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Concrete and reinforced-concrete structures

Constructions en béton et béton armé

Massivbau

I

Fundamental principles and the properties of concrete

Caractéristiques fondamentales et propriétés du béton

Grundlagen und Eigenschaften des Betons

General report — Rapport général — Generalbericht

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The question of materials has, during the last few years, assumed an ever-growing importance, and this has resulted in an intensification of research in this field. There are several reasons for this. The enormous activity of the building industry since the Second World War, combined with a general shortage of building materials, has necessitated that the materials be used as efficiently as possible, which, in its turn, has led to a more thorough study of their fundamental properties. For many new methods of construction, e.g. prestressed concrete, the material properties, e.g. creep, are of much greater importance than in older types of construction. Certain types of damage to bridges and other concrete structures have raised the question as to their origins, and how they may be avoided in the future.

Of the papers presented in this section of the Congress, two authors, K. F. Antia and A. Joisel deal with the subject of "the composition of concrete." One paper, by D. A. Stewart, deals with "the properties of concrete." The three papers are, however, discussed together. One paper, by M. Prot, deals with "the effect of repeated and continuous loading and creep" and three papers, by F. Campus, M. Prot, and L. Séméac and M. Boutron, deal with "the corrosion of concrete and reinforcement".

1. Composition of concrete

2. Properties of concrete

The main object of all concrete mix design is to ensure certain properties of the hardened product. For bridges and most other structures the following are the characteristics most desired:

specified strength;
good durability, e.g. good frost-resistant properties in districts where frost damage is liable to occur;
minimum shrinkage;
minimum plastic deformation;
high modulus of elasticity.

The first two of the above are the most important to be taken into account when proportioning the mix.

The strength requirement itself determines one part of the mix design, i.e. the water–cement ratio; it is, of course, assumed that the concrete can in fact be fully compacted with the method of compaction adopted on the site. To obtain a given strength, therefore, it requires that the water–cement ratio be below a certain maximum value, *and* that the workability of the concrete be sufficient for full compaction to be obtained. If the effects of particle shape, surface properties and water absorption properties of the aggregates are ignored, then the workability of the mix is mainly determined by the grading and the amount of aggregate. In general, that grading is chosen which requires a minimum amount of cement paste so long as the workability is not impaired. Workability, however, may be measured in several different ways, and in fact personal judgement often decides the most suitable grading. This may explain the relatively large variations that may be found in recommended gradings in the literature on the subject, although it must be borne in mind that variations in surface properties, etc., of materials in different places may have a considerable effect.

The frost-resistance of a homogeneous concrete made from a given aggregate depends on the water–cement ratio, the aggregate grading and the amount of cement paste. If the strength requirement is very low, it may be that the water–cement ratio corresponding to the strength may be such that the frost-resistance properties are impaired; in such a case the water–cement ratio must be governed by the frost-resistance requirements and not the strength. For a given water–cement ratio, however, and disregarding for the moment the workability, the frost-resistance will increase with increasing fineness of the aggregate or with decreasing amount of cement paste.* In order to maintain a suitable workability, however, it is evident that there will be an optimum combination of grading and amount of cement paste to give the best frost-resistance.

A concrete mix possessing good frost-resistance properties when homogeneous may, however, due to segregation during compaction, be rendered vulnerable to frost action in weak zones; a typical example of such a weak zone often occurs in the thin mortar layer produced on the surface of a concrete pavement during compaction. This surface layer has a lower frost-resistance and a higher shrinkage than the concrete below, and is thus likely to scale under the action of frost. A further requirement, therefore, is that the mix must be stable, i.e. must not segregate during compaction.

* J. A. Loe and F. N. Sparkes. "The deterioration of concrete: some factors affecting the resistance of concrete to frost action," *Preliminary Publication, 3rd Congress I.A.B.S.E.*, p. 201, 1948.

Turning now to shrinkage and plastic deformation, these are both intimately connected with the amount of cement paste and the water–cement ratio. The reasoning above, however, shows that these two factors are already largely determined by the strength and durability requirements. It is therefore probable that shrinkage and plastic deformation can only be taken into account to a very limited extent in the design of the mix; where frost-resistance is not of importance, e.g. in floor slabs, it is possible, of course, to reduce shrinkage and plastic deformation by a suitable mix design. If strength and durability requirements give a wide choice of mixes, however, naturally that mix will be chosen which gives the lowest shrinkage and plastic deformation.

Finally, the modulus of elasticity can only be varied within very narrow limits —if at all—when the above requirements have been fulfilled. There is obviously no point in increasing the modulus of elasticity by, say, 5% by increasing the amount of aggregate in the mix, if the rigidity of the resulting reinforced concrete is going to be reduced by perhaps 80% due to hair cracks.

Thus for concrete structures exposed to the weather, the essential requirements to be taken into account are the strength and the durability, the latter including the stability of the mix. These properties depend on all the essential factors of the mix design—water–cement ratio, amount of cement paste and the grading. Since the relationship between strength and water–cement ratio may be assumed to be known for the various types of cement, only the choice of amount of cement paste and grading remain to be decided. These are not independent, of course; for a given workability and a given water–cement ratio, the amount of cement paste is intimately dependent on the grading. It is at present impossible to give a general relationship between grading and amount of cement paste, as too little is yet known of the influence of the surface properties, etc., of aggregates. The relationship must be determined experimentally for a particular aggregate using trial mixes. The main task of the designer of the mix is thus to choose the most appropriate grading of the aggregate.

This problem of the choice of the aggregate grading is one of the main points of all three papers treating mix design. A. Joisel, in his paper "La composition du béton," presents a detailed study of the grading curve proposed by Caquot in 1937.* Caquot assumed that a minimum percentage of voids in the combined aggregate would give a desired strength with a minimum cement content; he then showed theoretically that the amount of aggregate of particle size less than d should be directly proportional to $d^{1/5}$. Exceptions must, however, be made for the largest particle sizes.

In his treatment, Caquot assumed a constant value (0·44) for the relative volume of voids in a single particle size. Joisel has extended Caquot's investigation by studying the changes in the grading necessitated by different values of the relative volume of voids, viz. 0·48, 0·44 and 0·40. The results are similar to those of Caquot, but the exponent of the particle diameter d varies from 1/6 at the highest volume of voids (0·48) to 1/4·5 at the lowest volume (0·40).

Joisel's results are of interest from a theoretical point of view and, granted the assumptions, irrefutable. It is open to doubt, however, whether such a grading curve will result in concrete of suitable workability, and it may in fact be desirable to use another grading which, although it might require a higher cement content to fill the voids, may result in a lower cement content to give the same workability. The reporter is not convinced that the volume of voids will alone determine the amount of cement paste needed to give a required workability even if the surface properties of

* A. Caquot. "Le rôle des matériaux inertes dans le béton," *Mem. Soc. Ing. Civils de France*, p. 562, 1937.

the aggregate are the same. The questions of frost-resistance and stability of the mix have not been taken into account in Joisel's treatment of the problem.

D. A. Stewart, in his paper "The design of concrete mixes for bridge and other constructions," has treated the fundamental principles governing concrete proportioning so that the concrete may be fully compacted and develop the required strength, good frost-resistance, high modulus of elasticity, and low shrinkage and creep, with a minimum amount of cement. To reach this goal, the mix should be designed so that the cement mortar just fills the voids in the coarse aggregate. Consolidation must be done by vibration; as is possible, according to Stewart's experience. It is relatively simple to determine the quantity of the aggregate required if we know:

(*a*) the water–cement ratio—this is determined by the strength requirement;
(*b*) the aggregate–cement ratio—this is determined by workability considerations;
(*c*) the specific bulk density of the coarse aggregate, obtained by the same method of compaction as is to be used on the final concrete.

The maximum size of the fine aggregate must be chosen so that it will all pass through the interstices in the coarse aggregate. A sieving method is described in the paper which makes such a determination possible. The average particle size of the combined aggregate in relation to the free space available must also be borne in mind when designing a mix; Stewart gives formulae which can be used to determine the average particle size.

A concrete mix designed in this way will probably meet very high requirements of quality; strength is obtained with a low cement content, and shrinkage and creep will be low. Moreover, stability will be automatically ensured, since, from geometrical reasons, a mortar layer cannot be formed. On the other hand, good frost-resistance is not necessarily obtained; further study of the cement mortar filling the voids is required. Furthermore, is it really practicable to consolidate mixes designed in this way on an actual building site? Is the workability really sufficient?

K. F. Antia's paper, "A rational method of proportioning concrete in India and its economic importance," is a comprehensive survey of mix design, based on the assumption that strength is required as cheaply as possible. The essential recommendation is to be found in Table IV of the paper, where suitable values of the fineness modulus of the combined aggregate are given for various maximum particle sizes. The available aggregates should be combined so as to give a fineness modulus lying within the limits given in the table. The recommendation is based on tests. The water–cement ratio is determined from the strength requirement, and an empirical formula is given for the determination of the amount of aggregate required for a given consistency.

The grading recommendation is thus based on experiments in which the workability was controlled by means of the slump test. It is a matter of opinion whether the slump test alone can give a satisfactory measure of workability. Frost-resistance is not taken into account in Antia's paper, which is quite natural when considering concrete practice in India.

As is evident from the review above, it is necessary to ensure that high-grade concrete does not segregate during compaction. It is also necessary, when comparing the economy of different mixes, only to consider mixes possessing the same workability. In order to make this possible, we must, in some way or other, be able to measure the stability and workability. With regard to workability, Stewart, in his paper, refers to an apparatus which, "used in determining the state of full compaction, will at the same time measure the workability of the concrete in terms of the time taken to reach that state." This same time for complete compaction may also be determined by the deformability meter which has been developed at the Swedish Cement and Concrete Research Institute.* In this apparatus the deformability of the fresh concrete is measured during vibration. So long as the deformability increases during the vibration, the concrete is not yet fully compacted. Decreasing deformability, on the other hand, means that the concrete is segregating due to the vibration. A stable concrete shows constant deformability after the maximum value has been attained. This apparatus thus reveals whether or not the mix is stable, and at the same time gives a measure of the required duration of vibration. It is the reporter's opinion that the use of such an apparatus would be of great value in comparing different mix designs.

3. Effect of repeated and continuous loading, creep

In his short paper, "Détermination des déformations des bétons sous les charges prolongées," M. Prot describes the main principles of a new testing machine intended for use in a study of the deformation properties of materials, with special reference to the time effect. It will be possible to vary the rate of application of load between wide limits, viz., in the ratio 1: 10,000. Stress and strain will both be recorded autographically. Details of the machine and, if available, preliminary results, will be given at the Congress.

4. Corrosion of concrete and reinforcement

As a building material, concrete possesses many excellent properties, and has thus been of great benefit in raising our general standard of living. Nevertheless, the poor durability of some bridges and other reinforced-concrete structures has given rise to a certain amount of concern. Much has been written on the subject of deterioration of concrete. A comprehensive and thorough survey is to be found in the excellent paper by Lea and Davey,† to which the reporter draws attention. In addition to the papers referred to in their survey, he would like to draw attention to an interesting paper on deterioration of bridges in America, by Jackson.‡ Another valuable investigation has been made by Ruth D. Terzaghi,§ which has recently been published. Of the more comprehensive works on this subject those by Kleinlogel|| and by Dreyfus¶ may be mentioned.

The main pattern of the paper by Lea and Davey is as follows:

A. Internal causes:

(i) Materials: aggregates, cement, air-entraining cement, water

(ii) Internal changes: thermal movement of concrete, drying shrinkage and reversible wetting movement

B. External causes:

(i) Frost attack and corrosion of reinforcement

* See *Proceedings*, No. 12, and *Bulletins*, Nos. 12 and 24, of the Swedish Cement and Concrete Research Institute.

† F. M. Lea and N. Davey. "The deterioration of concrete in structures," *J. Inst. Civ. Engrs.* **32**, 248–275, 1949.

‡ F. H. Jackson. "Disintegration of bridge concrete in the West," *Public Roads*, **24**, No. 4, 1945.

§ Ruth D. Terzaghi. "Concrete deterioration due to carbonic acid," *J. Boston Soc. Civ. Engrs.*, 1949.

|| A. Kleinlogel. *Einflüsse auf Beton und Stahlbeton*, 1950.

¶ J. Dreyfus. *La chimie des ciments*, Paris, 1950.

(ii) Erosion of concrete
(iii) Deterioration of concrete in sea-water
(iv) Deterioration of concrete in sulphate-bearing waters
(v) Attack of concrete by acid gases
(vi) Atmospheric attack
(vii) Tunnels and bridges
(viii) Sewers
(ix) Exposure to fire
(x) Architectural treatment of surface and attention to detail.

The reporter gives the above pattern in order to show where the three present papers fit in the general picture.

F. Campus, who has already published valuable papers on the subjects B(iii) and A(ii) in the above, deals in his present paper mainly with point B(vi), atmospheric attack, but also refers to points A(ii) and B(i).

M. Prot gives a new testing method in connection with point B(iii).

L. Séméac and M. Boutron mainly deal with points B(v) and B(x). As this paper has much in common with the paper by Campus, they will be treated together in the following paragraphs.

Campus describes some severe cases of damage that have occurred in reinforced-concrete transmission line poles in Belgium, in the form of both longitudinal and transverse cracks in the cover over the reinforcement, and severe corrosion of the reinforcement. He develops an interesting explanation of the cause of this damage, which, he states, is due to rainwater dissolving the lime in the concrete, thus rendering it porous. As long as the water is alkaline it does not attack the reinforcement, but if the water ceases to be alkaline and other conditions are favourable the steel will be attacked, will start rusting and swelling, and will finally burst the concrete covering the reinforcement.

The reporter has discussed this theory with several specialists. The chemists have nothing to say against it if the following distinction is made. As long as the concrete still possesses some strength, water bound by capillary forces, they say, will be alkaline, and will not, therefore, attack the reinforcement. If, however, pores or cracks exist of sufficient width, and if they are dry, then *moist air* may enter through them, and water vapour which is not alkaline may reach the reinforcement. There it may condense directly on the reinforcement, and possess such acidity that rusting may take place. This distinction does not invalidate any of the rest of Campus's treatment, which is based on an analysis of the inherent internal stresses and the additional stresses due to external causes such as atmospheric conditions, which, in unfavourable circumstances, may lead to disintegration.

Campus finishes with some practical recommendations for obtaining durable reinforced-concrete structures, taking into account the actual concreting, as well as the placing of the reinforcement.

Séméac and Boutron give a detailed and instructive account of damage to the concrete structure of railway sheds, and also, to a certain extent, to viaducts of railways in France. Their observations cover structures erected at various times over the last forty years. The damage is mainly due to attack from the smoke from the locomotives, but in the coastal districts the disintegration appears to develop more rapidly as a result of the deleterious effect of the salt in the air. As a result of their experience, two methods have been employed to minimise the destruction due to the smoke: first, reducing the source of attack—the smoke—by a more suitable design of the structures; second, increasing the resistance of the material of the structure to attack, by using dense concrete, etc.

The reporter would like to stress the observation made by the authors of the importance of a careful design of even the details of the structure if corrosion is to be minimised or eliminated.

There are two points in the paper by F. Campus to which the reporter would like to draw a little more attention. One concerns structures in which high-alumina cement has been used. Campus mentions some instances of damage due to instability of certain components of hydrated high-alumina cement. In Sweden, too, severe damage has occurred in bridges between 16 and 24 years after completion of the concreting, which, it is quite evident, is due to this slow recrystallisation of the hydration products of the high-alumina cement. Dreyfus, in his book (*loc. cit.*, p. 279), points out that permanent construction using high-alumina cement has been forbidden by the French authorities since 1943.

The other observation made by Campus which the reporter finds particularly noteworthy occurs in the final remarks, where the author quotes his colleague Professor Magnel. One case of corrosion of the wires at the anchorage of a prestressed concrete structure, mentioned by Magnel, suggests that such points may be particularly vulnerable to corrosive action—stress corrosion—and that such wires should always be protected by being embedded in concrete. This is of vital significance, and this problem ought to be the subject of detailed study by concrete specialists in collaboration with metallurgists.

M. Prot, in his paper, deals with the problem of finding a rapid method of testing the suitability of cements for use in structures in sea-water with regard to durability. After discussing several possibilities, the author concludes that the essential features of such a test should be:

(*a*) an increase of the free exposed surface in relation to the mass, and
(*b*) a rapid circulation of the fluid attacking the surface.

Prot has already, in I.A.B.S.E. publications and at the last Congress in Liège, pointed out the great importance of knowing the scatter of various properties of the materials. In this connection, he now asserts that the durability test must be such that large numbers of specimens can, without difficulty, be tested simultaneously.

In accordance with the above principles, two testing arrangements have already been put into service, one at Le Havre and the other at Marseilles. These are described in detail in the paper. Each enables 300 specimens to be tested simultaneously, and is under fully automatic control. The test specimens, which take the form of U-shaped plates about 3 mm. thick, are made of cement paste or cement mortar. During the corrosion test they are subjected to a bending moment equal in magnitude to one-half of their failure moment before test. Each specimen is supplied with an indicator which records the time at which failure occurs due to deterioration. The author hopes to give some preliminary results at the Congress.

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Summary

The fundamental requirements of hardened concrete are strength and durability. The limits of creep and shrinkage are usually of secondary importance, and can only be controlled to a limited extent in the mix design after the first two requirements have been satisfied. The usual aim in concrete mix design is to obtain a given strength with a minimum cement content; this, however, will not in general ensure a satisfactory frost-resistance either of the concrete as a whole or of planes of weakness which may occur due to segregation. For this purpose it is necessary to choose an optimum grading of the aggregate and an optimum content of cement paste for a given water–cement ratio.

The corrosion of concrete and reinforcement is a vast and complex problem. Two main aspects have been treated in the papers under discussion: deterioration due to atmospheric attack and deterioration due to acid gases. One of the authors has developed a theory of the causes of the first of these. Another paper draws attention to the importance of a careful design of structural details, so as to minimise the corrosive attack. A third aspect—deterioration in sea-water—has been treated from the point of view of testing the suitability of a given cement for use in such circumstances. A new method of test for this purpose is described.

Résumé

Les exigences fondamentales imposées au béton durci sont la résistance mécanique et la durée. Les limites d'écoulement plastique et de retrait sont généralement d'importance secondaire; on ne peut intervenir sur ces caractéristiques que d'une manière limitée dans l'étude des mélanges, après que les deux premières exigences ci-dessus mentionnées ont été satisfaites. Le but que l'on se propose généralement dans l'étude des mélanges de béton est d'obtenir une résistance mécanique donnée avec une teneur minimum en ciment. Cette disposition n'assure toutefois pas, en général, une résistance satisfaisante au gel, tant dans la masse du béton que dans des plans de moindre résistance qui peuvent se former par suite d'une ségrégation. Du point de vue de la résistance au gel, il est nécessaire de choisir une teneur optimum, tant en agrégat qu'en ciment, pour un rapport eau–ciment déterminé.

La corrosion du béton et de ses armatures constitue un problème vaste et complexe. Deux aspects principaux de cette question ont été traités dans les rapports qui sont soumis à la discussion: ce sont la détérioration résultant de l'attaque atmosphérique et la détérioration due aux gaz adices. L'un des auteurs a proposé une théorie sur les causes de la première de ces détériorations. Dans un autre rapport, l'attention est attirée sur l'importance d'une étude minutieuse des détails des ouvrages, en vue de réduire les risques de corrosion au minimum. Un troisième aspect—la détérioration dans l'eau de mer—a fait l'objet d'une étude portant particulièrement sur le contrôle de l'aptitude d'un ciment donné à être employé dans ces conditions. Une nouvelle méthode correspondante d'essai est décrite.

Zusammenfassung

Die grundlegenden Anforderungen an den erhärteten Beton sind Festigkeit und Dauerhalfigkeit. Die Kriechund Schwindgrenze sind meistens von sekundärer Bedeutung und können nur bis zu einem beschränkten Grad durch das Mischung-

sverhältnis beeinflusst werden, nachdem die zwei ersten Bedingungen erfüllt sind. Das gewöhnliche Ziel bei der Festlegung des Mischungsverhältnisses für Beton besteht darin, mit einem Minimum an Zementzusatz eine vorgeschriebene Festigkeit zu erreichen. Dies gewährleistet jedoch nicht allgemein einen befriedigenden Frostwiderstand, sei es des ganzen Betons oder für bestimmte Flächen, die durch Entmischung geschwächt werden. Zu diesem Zwecke ist es notwendig, eine günstige Kornzusammensetzung und einen günstigen Zementgehalt für einen gegebenen Zement–Wasser-Faktor zu wählen.

Die Korrosion von Beton und Armierung ist ein weites und verwickeltes Problem. Zwei hauptsächliche Gesichtspunkte wurden in den zur Diskussion stehenden Arbeiten behandelt: Zerfall durch Witterungseinflüsse und Zerfall durch Säuregase. Einer der Verfasser hat eine Theorie über die Ursachen des ersteren entwickelt. Eine andere Arbeit macht auf die Bedeutung einer sorgfältigen Konstruktion baulicher Einzelheiten aufmerksam, um den Angriff der Korrosion auf ein Minimum zu reduzieren. Ein dritter Gesichtspunkt, der Zerfall in Meerwasser, wurde dahin behandelt, dass die Eignung eines bestimmten Zementes für den Gebrauch in solcher Umgebung untersucht wurde. Eine Prüfmethode für diesen Zweck wird beschrieben.

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