the beams. The author of that report attributes this phenomenon to the presence of a higher moisture content in those parts than elsewhere in the beams. This higher moisture content in turn was attributed to the fact that during storage of the test beams in the climate-controlled room (22 °C/35% RH) there was not sufficient air circulation around their ends. Because of the low moisture content no destructive spalling according the description under a and d envisaged in Section 1.2 did occur.

At the same time as the execution of above-mentioned preliminary tests by IBBC-TNO, the German research on the spalling of normalweight and lightweight concrete, already referred to, was also in progress [3], [7]. Prior to the publication of the research work conducted in West Germany, some of the results thereof had already become available.

In [25] some previously described tests are reviewed. On the basis of the then available information, further research on the subject of spalling in relation to the material moisture content in conjunction with the existence of a compressive stress was recommended. This circumstance was one of the reasons for the setting up of the CUR Committee C 29. The fire tests which were performed within the context of this Committee's research will now be described.

4.4.2 Supplementary fire tests on lightweight concrete

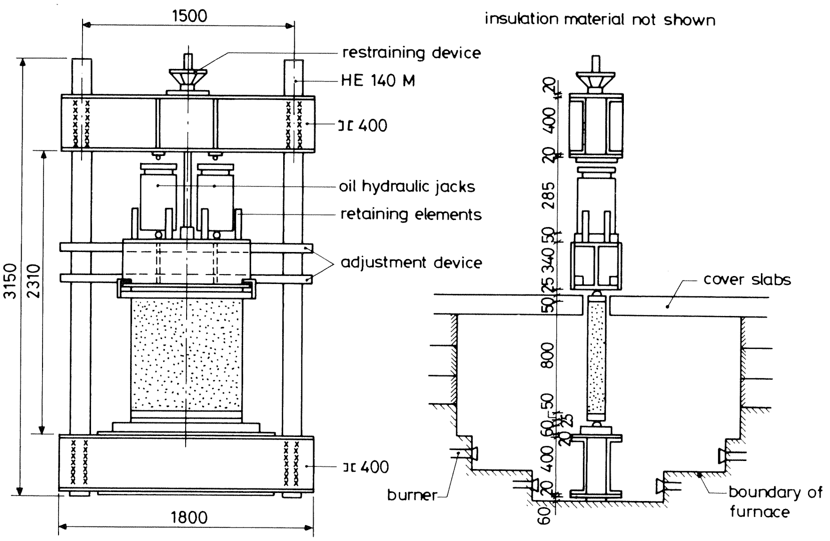
The fire tests performed by IBBC-TNO at the request of the Committee are reported in detail in [26] and [27]. Table 13 presents a summary of all the tests, the results of which are classified in accordance with the forms of spalling described in Section 1.2. The tests comprised four series a, b, c and d. Further information on each series will be given in Sections 4.4.3 to 4.4.6.

4.4.3 Results of four fire tests on slab-shaped units a_1 to a_4 and the test results reported in [7]

The slabs a_1 to a_4 formed part of an extensive series of tests which it has been originally intended to carry out in full. After the four fire tests, however, it was decided not to complete the series, for reasons which will be explained after the discussion of the results listed in Table 13.

Three of the four slabs were artificially dried to various values of the moisture content. The compressive stress applied to the slabs likewise varied from one to another. This stress was applied uniformly over the entire cross-section by means of a compression frame (see Figs 24a and 24b). The condition of the specimens after the fire tests is illustrated in Figs. 25 to 28. As stated in Table 13, a form of spalling, occurring between 8 and 25 minutes after the start of the test, was observed only in slab a_3. This spalling consisted in the explosive dislodgment of small pieces of concrete from the surface (see Section 1.2, point d). The phenomenon that manifested itself in slabs a_1 and a_2, in which the slab underwent total disruption after 24 minutes or a large flattish piece of concrete was dislodged from the surface, must be rated as what is called destructive spalling (see Section 1.2, point a). After the fire test the residual compressive strength was determined on cubes which had been kept in the fire test furnace during the test. This residual strength was found to be 15 N/mm^2 on average, which was higher than the stress that had existed in all the test specimens. In accordance with what has been pointed out in [8], the compressive strength of the slab specimens themselves will not have been lower, since the rise in temperature took place under load (see also Section 2.1).

The test results obtained can be compared with those of the tests on lightweight concrete in West Germany [7]. This comparison is made in Fig. 29. In this diagram it is indicated whether or not there occurred spalling in any particular test, with due regard to the conditions under which the tests were performed. The 74 tests reported in [7] were likewise carried out with the aid of a compression frame as shown in Figs. 24a and 24b.

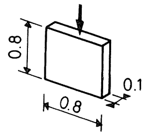
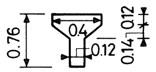
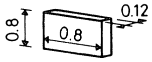
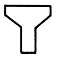
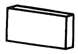
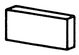


a test rig

b section through test rig

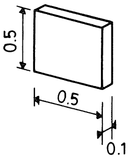
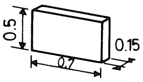
Fig. 24. Test equipment for fire tests series a and b.

Table 13. Summary of the fire tests carried out on behalf of Committee C 29 (TNO reports 26 and 2

se-ries	No.	aggregate	shape	dimensions [m]	heating	reinforcement stirrups	com-pressive stress [N/mm²]	moist $\overline{\psi}$ [vol.%]
a	a_1	Korlin B 5/10	slab		2-sided		10,0	5,3
	a_2						5,0	5,1
	a_3						5,0	12,2
	a_4						0,0	6,7
b	b_1	Korlin B 5/10	beam		2-sided	∅6-150 ∅6-370	0,8-7,2	12,9
	b_{11}		slab			∅6-370	0,8-7,2	15,5
	b_{12}		slab			∅6-370	0,8-7,2	14,4
	b_2		beam			∅6-150 ∅6-370	1,2-10,3	12,5
	b_{21}		slab			∅6-370	1,2-10,7	12,5
	b_{22}		slab			∅6-370	1,2-10,7	12,5
	b_3		beam			∅6-150 ∅6-370	1,2-8,3	2,3
	b_{31}		slab			∅6-370	1,2-8,6	2,9
	b_{32}		slab			∅6-370	1,2-8,6	1,0

m- essive ength /mm^2]	no spalling [min.]	destructive spalling with a few large pieces	destructive spalling with small pieces	local spalling	sloughing off	end of test f = failure s = stopped	remarks
,4	0–24	24 min. (entirely)				24 (f)	sudden explosive disintegration without preliminary warning
,4	0–24	24 min. (1 flattish lump)				45 (s)	
,1	0–8	25 min. (1 flattish lump)	8-25 min.	10 min. (edge)		45 (s)	
,1	0–60					60 (s)	
,8	0–6	10 min. (1 flattish lump) 11 min. (1 flattish lump)	6–28 min.			40 (f)	prestressing visible after 28 min.
,8	0–9	11 min. (1 flattish lump)	9–28 min.	9 min. (edge)		28 (f)	
,8	0–9	10 min. (1 flattish lump)	9–26 min.	9 min. (edge)		26 (f)	
,8	0–5	10 min. (flattish lumps)	5–25 min.			45 (s)	prestressing visible after 33 min.
,8	0–8,5		8,5–29 min.			29 (s)	
,8	0–8	9 min. (flattish lumps)	8–22 min.			22 (f)	
,1	0–29	29 min. (1 flattish lump)		34 min. (edges)		60 (s)	the lump spalled off at the end: probably incomplete drying
,1	0–31	31 min. (1 flattish lump)				45 (s)	
,1	0–29	(1 flattish lump)				30 (f)	

(continued Table 13)

series	No.	aggregate	shape	dimensions [m]	heating	reinforcement stirrups	compressive stress [N/mm^2]	moist $\overline{\psi}$ [vol.%]
c	c_1	Korlin A dry	slab		2-sided	none		10,0
	c_2	Agral 650						10,0
	c_3	Korlin A wet						7,7
	c_4	Korlin A wet						13,0
	c_5	Agral 650 wet						7,7
	c_6	Agral 650 wet						15,9
	c_7	Korlin B wet						10,7
	c_8	Korlin B wet						15,0
	c_9	Agral 650 wet						12,0
	c_{10}	Agral 650 wet						16,0
	c_{11}	Agral 650 dry						9,4
d	d_1	Korlin A 4/10	slab		2-sided		4,0	$\overline{\psi}>1$

The thickness of the specimens ranged from 80 to 120 mm. From the results of the 74 German and the four Dutch tests it can, with the available information, be concluded that for a slab thickness of 80–120 mm:

- if there is no reinforcement and if heating is applied on one side only, no spalling will occur if $\overline{\psi} \leqq 7.0\%$ (by volume); this is valid for all values of the compressive stress in the concrete;
- if there is no reinforcement and if heating is applied on two sides, there is no assignable safe region;
- if there is reinforcement and if heating is applied on one side only, no spalling will occur if $\overline{\psi} \leqq 7.0\%$ (by volume); this is valid only if the compressive in the concrete is practically zero;

om- ressive rength N/mm^2]	no spalling [min.]	destructive spalling with a few large pieces	destructive spalling with small pieces	local spalling	sloughing off	end of test f = failure s = stopped	remarks
3,3	0–45			6 min. (edge)		45 (s)	crazing (chunks 50 × 50 mm)
8,8	0–45			6 min. (edge)		45 (s)	crazing (chunks 50 × 50 mm)
7,0	0–45					45 (s)	entirely intact
4,3	0–45			(edge)		45 (s)	crazing (chunks 25 × 25 mm) specimen disintegrated
0,2	0–45					45 (s)	entirely intact
2,9	0–45			6–12 min. all edges		45 (s)	specimen disintegrated
2,9	0–45					45 (s)	entirely intact
2,8	0–45			6–30 min. same edges		45 (s)	
9,5	0–45					45 (s)	entirely intact
8,4	0–45			8–15 min. along the edges	(10 min.?)	45 (s)	a piece felt off after 10 min.
4,3	0–45			8 min. (edge)		45 (s)	entirely intact
0,0	0–7	26 min. (entirely)	7–26 min.			26 (f)	after 26 min. failure occurred with a distinctly audible bang

- if there is reinforcement and if heating is applied on two sides, there is no assignable safe region.

In Fig. 29a the test results have been presented in simplified diagrammatic form. It appears that for a moisture content $\overline{\psi} < 7{,}0\%$ (by volume) the application of heat on one side is distinctly more favourable than on two sides. This is in agreement with the description that has been given for normalweight concrete (Section 2.1, point c). With regard to the trend that emerges it can be inferred that the type of lightweight aggregate employed is of no importance.

The analysis presented here calls for four comments:
- the data given in Fig. 29 relate only to the results of fire tests on slab-type members,

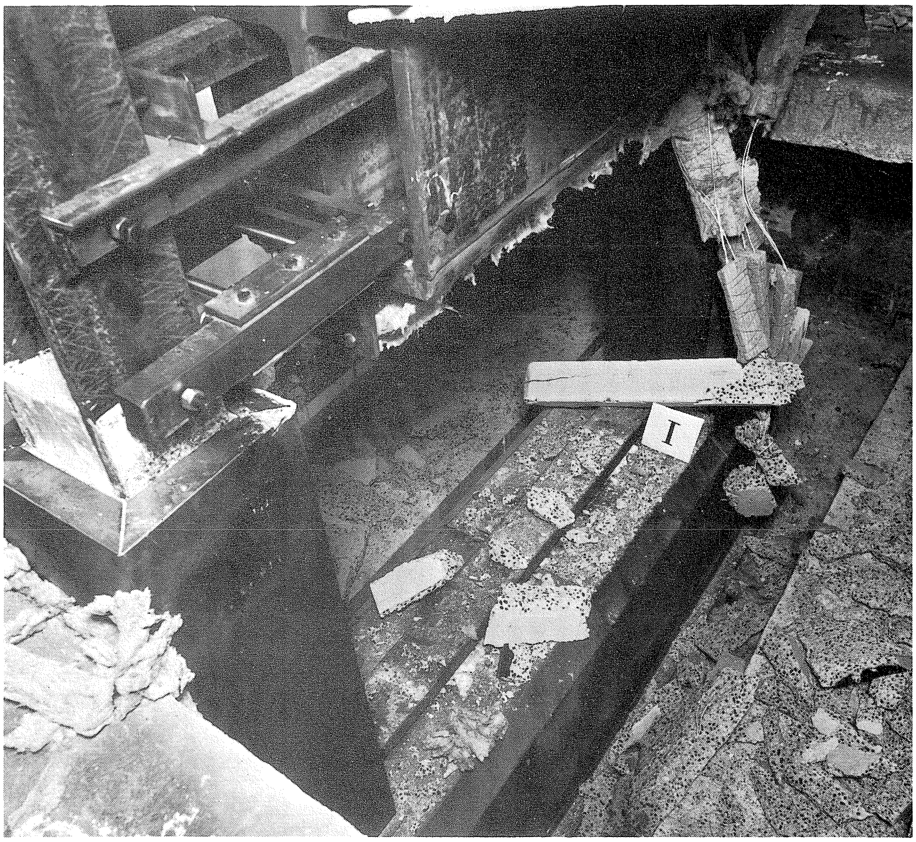


Fig. 25. Slab a_1 after the fire test.

- in plotting the data in Fig. 29 no distinctions have been made with regard to the intensity of spalling, since the available details in [7] do not permit this; it may be asked whether it might not be possible to give a more precise demarcation of a "safe region" if an objective criterion for spalling intensity were applied,
- during the fire test there occurs a reduction in cross-section as a result of spalling, as a result of which the initially existing stress distribution is changed,
- the thickness of the slab-type members ranged from 80 to 120 mm; in [7] it is stated that with increasing thickness the susceptibility to the occurrence of spalling diminishes; this was not clearly ascertainable on the evidence of the 78 tests performed; on the basis of the theoretical analysis for normalweight concrete in [3] it emerged that for a thickness of $\geqq$ 200 mm there was likely to be less spalling (see Section 2.1, point c); the fact that the above-mentioned trend does not clearly emerge from the 78 tests on lightweight concrete specimens may be attributable to the rather limited range of variation in the thickness of these specimens; their average thickness was about 100 mm, i.e., only about half the 200 mm limit indicated in [3].

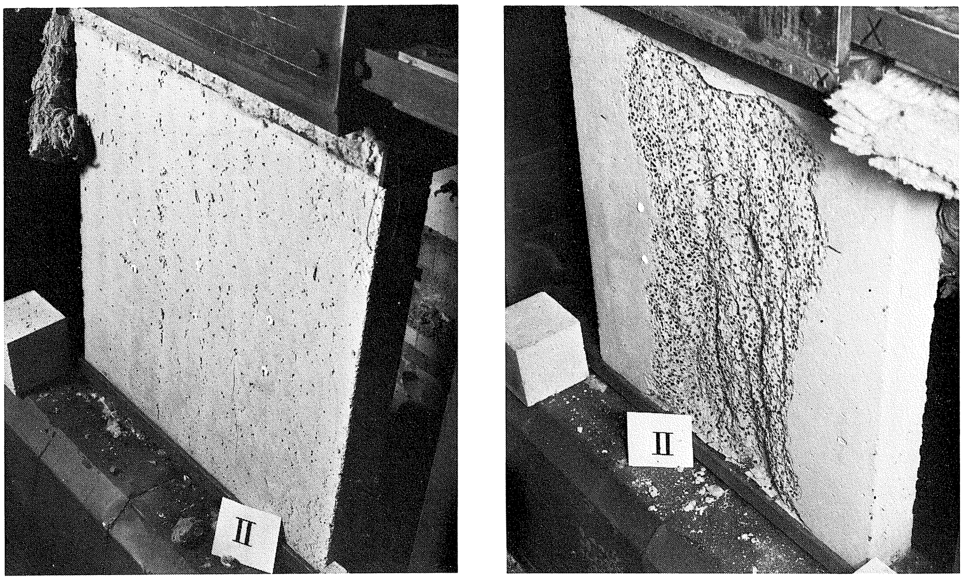


Fig. 26. Slab a_2 after the fire test.

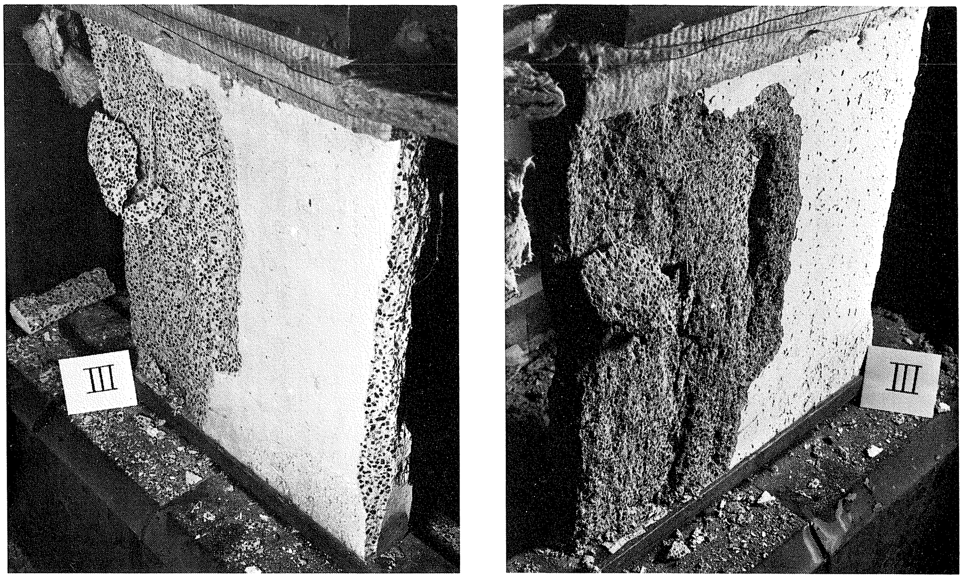


Fig. 27. Slab a_3 after the fire test.

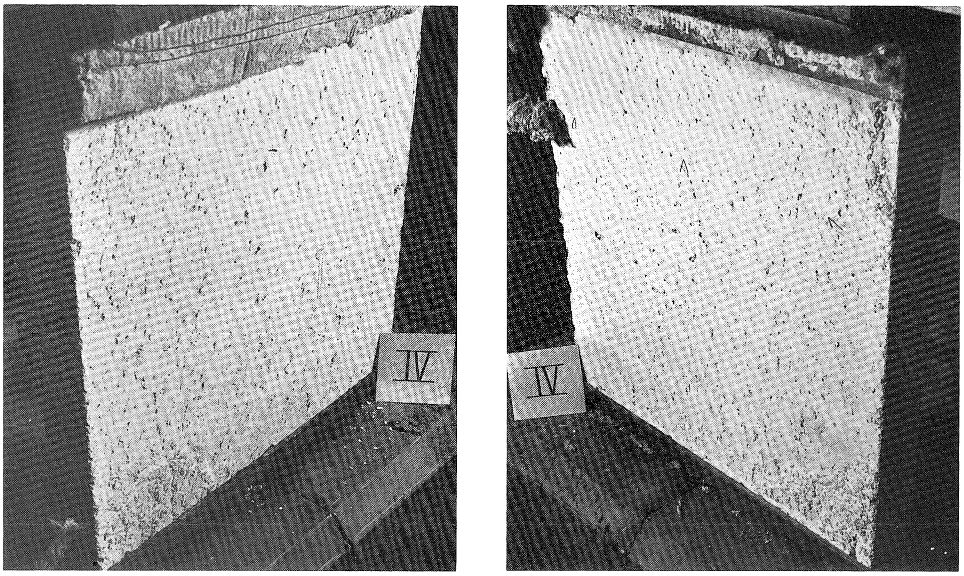


Fig. 28. Slab a_4 after the fire test.

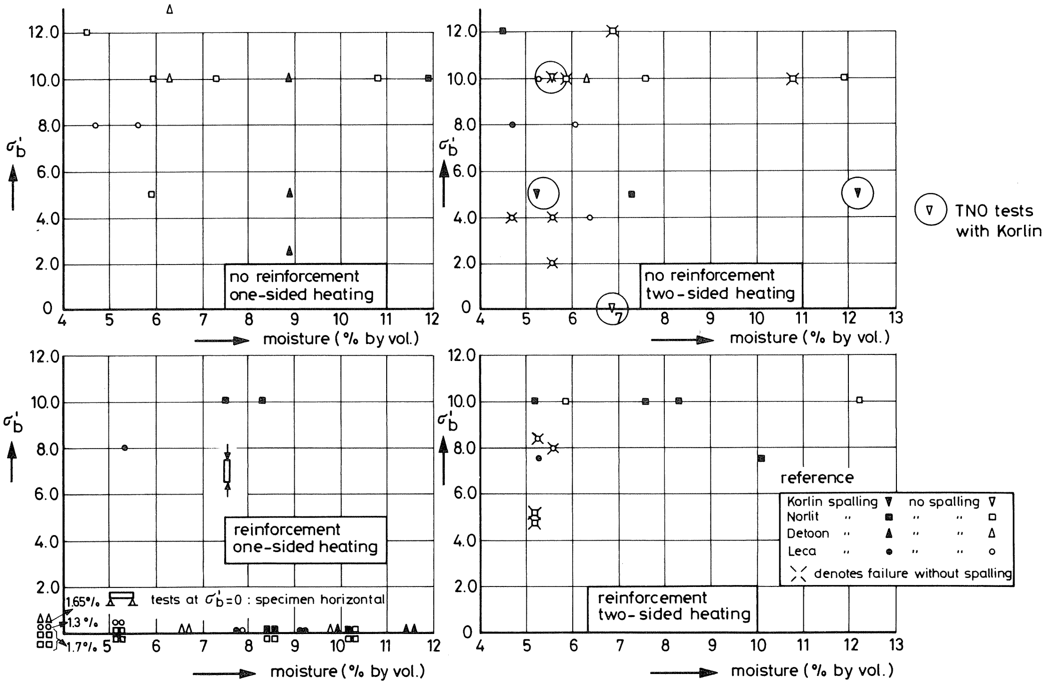


Fig. 29. Summary of the fire tests according to [7].

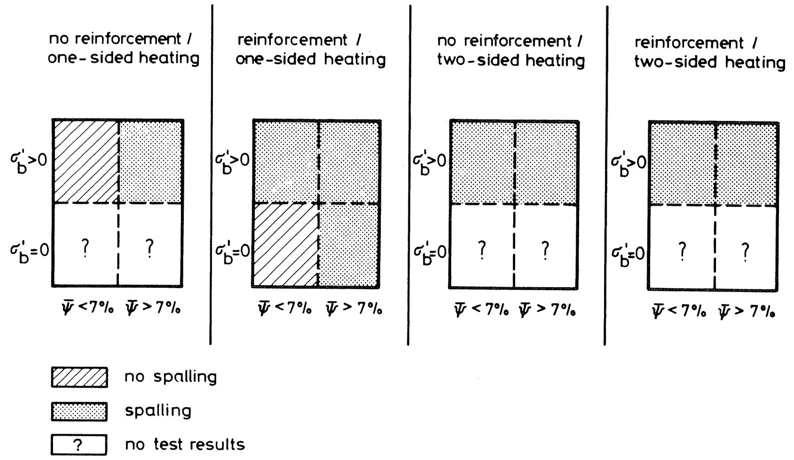


Fig. 29a. Simplified diagram of the test results presented in Fig. 29 [7]. Slab thickness d conforming to $80 < d < 120$ mm.

From Fig. 29 it is apparent that there is fairly considerable scatter in the results of the (74+4) tests. The four comments given above, together with this scatter, give rise to some doubt as to the success that fire tests performed by the method described here (tests on slab-type specimens mounted in a compression frame) can be expected to achieve. For this reason only four tests out of the extensive series originally envisaged were actually carried out.

4.4.4 Results of the fire tests on three beams b_1 to b_3 and six slab-type specimens b_{11} to b_{32}

In the fire testing of slab-type specimens mounted in a compression frame it is presupposed that the specimen can be conceived as part of the web of a beam. In this connection it is important that there should be some certainty on the question whether the spalling behaviour of a beam web does indeed conform to that of such a slab-type specimen. For this reason three fire tests were performed on prestressed lightweight concrete T-beams and on six slab-type specimens as indicated in Table 13.

The reinforcement and dimensions of the beams and the corresponding slabs are shown in Figs. 30a and 30b. These beams and slabs were made from the same concrete mix and were subjected to exactly the same treatment during the period preceding the fire test (except for the prestress applied to the beams).

Before and after the prestressing of the beams and just before testing in the furnace the deformations of the beams were measured. These measurements gave a good idea of the stress distribution in the beams. By means of the compression frame installed

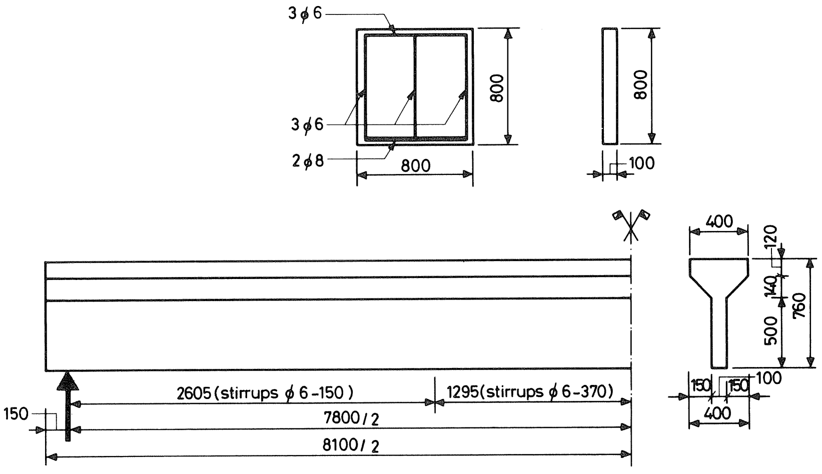


Fig. 30. Beam and slab dimensions as applied in test series b.

around the slabs a stress pattern was applied which corresponded to that which was set up by prestress in the beams. The stress distribution over the depth was approximatly linear. During the fire tests the stress distribution in the beams could of course no longer be modified. In the slab tests the forces exerted by the jacks in the frame were kept constant. In order to obtain a particular moisture content, artificial drying was applied to one beam and two slabs. The average moisture content that could be presumed to exist in the slabs and in the web of the beams was determined on separate concrete specimens with the "drilling method" (core samples). These specimens were treated in exactly the same way as the beams and corresponding slabs. The condition of the fire test specimens after testing is shown in Figs. 31 to 39. The test results are listed in Table 13.

The events during the fire tests, as recorded in this table, suggest the following tentative conclusions:

- the spalling behaviour of slabs and beams shows good agreement; this applies both to the point of time at which the various events were observed to occur and to the form in which spalling manifested itself; this being so, the spalling behaviour can indeed be studied by means of tests on slab specimens,
- there is no agreement in the point of time at which failure occurs in the slabs and beams respectively; of course, this is to be expected, having regard to the difference in structural system;
- the form of spalling already referred to in point d of Section 1.2, namely, the continual dislodgement of small pieces of concrete in the first 8–25 minutes, occurs only if the moisture content is high; it also emerges that there must be a transition between the occurrence and non-occurrence of spalling at a moisture content from 6,7% to 12,2% (by volume). Whether or not this is a "sharp" transition or whether it is closer to the

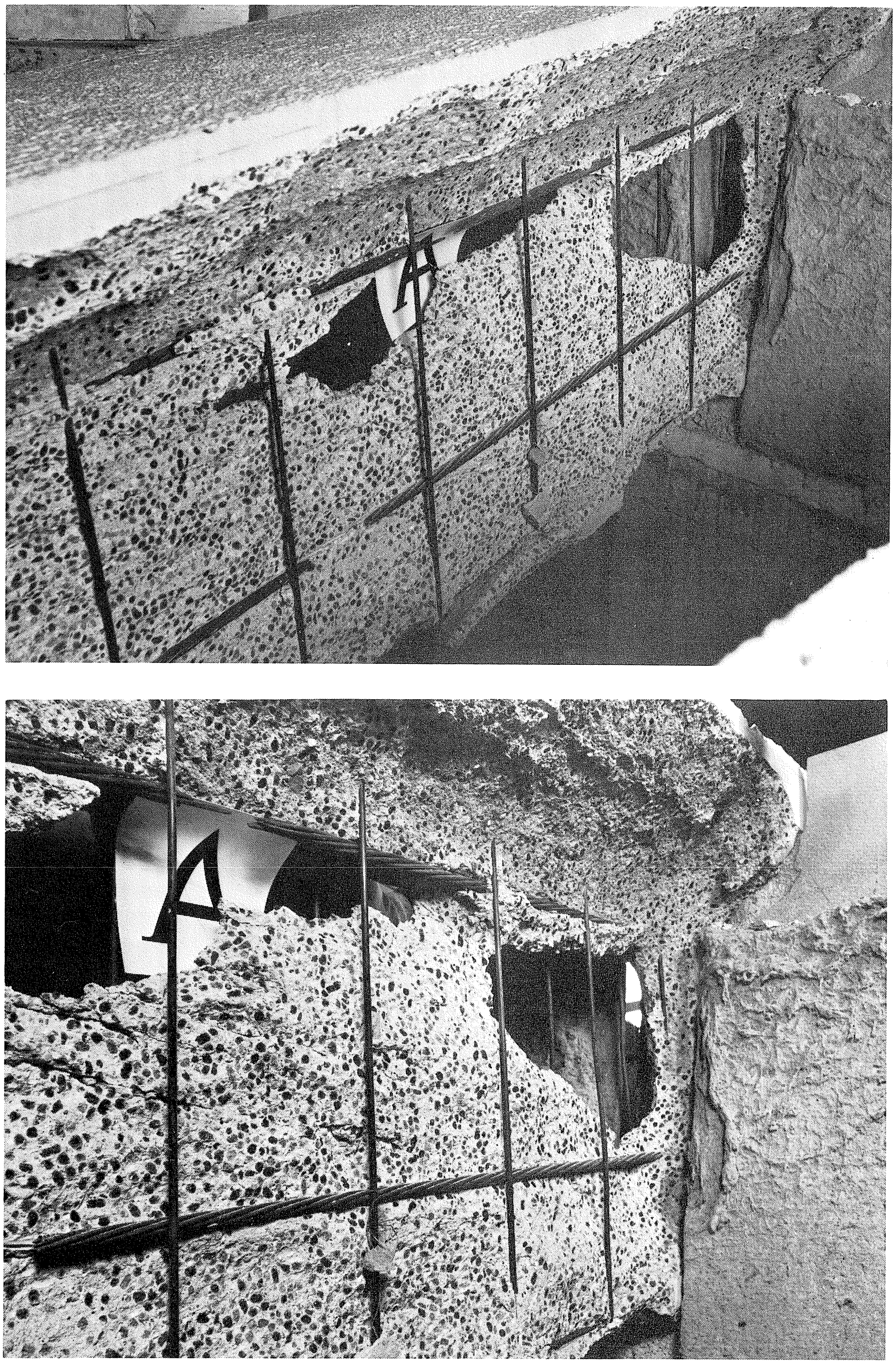


Fig. 31. Beam b_1 after the fire test.

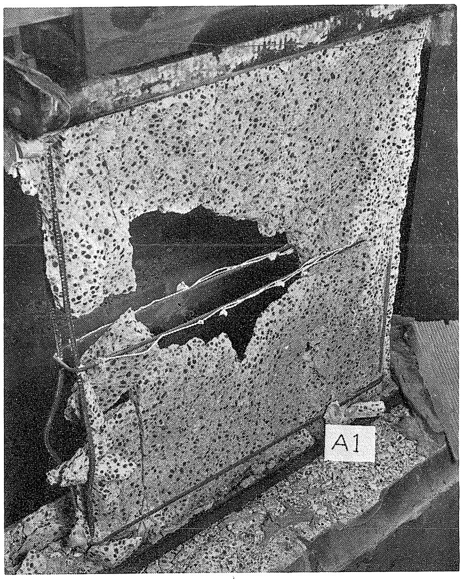


Fig. 32. Slab b_{11} after the fire test.

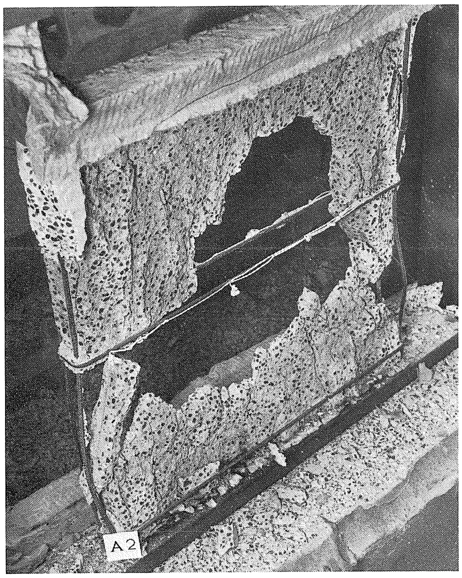


Fig. 33. Slab b_{12} after the fire test.

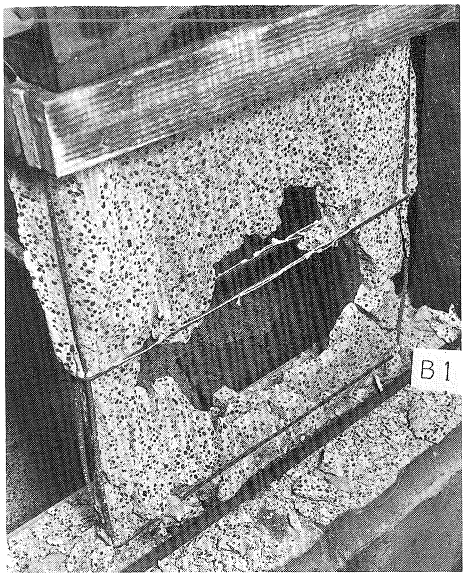


Fig. 35. Slab b_{21} after the fire test.

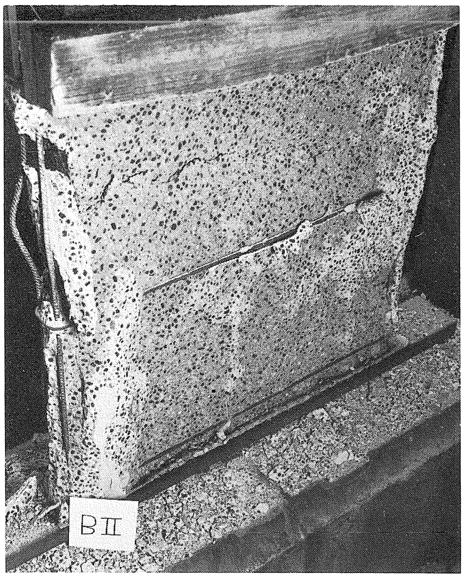


Fig. 36. Slab b_{22} after the fire test.

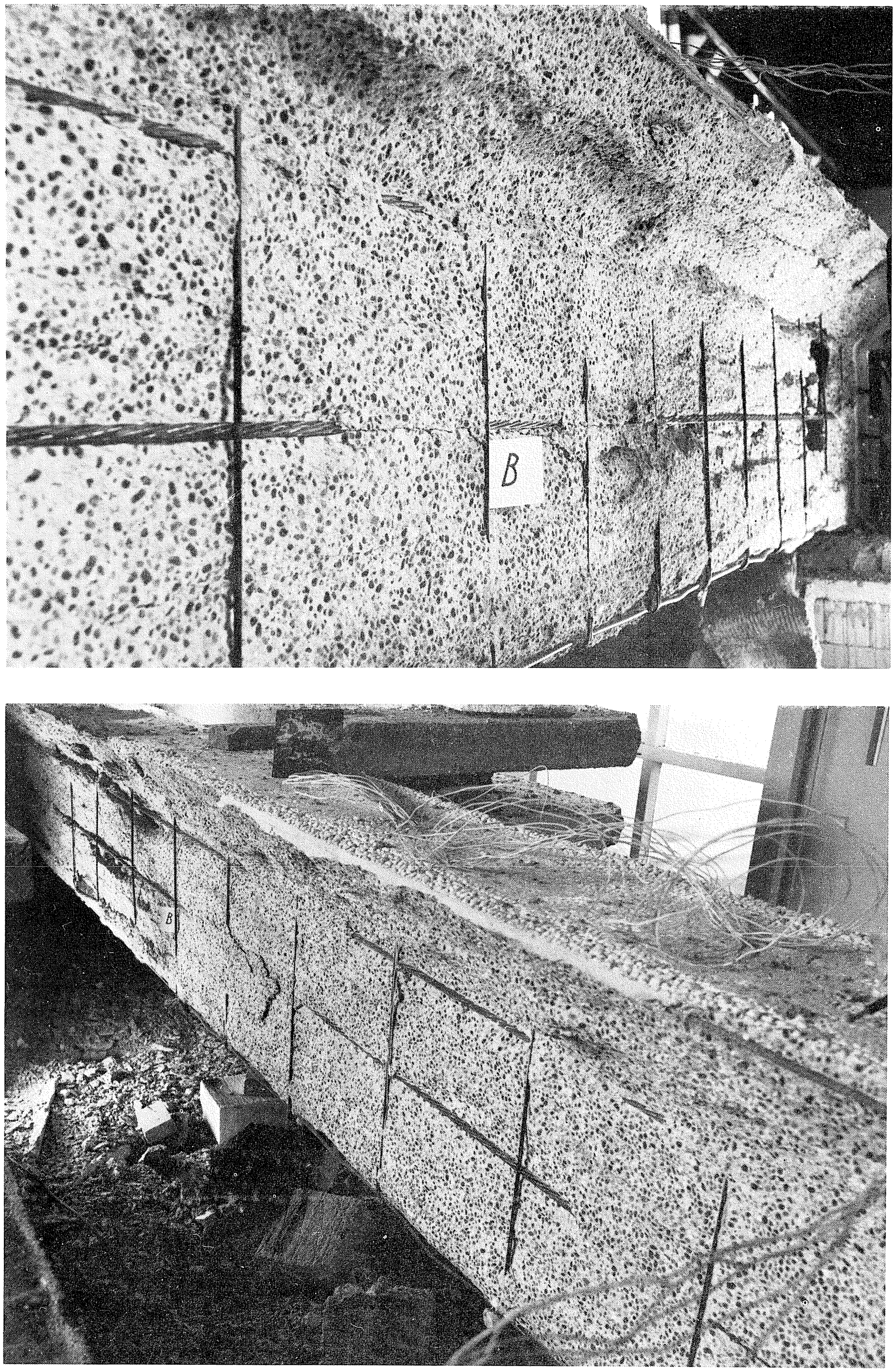


Fig. 34. Beam b_2 after the fire test.

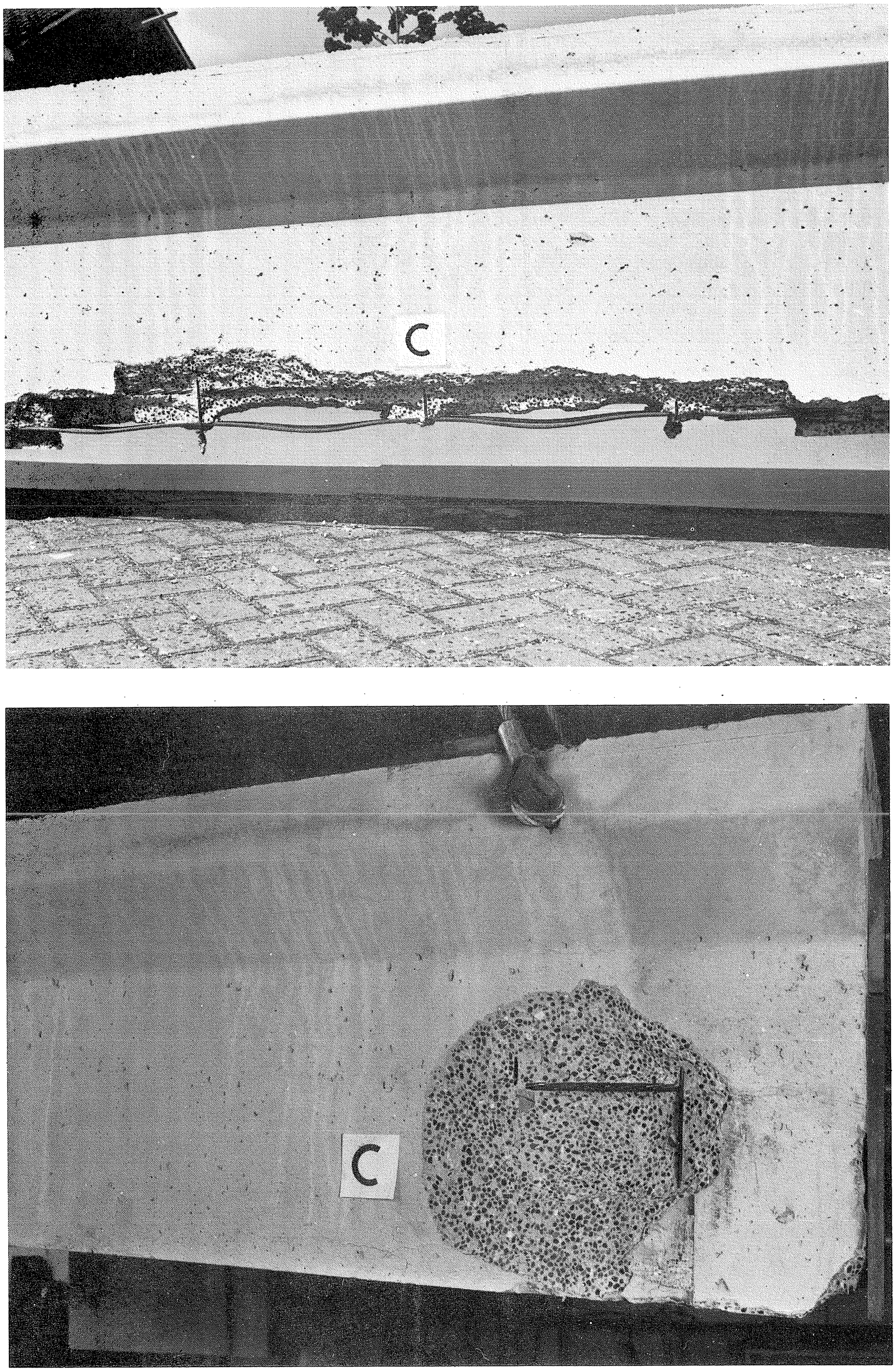


Fig. 37. Beam b_3 after the fire test.

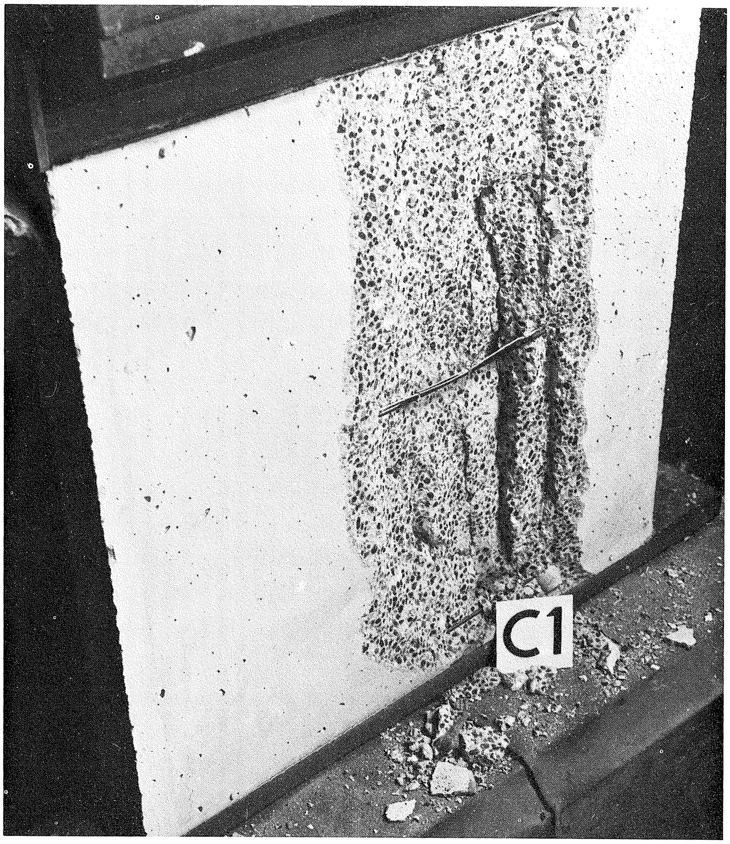


Fig. 38. Slab b_{31} after the fire test.

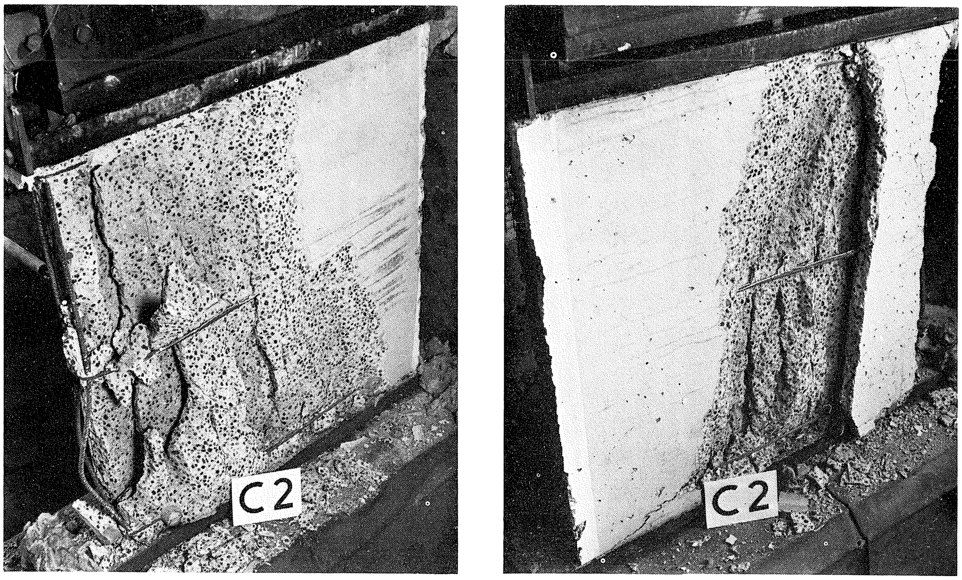


Fig. 39. Slab b_{32} after the fire test.

lower limit than to the given upper limit cannot be ascertained with the available data (heating on two sides is envisaged here),
- from Table 13 it furthermore appears that the dislodgement of one or a few large pieces of concrete generally commences somewhat later (according to the table: after 20 minutes, on an average); Fig. 40 shows that, for diminishing moisture content, the point of time at which a large piece is explosively dislodged undergoes a shift; with the available information on the tests reported in [7] it was not possible to ascertain this trend.

4.4.5 Results of the fire tests on eleven slab-type specimens c_1 to c_{11}

The test results described in 4.4.3 and 4.4.4 did not reveal that variations in the compressive stress acting in the concrete have any effect on the occurrence or non-occurrence of spalling. For this reason it was decided to carry out supplementary research on slab-type specimens with a high moisture content and no applied compressive stress. The lightweight aggregates employed were either fully saturated or completely dried to constant weight before mixing.* After the specimens had been cast, they were stored in an air-conditioned room at 20 °C/98% RH for 22 days, after which they were stored either at 20 °C/60% RH or at 60 °C/50% RH. Storage under these last-mentioned conditions aimed at quickly attaining a certain average moisture content with the aid of as natural a drying process as possible. The moisture content measured before the fire test is given in Table 13, in which these tests are enumerated. The following observations were made during the fire tests:
- in none of the eleven specimens was there any serious spalling during the fire test; spalling only occurred incidentally in a few places along the edges of some specimens; broadly speaking, this occurred somewhat more in the specimens with a moisture content above 10% (by volume),
- in nearly all the specimens with a moisture content above 10% (by volume) a finely divided pattern of cracks (crazing) developed: see Fig. 41,
- during the fire test the slabs were suspended from a weighing apparatus by means of which the decrease in weight was recorded with a view to obtaining an objective measure of the intensity of spalling; to this end, two horizontal and two vertical 6 mm diameter bars had been embedded in each slab and served as the attachment for the suspension structure; at this reinforcement a large numer of cracks occurred, with the result that pieces of concrete were detached, but not in the manner of spalling.

From these observations it can be concluded that in the absence of compressive stress in the concrete there occurs no, or hardly any, spalling in the case of "no reinforcement and two-sided heating" (see also Fig. 29 and the result of the slab test a_4).

Since no spalling occurred during these tests, the result obtained in recording the loss of weight will not be further discussed. The principle of the procedure is, however, explained in Appendix C.

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* For this case this did not give rise to any differences.

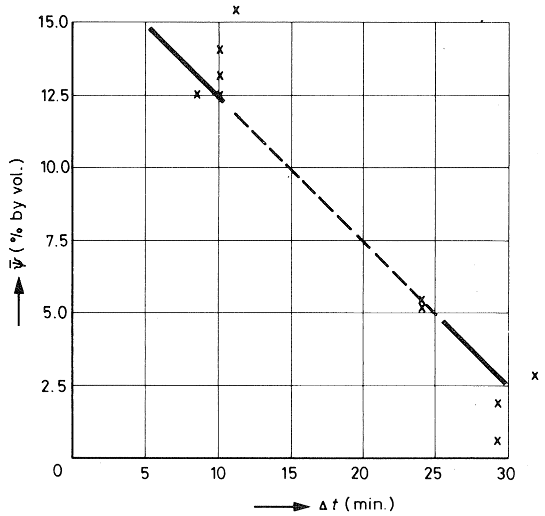

Fig. 40. Moisture content ψ as a function of time Δt, this being the period after which one or more pieces of concrete were explosively dislodged (test series a and b).

Fig. 41. Slab in series c after the fire test.

4.4.6 Result of the fire test on one slab-type specimen d_1

Finally, the series of fire tests was completed by the testing of a 150 mm thick prestressed slab-type specimen with a high moisture content ($\overline{\psi} \geqq 10\%$ by volume). It was given a compressive stress of 4 N/mm^2 by means of three prestressing cables (unbonded tendons). In order to distribute this stress as uniformly as possible, the anchorages at each end of the cables were fixed to two NP 100 rolled steel channel sections whose contact faces with the test specimen comprised a thin interposed layer of gypsum plaster to ensure even bearing. The anchorage zone was carefully insulated with glass-wool. Since the weight of the specimen as a whole was considerably greater than that of the slabs described earlier on, it was not possible in this test to record the loss of weight (see Appendix C), as the measuring beams had not been designated for this. The events observed during the test are stated in Table 13. The remains of the specimen after enduring the test are illustrated in Fig. 42. This result in combination with the results of series C indicates that a certain amount of compressive stress must be present for spalling to occur in a case where there is no reinforcement and a high moisture content.

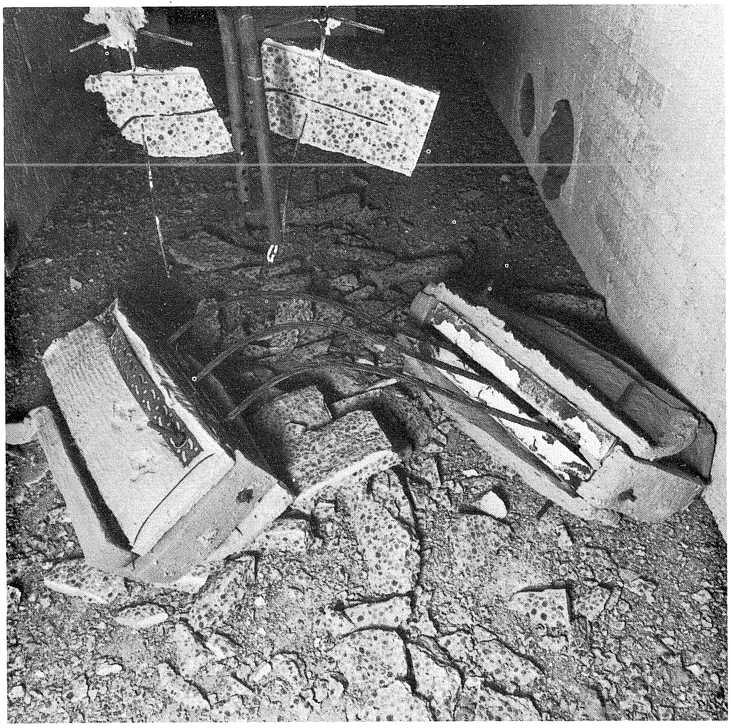

Fig. 42. Slab in series d after the fire test.

4.5 *Analysis of the results of the fire tests*

The results of the 74 fire tests comprised in Fig. 29 (obtained from [7]) and the 25 tests listed in Table 13 will be summarized in this section of the report. All forms of spalling can be accommodated in the classification given in Section 1.2; in short it amounts to this:

a. explosive dislodging of a few pieces of concrete or complete shattering (destructive spalling with large pieces);
b. dislodging of a few small pieces, including the edges (local spalling);
c. gradual reduction of cross-section (especially at high temperatures) (sloughing off);
d. explosive dislodging of small pieces of concrete, which occurs continuously (destructive spalling with small pieces).

In Fig. 43 all the test results reported in [7], [26] and [27] are presented in simplified diagrammatic form. Having due regard to what has been stated in Section 4.4.2, the following emerges.

For a slab thickness of 80–120 mm the forms of spalling envisaged in points a and d do not occur if:

- no reinforcement is provided and heating is applied on one side, for a moisture content $\overline{\psi} < 7\%$ (by volume) and a concrete compressive stress $0 \leqq \sigma'_b < 12$ N/mm^2;
- reinforcement is provided and heating is applied on one side, for a moisture content $\overline{\psi} < 7\%$ (by volume) and a concrete compressive stress $\sigma'_b = 0$;

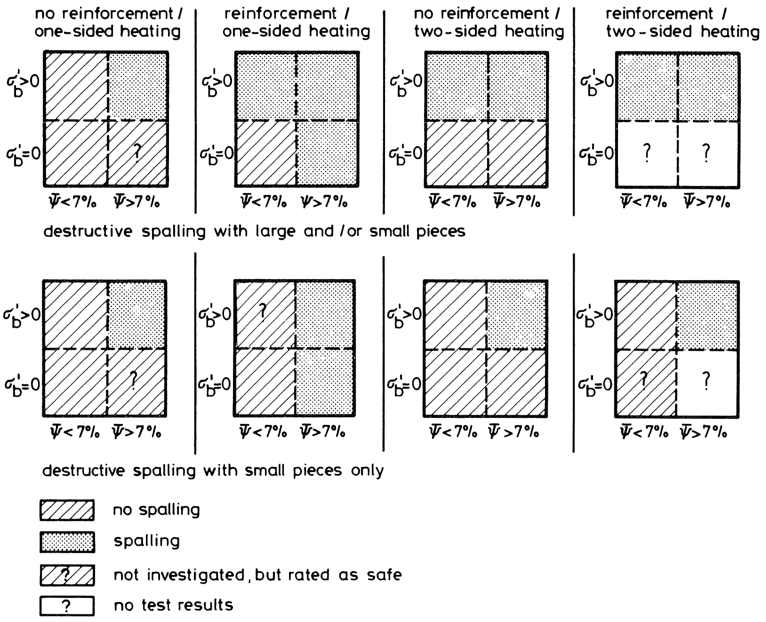

Fig. 43. Simplified diagram of the test results reported in [7], [26] and [27] for 80 < d < 120 mm.

- no reinforcement is provided and heating is applied on two sides, for a moisture content $\overline{\psi} < 16\%$ (by volume) and a concrete compressive stress $\sigma'_b = 0$.

The form of spalling envisaged in point d does not occur if:

- heating is applied on two sides, whether reinforcement is provided or not, for a moisture content $\overline{\psi} < 7\%$ (by volume)* and a concrete compressive stress $0 \leqq \sigma'_b < 10$ N/mm^2.

The form of spalling envisaged in point a may occur if:

- heating is applied on two sides, whether reinforcement is provided or not, for a moisture content $\overline{\psi} < 16\%$ (by volume) (i.e., also for $\overline{\psi} < 7\%$ by volume) and a concrete compressive stress $0 < \sigma'_b < 10{,}7$ N/mm^2 and probably also for higher values of the compressive stress (but this has not been established by testing).

The test results given in Table 13 indicate that, for decreasing moisture content, the instant when destructive spalling with large pieces occurs undergoes a shift. With the available data of the results presented in Fig. 29 (German tests) it is not possible to detect this trend.

The above conclusions are valid for thicknesses of between 80 and 120 mm. With increasing thickness a distinctly more favourable pattern of behaviour can be expected on the evidence of the literature [3]. This is especially important for preventing the occurrence of spalling of form a (destructive spalling with large pieces) in the case of two-sided heating, with or without reinforcement, for a moisture content $\overline{\psi} < 16\%$ (by volume) and a concrete compressive stress $0 < \sigma'_b < 10$ N/mm^2. From the foregoing summary of the spalling behaviour it can be inferred in a general way that the magnitude of the moisture content is of essential importance. The probability of spalling decreases if the moisture content decreases. For a particular moisture content no spalling will occur if the amount of moisture is such that no excess pressure is developed in the pores or other voids, this being so because there is sufficient space to accommodate the moisture in the interior of the concrete or because the moisture can escape out of the concrete. In connection with this it is understandable that the following trends emerge from the tests:

- heating applied on one side is distinctly more favourable than heating applied on two sides;
- heating applied on two sides approaches the more favourable behaviour associated with one-sided heating according as the member is thicker;
- the effect of reinforcement appears similar to that of an applied compressive stress in the concrete; this can be explained on the assumption that both reduce the risk of the formation of small cracks in the concrete and thus make moisture transport more difficult; this also explains why in the tests the events that occur are not clearly related to the magnitude of the compressive stress: what seems to be more important is whether or not there is some compressive stress at all.

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* This values is a lower limit with regard to the tests performed (see Section 4.4.4).

The form in which spalling manifests itself, as envisaged in points b and c (being local spalling and sloughing off), cannot be related to the moisture content of the concrete. In connection with the need to ensure adequate fire resistance the possible spalling at edges can be taken into account by giving the corner bars (e.g., in beams) a somewhat greater depth of concrete cover. The deterioration in the quality of the concrete proceeds according as the temperature becomes higher. In thicker members the temperature will be lower with increasing distance into the interior thereof. The spalling phenomenon as envisaged in c (sloughing off) therefore occurs mainly along the edges. Particularly when the depth of cover is large, as is generally adopted in cases where stringent fire resistance requirements have to be met, the outer layer constituted by the concrete cover will be subjected to high temperatures. For this reason it is sometimes recommended to provide "skin reinforcement" (e.g., mesh reinforcement with not too small apertures) within the concrete cover if the latter exceeds 40 mm. With this precaution, dislodgment of the concrete is prevented, so that the cover can continue to perform its function. It is, however, important also to ensure that the moisture content will be as low as possible.

5 Conclusions and recommendations

The principal cause of spalling is found to lie in the moisture content of the material. This has been found to apply both to normalweight concrete [3] and to lightweight concrete (see Section 4.5). In conjunction with a certain moisture content each of the following factors, singly or in combination, plays an important part:
- heating applied on one side or on two sides;
- reinforcement or no reinforcement;
- compressive stress or no compressive stress;
- thickness of the member.

Less important factors are:
- the quantity of reinforcement (provided that the bars are not too closely spaced);
- the magnitude of the compressive stress applied;
- for lightweight concrete: the type of lightweight aggregate (so far as has been investigated);
- the quality of the concrete (if suitable for structural purposes);
- the distribution of the moisture in the cross-section.

On account of the presumed causes, measures for the avoidance of spalling in normalweight concrete and in lightweight concrete are similar in principle (see Section 2.2). According to [3], for normalweight concrete the probability of spalling is very low for a material moisture content $\overline{\psi} < 5\%$ (by volume)* (see Section 2.2.3). For a moisture con-

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* The figure of 5% adopted here is on the safe side. On the evidence of the tests and according to the theory [3] a value of about 7% would be appropriate.

tent $\overline{\psi} < 5\%$ (by volume) the occurrence of spalling in normalweight concrete can be prevented by basing the detailling of the members on Fig. 4. This presupposes that the risk of spalling increases with increasing compressive stress and decreasing thickness. The shape of the curve in that diagram indicates only a low degree of dependence on the magnitude of the compressive stress. This is not at variance with the results found for lightweight concrete, because for this type of concrete it has not been demonstrated that a high compressive stress is more dangerous than a low one. It has emerged, however, that the presence of compressive stress in itself, together with other factors (moisture), may give rise to spalling. For lightweight concrete it is, as also for normalweight concrete, held that greater thickness is favourable. This is based on theoretical considerations as presented in Section 2.1. On the evidence yielded by the experimental research on lightweight concrete a recommendation $\overline{\psi} < 7\%$ (by volume) for the moisture content to be aimed at would appear appropriate. This value is in fact also applicable to normalweight concrete, and in [3] the limit has been set lower, namely, at $\overline{\psi} < 5\%$ (by volume), probably for reasons of safety. In practice it will taken a fairly long time to reach an average moisture content of 5-7% (by volume). This length of time can, however, be reduced (see Section 4.1). In Section 4.2.3 it was stated that the drying which occurs in dwellings and office buildings during the first two years after concreting is determined by a weighted climate of 16 °C/65% RH. For the concretes under investigation the hygroscopic moisture content at 65% relative humidity ranges from 5,5 to 7,5%. After the first two years it can permissibly be assumed that drying is determined by a weighted climate of 20 °C/55% RH.

For all the materials investigated, the hygroscopic moisture content at 55% RH was found to be about 5% (by volume). It is therefore not meaningful to aim for an initial moisture content of less than 5% (by volume), because in that case the concrete would actually increase its moisture content. In humid rooms, other than offices, with RH > 55% even the limit $\overline{\psi} = 5\%$ (by volume) is not attainable.

In conclusion, the following can be said with regard to lightweight concrete. The point of time when a moisture content of about 7% (by volume) is attained will depend on the thickness, the temperature, the relative humidity, the concrete properties (such as diffusion resistance), the initial moisture content and the course of the hygroscopic curve.

From Table 10 it appears that after two years the average moisture content of the concretes made with Korlin, Agral and gravel aggregate is of the order of 7,5% for a thickness of 0,22 m. In view of what has been stated in Section 4.5 it can, on the basis of this, be assumed for dwellings and office buildings that after two years the probability of destructive spalling with small pieces will not, or hardly, exist (see Fig. 43). This is so, regardless of the quantity of reinforcement provided and/or the magnitude of the compressive stress acting in the concrete. From Table 10 it also appears that concrete made with Argex aggregate dries less rapidly, so that it requires a longer period (about 4 years) before the probability of the occurrence of destructive spalling with small pieces will have become low.

As regards the occurrence of destructive spalling with large pieces it is not possible to make such definite pronouncements. Hence the following somewhat speculative conclusion is drawn: from a thickness of 120 mm upwards the probability of dislodgment of large pieces of concrete likewise diminishes after two years and will, on the basis of the theory presented in [3], have become low for a thickness of the order of 0,2–0,3 m, provided that the moisture content $\overline{\psi} < 7\%$ (by volume).

This speculative conclusion is in agreement with what has been adopted for normal-weight concrete (see Fig. 4), except that for lightweight concrete no connection with the magnitude of the existing compressive stress is established. The presence of a compressive stress and/or reinforcement has an unfavourable effect, though the actual quantity of the reinforcement or magnitude of the compressive stress seems to be of rather less importance. The results of fire tests, as given in Tables 12 and 13, and also the rest results according to [24] mentioned in Section 4.4.1 support this conclusion.

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APPENDIX A

A1 Theoretical description on the drying process

A1.1 *Physical data*

In connection with describing the drying process with the aid of a mathematical model the hygroscopic curve is used (see Figs. 16–20), which comprises the values of the equilibrium moisture content ψ plotted against the corresponding relative humidity of the air φ. This functional relationship can be written as follows in general terms:

$$\psi = \psi(\varphi) \qquad \text{(A.1)}$$

where the relative humidity is:

$$\varphi = p/p' \qquad \text{(A.2)}$$

and:

p' = the saturation vapour pressure
p = the actual vapour pressure

Equation (A.1) can now be written as:

$$\psi = \psi(\varphi(p)) \qquad \text{(A.3)}$$

The temperature in a building will vary rather rapidly in comparison with the rate of moisture transport. All the same, the temperature variations are slow enough to justify the assumption that $\overline{\nabla} T = 0$, which means that the temperature does indeed vary but that no temperature differences occur within the concrete section. For this reason, in the analytical treatment of the drying process the temperature-time behaviour will be divided into time intervals with a constant temperature per interval. Hence the temperature-time dependence relationship is not introduced into the derivation of the mathematical model for describing the drying process, as given in Section A1.2. If the vapour pressure in a material varies from one point to another, diffusion of vapour will take place. The quantity of moisture in the form of vapour that diffuses through a given area as a function of the vapour pressure difference can be empirically established with the aid of Fick's law:

$$q = -\delta \frac{\mathrm{d}p}{\mathrm{d}r} \qquad \text{(A.4)}$$

For practical reasons the diffusion resistance index μ is introduced, which indicates the ratio between the amount of water vapour that would diffuse through a layer of stationary air of a certain thickness and the amount of vapour that diffuses under the same conditions through a layer of the same thickness of the material under consideration. Adopting the notation:

δ = the water vapour conduction coefficient in the material
δ_a = the water vapour conduction coefficient in air

we may write:

$$\delta = \delta_a / \mu \quad \text{where} \quad \mu > 1$$

Substitution of this expression into (A.4) gives:

$$q = -\frac{\delta_a}{\mu}\frac{\mathrm{d}p}{\mathrm{d}r} \tag{A.5}$$

A1.2 *Mathematical model for the drying process*

Using the physical data given in A1.1, a differential equation can be established for describing the drying process. The quantity of moisture at a particular point of the material at a particular time is equal to $(\psi/100)\rho_1$. As a result of moisture transport the moisture content will vary with place and with time.

Since there is no loss of mass, the sum of the changes with respect to place and to time will have to be zero, and hence:

$$\frac{\mathrm{d}q}{\mathrm{d}r} + \frac{\partial}{\partial t}\left(\rho_1 \frac{\psi}{100}\right) = 0 \tag{A.6}$$

This expression (A.6) is called the equation of continuity. With the aid of equation (A.5) we obtain:

$$\frac{1}{100}\frac{\partial \psi}{\partial t} - \left(\frac{\delta_a}{\mu}\frac{\mathrm{d}^2 p}{\mathrm{d}r^2}\right) = 0 \tag{A.7a}$$

where ρ_1, δ_a and μ are assumed to be constant. According to equation (A.3):

$$\frac{1}{100}\frac{\partial \psi}{\partial t} = \frac{\mathrm{d}\psi}{\mathrm{d}\varphi} \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}p} \cdot \frac{\partial p}{\partial t}$$

With reference to equation (A.2) we can now write:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}p} = \frac{1}{p'}$$

where p' is assumed to be constant. This is the case if T (temperature) is constant. The change in moisture content with time is then:

$$\frac{1}{100}\frac{\partial\psi}{\partial t}=\frac{1}{p'}\frac{\partial\psi}{\partial\varphi}\frac{\partial p}{\partial t}$$

On substitution into equation (A.7a) we obtain:

$$\frac{\partial p}{\partial t}=\frac{p'\delta_a}{\rho_l\mu(\mathrm{d}\psi/\mathrm{d}\varphi)}\cdot\frac{\mathrm{d}^2p}{\mathrm{d}r^2} \tag{A.7b}$$

This equation, which describes vapour transport at constant temperature, will be used for the analytical treatment of the drying process. It can be validly used only if the drying process of concrete can be described in terms of diffusion.

Within the scope of the problem under consideration this assumption of diffusion-based drying will indeed be found a justifiable one. In actual building practice, however, there are situations conceivable in which this simplification cannot permissibly be introduced, e.g., with regard to the drying process of thick-walled concrete vessels of nuclear reactors. The description of such process is, however, quite satisfactorily possible with an extended model. The equations applicable to problems of this kind, and also the electrical analogy needed for solving them, have been developed by Boekwijt [12] and are held available by IBBC-TNO.

Since equation (A.7b) is of the second order, two boundary conditions are required for its solution, namely:

- the measured initial moisture content and initial moisture distribution;
- the measured climate (temperature and relative humidity) which governs the vapour pressure p at the boundary of the member.

During the drying process the vapour pressure p at the boundary continuously changes as time goes by. Because of this, despite the above-mentioned simplifications, an analytical solution for equation (A.7b) is impracticable.

For this reason IBBC-TNO has devised an electrical analogue procedure which establishes the relationship between a number of electrical quantities in analogy with equation (A.7b). By monitoring the process as a function of time in this electrical model the solution to the problem, characterized by continuously varying boundary conditions, can be obtained.

All the same, with the aid of equation (A.7b) it is possible directly to pinpoint some symptoms of the drying process. These will be considered in Section A1.3.

A1.3 *Symptoms of the drying process on the basis of the theoretical model*

An interesting factor B_0 can be determined from the differential equation (A.7b) with the aid of the laws of similitude. The interrelationships of a number of quantities which determine the drying process can be studied with this factor B_0, which is called the Boekwijt number. The procedure for determining B_0 is as follows:

Suppose there are two situations to which equation (A.7b) is applicable and for which there exists a constant ratio (C_ζ) between the quantities in the two processes, so that:

$$\begin{aligned}
\mu_1 &= C_\mu \mu_2 \\
\psi_1 &= C_\psi \psi_2 \\
\varphi_1 &= C_\varphi \varphi_2 \\
r_1 &= C_r r_2 \\
t_1 &= C_t t_2
\end{aligned}$$

$$\left(\frac{p'\delta_a}{\rho_1}\right)_1 = C_T \left(\frac{p'\delta_a}{\rho_1}\right)_2$$

On substitution into equation (A.7b) it is found that the vapour pressure p in the two processes behaves identically if the following condition is satisfied:

$$\frac{C_T C_t C_\varphi}{C_\mu C_r^2 C_\psi} = 1$$

Base on this last-mentioned expression, the Boekwijt number B_0 is given by:

$$B_0 = \frac{(p'\delta_a/\rho_l)t}{\mu r^2 \psi/\varphi} = \text{constant} \tag{A.8}$$

Two different moisture distributions can be adopted in applying the Boekwijt number:

It can readily be seen that:
- doubling the diffusion resistance index μ will entail doubling of the drying time;
- doubling the thickness r will entail quadrupling the drying time.

It is known that the saturation pressure p' varies greatly with temperature. The water vapour conduction coefficient δ_a is less temperature-dependent, while the temperature-dependence of the specific mass of water ρ_1 is very slight.

At 15 °C the factor $p'\delta_a/\rho_1$ is equal to $0{,}33 \times 10^{-9}$ m^2/s. A calculation shows that this factor is approximately doubled if the temperature rises by 10 °C. The drying period is then halved.

The effect of the factor ψ/φ is not easy to estimate. Calculations show that the drying time (and therefore implicitly the factor ψ/φ) is largely determined by the shape of the hygroscopic curve.

To obtain the shortest possible drying time, the hygroscopic curve should descend rapidly from the initial moisture content (at 100% relative humidity). This means that the pores or voids in the concrete should be as coarse as possible. A coarse pore structure can moreover have the effect of lowering the diffusion resistance index μ, which helps to speed up drying and thus shorten the drying time. The pore structure of concrete will in part depend on the quantity of mixing water used (i.e., the water-cement ratio).

A2 Comparison of the theoretically and the experimentally determined moisture content

A2.1 *Carbonation and hydration in relation to the drying process*

The mathematical model described in Section A1.2 is based on the physical data stated in Section A1.1. For this purpose concrete was assumed to be chemically inert, which of course is not really so. Some important reaction phenomena are, for example, hydration and carbonation. As a result of hydration some of the initially present moisture will be chemically combined, a phenomenon not described by the diffusion equation (A.7b). For this reason the moisture content ψ in that equation was modified during the course of the calculation process. To this end, a simultaneous time function obtained from the literature [15] and represented in Fig. A.1 was introduced [12]. In accordance with the information given in [15], Fig. A.1 was applied only so long as the relative humidity in the pores at the location concerned was above 85%.

Carbonation gives rise to effects in relation to the drying process which are not included in equation (A.7b) either. By carbonation is understood the reaction that occurs between the free lime in concrete and carbon dioxide from the atmosphere. The pores of the concrete at the boundary surfaces of a member may become partly clogged up as a result of this reaction, so that the diffusion resistance through the thin outermost layer is increased. In introducing carbonation into the drying process the three following considerations were applied:

a. Proceeding from the exterior to the interior, a concrete member can be conceived as comprising two layers of material. The inner layer has a thickness corresponding to roughly half the cross-sectional dimension of the member; it is bounded by the thin

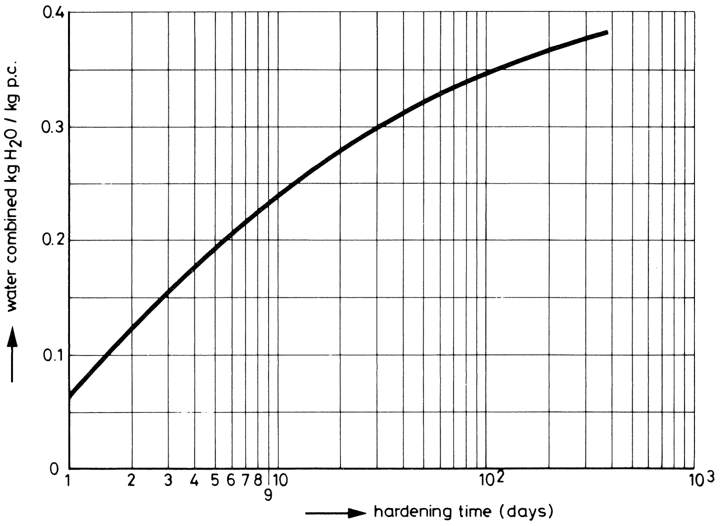

Fig. A1. The reaction of water with portland cement (according to Hilsdorf [15]).

Table A1. Diffusion resistance index $\mu(-)$.

type of concrete	triple			average
Korlin-A	92	85	78	85
Korlin-B	77	77	85	80
Agral-650	66	75	69	70
Argex-S	75	91	59	75
gravel	99	95	107	100

outer layer which has a thickness equal to the depth of carbonation and a higher resistance to diffusion. With the aid of the Boekwijt number given in Section A1.3 it can be deduced that the effect of the carbonation front upon the rate of drying is in fact negligible.

b. On the other hand, if an experimentally determined value of the diffusion resistance is used in the calculation, carbonation may have a non-negligible effect. This can be explained as follows.
   The diffusion resistance index is determined by means of the so-called wet cup method, in which a vessel containing water is provided with a "cover" of the material under investigation. The vessel covered in this way is placed in surroundings in which a certain constant temperature and relative humidity are maintained. The diffusion resistance index μ can be calculated from the decrease in weight (determined by weighing) after a known length of time, using equation (A.5). Since the thickness of the sample of material is small (0,02 m) in order to keep the testing time as short as possible, the depth of carbonation will nevertheless be large in relation to the cross-sectional dimensions. The diffusion resistance index determined by this testing method will therefore be too high for calculations applied to concrete members with larger cross-sectional dimensions.* The diffusion resistance indices determined by the method described here and listed in Table A1 have accordingly been reduced by 25% for the purpose of the calculations.

c. The determination of the hygroscopic curves was likewise done in atmospheric air, i.e., air containing carbon dioxide. On completion of the measurements it was found that for all the samples the dry weight had increased in relation to the initial weight. This increase was due to the occurrence of carbonation and to continuing hydration [12].
   For the calculation of the hygroscopic curves in Figs. 16 to 20 the heavier weights were in all cases adopted as the basis, the reason for this being that in determining the moisture content in practice it is also usual to start from a "zero mass" (basic reference weight) in an advanced stage of hydration. Applying the initial weights

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* At the time of the research a method was developed which would enable the diffusion resistance to be determined in an environment free from carbon dioxide. It was not possible to perform these measurements within the limits of the available budget.

would cause all the values of the hygroscopic moisture content to be about 2% (by volume) higher. Here again the determination of the hygroscopic curves should be done in an environment free from carbon dioxide. The method of doing this has indeed been developed, but not yet applied.

A2.2 *Results of moisture content calculations for the specimens*

Using the mathematical model incorporating the modifications referred to in Section A2.1, a calculation was done with the electrical analogy. For this purpose the measured initial moisture content and the measured climate around the specimens were used. In equation (A.7b) the coefficient $p'\delta_a/\rho_1$ is not material-dependent, but it is temperature-dependent. The coefficient can be calculated for any temperature, using values published in existing manuals. As already stated, the temperature-dependent was introduced into the calculation procedure in that the value of the coefficient $p'\delta_a/\rho_1$ corresponding to a particular temperature was continually adjusted. Besides the measured values of the moisture content, the calculated values are given in Figs. 6 to 11. In general, there can be said to be reasonably good agreement between the measured and the calculated values. The rather erratic behaviour of the measured values is mainly due to the comparatively small diameter of the drilled cores in relation to the size and distribution of the lightweight aggregate particles.

From statistical calculations as performed in [12] it emerges that the moisture content calculated with the electrical analogy shows an average deviation of 0,6% (by volume) from the moisture content determined by drilling. The calculated result can therefore claim to be satisfactory. Hence it can be concluded that, if the concrete properties, the dimensions and the climate are known, it is indeed possible to calculate the material moisture content as a function of time.

APPENDIX B

Determination of a "weighted" climate for the analysis of the drying process [12]

The determination of a so-called "weighted" climate is centred on the following two questions:

a. Is the rapid attainment of a low average moisture content favourably affected to a significant degree if the data of concreting occurs within a certain season?
b. What error is introduced by basing the calculation on average climatic data?

For answering question a it will be necessary to chose a particular (arbitrary) climatic behaviour pattern and some concreting dates.

For the outdoor climate the standard data compiled by the Royal Netherlands Meteorological Institute at De Bilt, already referred to earlier on, will be used [16]. The test specimens adopted for the purpose are the small slabs made with Korlin B, Argex S and Agral 650 lightweight aggregates and with normalweight (gravel) aggregates (0,15 m thick, one-sided), while the concreting dates are taken as 1 January (climate I), 1 May (climate II) and 1 September (climate III). The fictitious buildings are assumed always to be fully glazed $4\frac{1}{2}$ months after concreting, after which the temperature during the remainder of the drying period under consideration ($13\frac{1}{2}$ months) is constant at 22 °C. The humidity of the air within this second period is calculated by superposition upon the outdoor humidity with the aid of the IBBC line in Fig. 14. The climates I, II and III determined in this way are listed in Table B1; the calculated moisture contents are given in Tables B2, B3, B4 and B5, while the average values have been plotted in Figs. B1, B2, B3 and B4. From the data in Tables B2 to B5 it emerges that the principal differences occur near the surface. In the first month the most rapid drying is obtained with climate III. As already stated, this drying occurs chiefly in the outer layer of the concrete (to a depth of about 0,05 m).

At greater depths the differences in moisture content at different ages are relatively small. All the same, the differences observed are still distinctly discernible in the average moisture contents, as Figs. B1 to B4 show. It is also evident that the differences remaining after one year are only very minor ones. Hence the differences would appear to be of no practical importance.

These facts lead on to the question whether the calculation may indeed be based on average climatic data (question b). That this is not directly permissible in so far as, for instance, the temperature is concerned will be demonstrated by the following example. Suppose for the sake of convenience that the factors such as relative humidity and the hydroscopic curve are constant. Furthermore, suppose that drying first takes place at a temperature of 100 °C for 5 days and then at 20 °C for 360 days. The average temperature will thus be: $(5 \times 100+360 \times 20)/365 = 21{,}1$ °C. It is evident that with a constant temperature 21,1 °C over the whole period under consideration (365 days) a much lower degree of drying would be attained. This is clearly shown by equation (A.9) (in Appendix A, Section A1.3).

Table B1. The standard climate at De Bilt (1901–1930) and three derived indoor climates I, II and III, if concreting takes place on $^1/_1$, $^1/_5$ and $^1/_9$ respectively and the glazing is installed after $4^1/_2$ months, after which the indoor temperature remains constant at 22 °C (concentration difference obtained from Fig. 11).

	De Bilt 1931–1960		climate I 1/1–15/5 outdoor 15/5–1/7 indoor		climate II 1/5–15/9 outdoor 15/9–1/11 indoor		climate III 1/9–15/1 outdoor 15/1–1/3 indoor	
month	$\overline{T}_e$ (°C)	$\overline{\varphi}_0$ (%)	$\overline{T}_i$ (°C)	$\overline{\varphi}_i$ (%)	$\overline{T}_i$ (°C)	$\overline{\varphi}_i$ (%)	$\overline{T}_i$ (°C)	$\overline{\varphi}_i$ (%)
1	2,2	88	2,2	88				
2	2,5	85	2,5	85				
3	4,8	79	4,8	79				
4	7,8	74	7,8	74				
5	12,5	72	17,3	58	12,5	72		
6	14,7	72	22	53	14,7	72		
7	16,7	73	22	59	16,7	73		
8	16,2	75	22	53	16,2	75		
9	13,7	79	22	55	17,9	66	13,7	79
10	9,8	83	22	48	22	48	9,8	83
11	5,1	86	22	41	22	41	5,1	86
12	3,0	88	22	39	22	39	3,0	88
1	2,2	88	22	38	22	38	12,1	57
2	2,5	85	22	37	22	37	22	37
3	4,8	79	22	37	22	37	22	37
4	7,8	74	22	40	22	40	22	40
5	12,5	72	22	48	22	48	22	48
6	14,7	72	22	53	22	53	22	53
7	16,7	73			22	59	22	59
8	16,2	75			22	59	22	59
9	13,7	79			22	55	22	55
10	9,8	83			22	48	22	48
11	5,1	86					22	41
12	3,0	88					22	39
1	2,2	88					22	38
2	2,5	85					22	37

Actually, the average value of the temperature factor $p'\delta_a/\rho_1$ should be determined from equation (A.9). Since this factor is $25{,}4 \times 10^{-9}$ m^2/s at 100 °C and $0{,}455 \times 10^{-9}$ m^2/s at 20 °C, the average is:

$$(5 \times 25{,}4 \times 10^{-9} + 360 \times 0{,}455 \times 10^{-9})/365 = 0{,}80 \times 10^{-9}\ \text{m}^2/\text{s}.$$

This average value corresponds to a temperature of 29,3 °C. It implies that drying at this constant temperature for 365 days would result in the same moisture content as 5 days at 100 °C and 360 days at 20 °C. It is important to note that this applies only to a period of 365 days, not to just a portion thereof. For example, after 5 days at 100 °C quite a lot of drying will have occurred, but very little after 5 days at 29,3 °C.

Table B2. Moisture content (% by vol.) as a function of place and time for Korlin B in the case of one-sided drying (slab thickness 0,15 m) and three climates.

depth (m)	climate	time (days)							
		30	64	106	148	232	303	442	543
0,01	I	14,2	13,4	12,1	10,1	7,2	5,6	3,9	5,0
	II	13,7	11,1	9,5	8,3	5,1	4,3	5,5	5,0
	III	12,1	11,0	10,8	9,7	6,1	6,0	4,7	3,9
0,03	I	14,5	14,2	13,8	13,4	12,0	10,0	6,5	6,2
	II	14,4	13,8	13,0	12,1	9,4	7,5	6,5	6,7
	III	13,9	13,5	13,3	12,9	11,6	9,4	7,3	6,1
0,05	I	14,5	14,2	13,8	13,6	13,0	12,5	9,4	8,5
	II	14,4	13,9	13,4	13,1	12,4	11,1	9,2	9,0
	III	13,9	13,6	13,5	13,3	12,9	12,0	10,0	8,8
0,07	I	14,5	14,2	13,8	13,6	13,0	12,8	11,4	10,2
	II	14,4	13,9	13,4	13,1	12,8	12,4	10,9	10,3
	III	13,9	13,6	13,5	13,3	13,0	12,5	11,4	10,4
0,09	I	14,5	14,2	13,8	13,6	13,1	12,9	12,3	11,5
	II	14,4	13,9	13,4	13,1	12,8	12,5	11,9	11,3
	III	13,9	13,6	13,5	13,4	13,0	12,5	12,0	11,4
0,115	I	14,5	14,2	13,8	13,6	13,0	12,8	11,9	11,2
	II	14,4	13,9	13,4	13,1	12,7	12,3	11,5	11,1
	III	13,9	13,6	13,5	13,3	13,0	12,4	11,9	11,2
average	I	14,5	14,1	13,5	13,0	11,9	11,1	9,2	8,8
	II	14,3	13,4	12,7	12,1	10,9	10,0	9,3	8,9
	III	13,6	13,2	13,0	12,7	11,6	10,8	9,6	8,6

Table B3. Moisture content (% by vol.) as a function of place and time for Argex-S in the case of one-sided drying (slab thickness 0,15 m) and three climates.

depth (m)	climate	time (days)							
		30	64	106	148	232	303	442	543
0,01	I	17,6	16,3	14,6	12,1	7,6	5,8	4,1	4,8
	II	17,0	13,7	10,2	8,2	5,3	4,4	5,2	5,0
	III	14,9	13,1	12,0	10,3	6,4	5,9	4,7	4,0
0,03	I	17,9	17,6	17,1	16,8	15,3	12,7	6,6	6,4
	II	17,9	17,3	16,5	15,5	11,8	8,7	6,9	6,9
	III	17,4	16,9	16,6	16,3	14,8	11,4	7,5	6,1
0,05	I	17,9	17,6	17,2	16,9	16,3	15,9	12,1	8,7
	II	17,9	17,4	16,7	16,2	15,6	14,2	11,0	9,2
	III	17,4	17,1	16,8	16,6	16,2	15,2	12,6	9,5
0,07	I	17,9	17,6	17,2	16,9	16,3	15,9	15,2	13,8
	II	17,9	17,4	16,7	16,4	15,8	15,4	14,6	13,7
	III	17,4	17,1	16,8	16,6	16,2	15,6	14,9	14,1
0,09	I	17,9	17,6	17,2	16,9	16,4	15,9	15,2	14,6
	II	17,9	17,4	16,8	16,4	15,8	15,4	14,8	14,5
	III	17,4	17,1	16,8	16,6	16,2	15,6	14,9	14,3
0,115	I	17,9	17,6	17,2	16,9	16,3	15,7	14,8	14,0
	II	17,9	17,4	16,8	16,4	15,8	15,1	14,3	13,8
	III	17,4	17,1	16,7	16,6	16,2	15,5	14,5	13,8
average	I	17,9	17,4	16,8	16,1	14,7	13,7	11,3	10,4
	II	17,8	16,8	15,6	14,9	13,4	12,2	11,1	10,5
	III	17,0	16,4	16,0	15,5	14,3	13,2	11,5	10,3

Table B4. Moisture content (% by vol.) as a function of place and time for Agral-650 in the case of one-sided drying (slab thickness 0,15 m) and three climates.

depth (m)	climate	time (days)							
		30	64	106	148	232	303	442	543
0,01	I	13,7	12,6	11,2	9,0	6,1	4,9	3,7	4,3
	II	13,2	10,2	8,1	6,9	4,4	3,9	4,6	4,4
	III	11,4	9,8	9,2	8,3	5,6	5,0	4,1	3,7
0,03	I	13,9	13,6	13,3	12,9	11,3	9,2	5,3	5,3
	II	13,9	13,3	12,5	11,6	8,5	6,4	5,7	5,8
	III	13,5	12,9	12,5	12,2	11,3	8,1	6,0	5,0
0,05	I	13,9	13,6	13,3	13,0	12,4	12,0	8,3	7,2
	II	13,9	13,4	12,9	12,6	11,8	10,4	8,0	7,8
	III	13,5	13,2	12,9	12,7	12,4	11,3	8,7	7,3
0,07	I	13,9	13,6	13,3	13,0	12,5	12,4	11,2	9,5
	II	13,9	13,4	12,9	12,6	12,2	11,8	10,1	9,4
	III	13,5	13,2	12,9	12,8	12,5	11,8	10,6	9,2
0,09	I	13,9	13,6	13,3	13,0	12,5	12,3	11,9	11,1
	II	13,9	13,4	12,9	12,6	12,2	11,9	11,4	10,9
	III	13,5	13,2	12,9	12,8	12,5	11,8	11,2	10,6
0,115	I	13,9	13,6	13,3	13,0	12,5	12,3	11,3	10,6
	II	13,9	13,4	12,9	12,6	12,2	11,7	11,0	10,4
	III	13,5	13,2	12,9	12,7	12,5	11,7	10,9	10,1
average	I	13,9	13,4	13,0	12,3	11,2	10,5	8,6	8,0
	II	13,8	12,9	12,0	11,5	10,2	9,4	8,5	8,1
	III	13,2	12,6	12,2	11,9	11,1	10,0	8,6	7,7

Table B5. Moisture content (% by vol.) as a function of place and time for normalweight gravel concrete in the case of one-sided drying (slab thickness 0,15 m) and three climates.

depth (m)	climate	time (days)							
		30	64	106	148	232	303	442	543
0,01	I	11,4	10,3	9,2	8,0	6,9	6,1	5,1	5,9
	II	10,8	8,8	8,0	7,5	5,7	5,3	6,2	6,0
	III	9,3	8,8	8,8	8,1	6,0	6,4	5,6	5,1
0,03	I	11,5	11,2	10,8	10,3	8,9	7,7	6,4	6,5
	II	11,4	10,8	9,8	9,1	7,5	6,6	6,7	6,7
	III	10,9	10,4	10,1	9,8	8,6	7,6	6,8	6,4
0,05	I	11,5	11,3	10,9	10,6	10,0	9,4	7,4	7,2
	II	11,4	11,0	10,5	10,1	9,3	8,1	7,5	7,5
	III	11,0	10,7	10,6	10,3	10,0	9,0	7,9	7,2
0,07	I	11,5	11,3	10,9	10,6	10,1	9,8	8,3	7,9
	II	11,4	11,0	10,5	10,3	9,7	9,0	8,2	8,0
	III	11,0	10,7	10,6	10,4	10,2	9,5	8,6	8,0
0,09	I	11,5	11,3	10,9	10,6	10,1	9,9	9,2	8,6
	II	11,4	11,0	10,5	10,3	9,9	9,6	8,8	8,5
	III	11,0	10,7	10,6	10,4	10,2	9,7	9,2	8,6
0,115	I	11,5	11,3	10,9	10,6	10,1	10,1	9,9	9,6
	II	11,4	11,0	10,5	10,3	10,1	9,9	9,7	9,5
	III	11,0	10,7	10,6	10,4	10,2	9,9	9,8	9,5
average	I	11,5	11,1	10,6	10,1	9,4	8,8	7,7	7,6
	II	11,3	10,6	10,0	9,6	8,7	8,1	7,9	7,7
	III	10,7	10,3	10,2	9,9	9,2	8,7	8,0	7,5

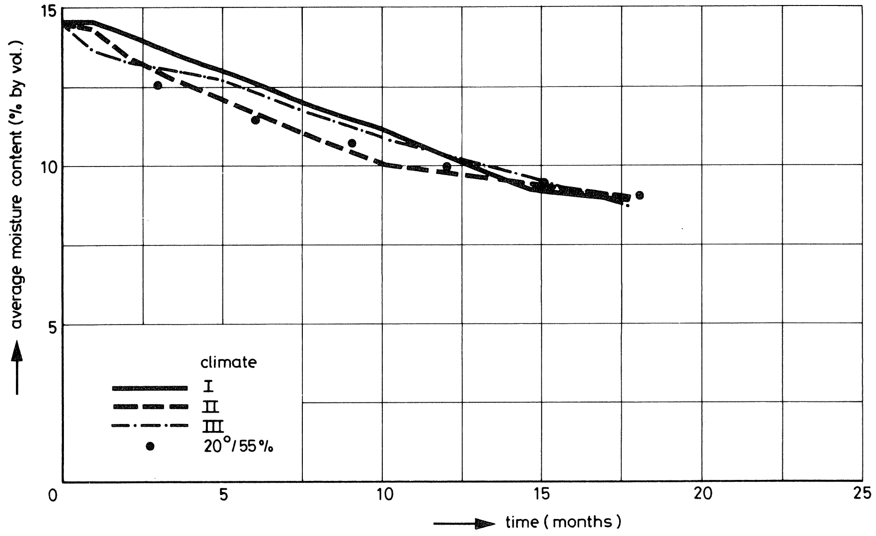

Fig. B1. Average moisture content as a function of time for Korlin concrete (one sided drying, in three climats, slab thickness d = 0,15 m).

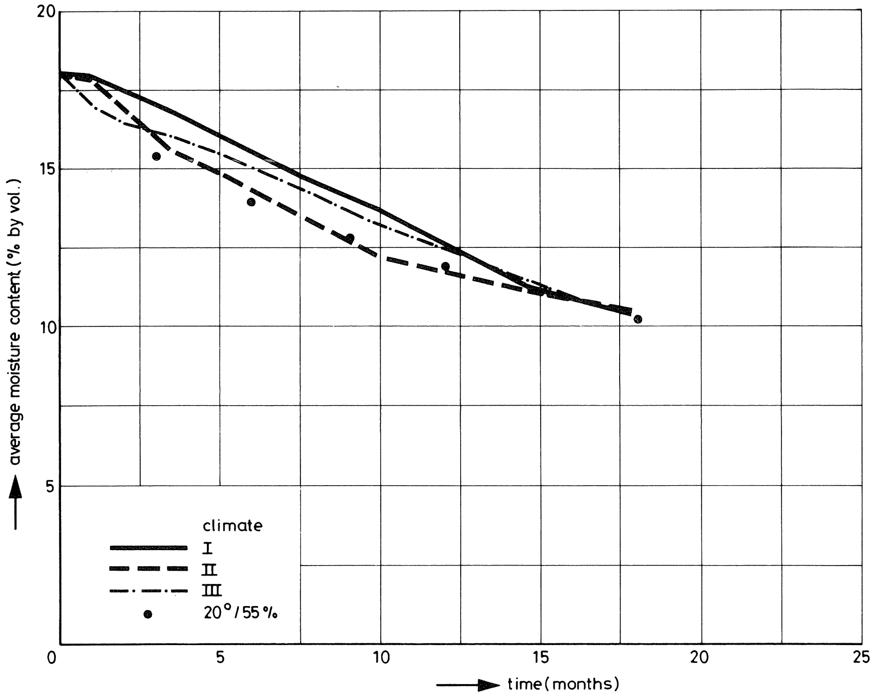

Fig. B2. Average moisture content as a function of time for Argex concrete (one sided drying, in three climates, slab thickness d = 0,15 m).

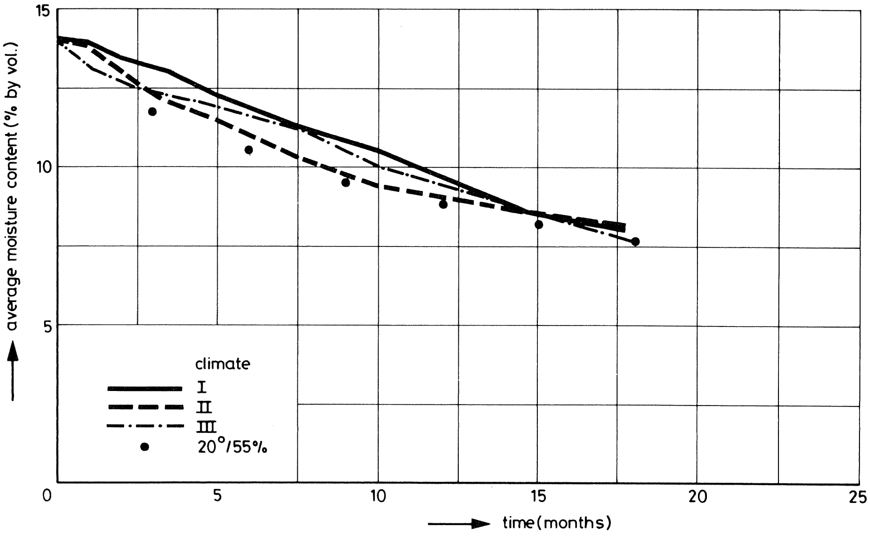

Fig. B3. Average moisture content as a function of time for Agral concrete (one sided drying, in three climates, slab thickness d = 0,15 m).

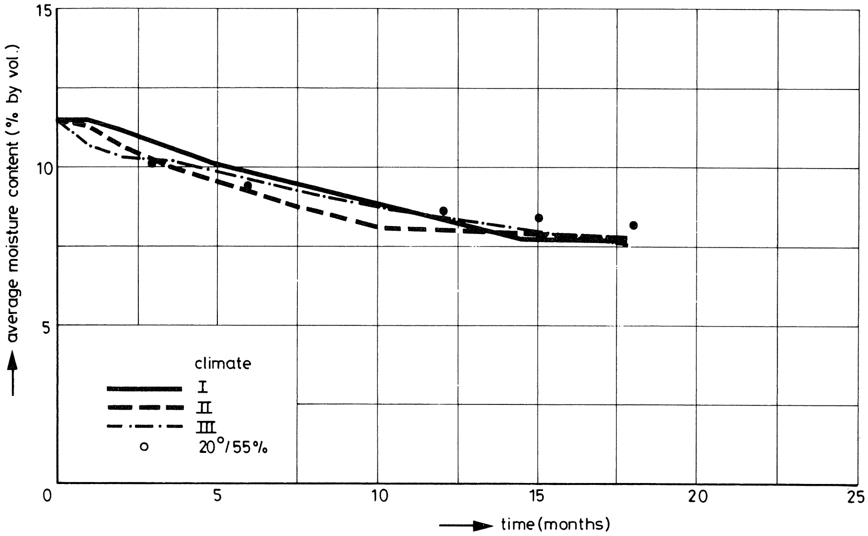

Fig. B4. Average moisture content as a function of time for normalweight concrete (one sided drying, in three climates, slabs thickness d = 0,15 m).

At the same time, it must not be supposed that the line of reasoning adopted in this extreme example is entirely in agreement with what actually happens in practice. In reality the temperature of 29,3 °C will have to be chosen a few degrees higher in order to achieve the same moisture content at the end of 365 days. This is bound up, inter alia, with Thomson's law [17], on account of which the ratio ψ/φ changes. However, this may be neglected in cases where the temperature variations over the period concerned are much smaller than the 80 °C envisaged in the above example.

If the calculation is based on an average relative humidity, this value may, during the drying period under consideration, differ quite considerably from the actual relative humidity at any given time. This will of course result in deviations from the calculated behaviour, particularly near the surface of the specimen.

The calculation of the material moisture content for a "weighted" average climate was based on the climate measured in the Rabo Bank building (Table 4) and on the climates I, II and III (Table B1). The corresponding constant climates are 16,5 °C/65% RH and 20 °C/55% RH respectively. The results of the Rabo Bank observations are fully presented in [12].

With varying climate it is found that, in comparison with constant climate, drying proceeds somewhat more rapidly only at the beginning and at the end of the period envisaged in the calculation. In the intermediate period the differences are relatively small. The greatest differences occur at small depths below the surface, as is indeed to be expected. The averages of the results obtained for 20 °C/55% RH are shown dotted in Figs. B1 to B4. Here, too, the differences are small, whence it can be inferred that, if a high degree of accuracy is not required, the moisture content calculations can permissibly be based on a weighted average climate. As has been explained, a climate of 16,5 °C/65% RH can in that case be adopted as a suitable practical value.

APPENDIX C

Determination of a more objective criterion for the intensity of spalling [27]

In the fire tests performed for series c and d the loss of weight was recorded in order to obtain a more objective criterion for assessing the intensity of spalling. To this end, the specimen in the fire testing furnace was suspended from a beam whose change in deflection provided a measure of the loss of weight (Fig. C1). Two vertical and two horizontal bars of 6 mm diameter were embedded in each slab and were attached to the suspension structure.

Let $G(t_0)$ be the weight of the slab at room temperature and $G(t)$ be its weight during the fire test; then the parameter for the degree of spalling is:

$$\zeta(t) = G(t)/G(t_0) \quad \text{where} \quad 0 < \zeta < 1$$

The parameter $\zeta(t)$ is affected also by the amount of moisture driven out during the test, and for this reason a correction is applied which is important particularly with regard to

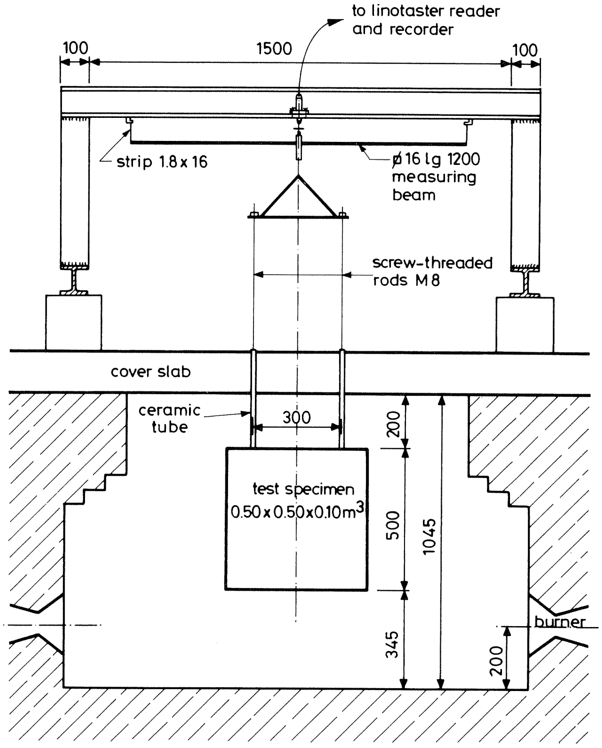

Fig. C1. Measuring equipment in fire test furnace (series c and d).

specimens having a high moisture content. This correction can be based on the following data:

a. the loss of moisture as a function of the initial moisture content can be directly measured during the fire test in a case where no spalling occurs;
b. as a result of spalling, the line for $\zeta=\zeta(t)$ will display abrupt transitions; in between these transitions this line is determined by the loss of moisture from the remaining concrete;
c. the quantity of moisture in % by volume can be determined both before and after the fire test; the quantity of moisture driven out during the test can be calculated from these data.

By combining the data mentioned in points b and c it is possible to obtain some idea of the course of the moisture loss. The result obtained can be further improved by performing a check on the directly measured course of the moisture loss for the case where no spalling occurs, as envisaged in point a. The fire tests can then be interpreted with the aid of:

- the course displayed by the measured line $\zeta=\zeta(t)$;
- the events recorded during the fire test;
- the magnitude of the average moisture content and of the compressive stress (if any) before the fire test.

The course of the parameter $\zeta(t)$ during each of the fire tests in series c was recorded. However, since there was no spalling in these tests, the measurements in respect of this parameter are not discussed in the present report (see [27]). If fire tests are performed on slabs with reinforcement and /or compressive stress in the concrete, the dislodging of fragments as in the tests in series c will probably not occur. More particularly in that case the possibility of recording the parameter $\zeta(t)$ in the event of spalling can be a valuable aid.