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Contents

UNDERWATER CONCRETE

Preface

The study on placing concrete under water has been carried out by the Institute TNO for Building Materials and Building Structures. This study was financially supported by the Netherlands Committee for Concrete Research (CUR) and published in Dutch as CUR report no 56 „Onderwaterbeton". As the results seem to be of wider than national interest a translation is published in Heron.

The study was coached by the CUR Committee group C 17. This committee began its activities, in 1966, by carrying out research in the literature. Thanks to co-operation both in the Netherlands and abroad, hitherto unpublished information was placed at its disposal. With the available data it was not, however, possible to establish a relationship between the composition of the concrete, the method of placing and the eventual quality of the concrete. Further investigation was therefore necessary.

For determining the effect of the composition, laboratory tests were carried out by the Institute TNO for Building Materials and Building Structures. The effect of the method of placing the concrete was assessed with reference to test cores obtained from actual structures, for which the committee wishes to record its indebtedness to the organisations and public authorities that gave their assistance in connection with these investigations. The flow pattern of concrete deposited under water through a pipe was theoretically analysed by G. E. J. S. L. Voitus van Hamme and H. van Koten.

The committee was constituted as follows:

J. H. van Loenen, chairman
P. D. Steijaert, secretary
P. Blokland, mentor
J. Boon
L. A. Jonker
C. van de Kerk
J. F. Th. Lem

When the committee was set up, J. Boon was appointed secretary. In 1970 he was succeeded by the present secretary, who is the author of this report.

Thanks are due to the Netherlands Committee for Concrete Research for financing the investigations.

A. C. van Amerongen translated the original Dutch report into English.

UNDERWATER CONCRETE

Summary and conclusions

Until fairly recently in the Netherlands little structural value was attached to underwater concrete. The reason for this was really quite obvious. In the specifications a high cement content was usually laid down (to compensate for loss by washing-out), but the contractor was free in his choice of the method for placing the concrete under water. The quality of the concrete thus eventually obtained was generally unknown.

Investigations conducted by the Committee showed that the method of placing concrete under water constitutes the most important factor with regard to the final quality of the concrete:

- With the grouting methods low compressive strengths were found (15 to 20 N/mm^2). Besides, this concrete is not homogeneous, while the cost of making and placing such concrete per m^3 is higher than that of concrete mixed in the usual way before being placed under water.
- With the tremie method, the pumping method and the hydrovalve method high compressive strengths were found (of the order of magnitude of 40 N/mm^2). These strengths are amply sufficient for structural concrete. This concrete is moreover homogeneous (very few loose layers).
  In terms of quality of the concrete there is little to choose between these three methods. The choice will ultimately have to be decided by considerations of cost of concreting, technical feasibility and speed of concreting.
- High strengths were also found for concrete placed under water with the aid of skips (order of magnitude 40 N/mm^2). This concrete contains a relatively high proportion of loose (not properly bonded) layers. Hence this method appears not very attractive for making structural concrete.

For underwater concrete it is necessary to use mixes having a high slump (150 mm), besides possessing good cohesion. This latter requirement is fulfilled by using a sufficiently high content of fine particles in the mix, which for this purpose is made with a higher content of sand than is normally adopted in concrete placed in the ordinary way.

It is preferable *not* to use more cement than is strictly necessary for attaining the desired strength. Any fine-grained constituents that may additionally be necessary may consist of fillers such as quartz powder, fly-ash, trass, etc.

No important conclusions could be drawn with regard to the use of additives for improving the cohesion of the concrete. It does not appear likely, however, that the concrete quality pattern achieved by the various methods of underwater placing, as outlined above, will be improved by the use of additives.

The following are some practical points of particular importance in connection with underwater concrete:

- proper preparation and accuracy in carrying out the job are essential;
- the slump should be carefully watched, especially if there is some delay in concreting;
- the use of retarders as additives should be considered with reference to the concreting capacity of the equipment employed;
- the maximum slopes attainable with concrete surfaces placed under water are 1 in 5;
- in determining the largest permissible dimensions of floors (or parts thereof) the risks of cracking due to temperature shrinkage should be given due consideration;
- generally speaking, it is very undesirable to vibrate underwater concrete;
- in a cofferdam, silt (consisting of cement and other fine particles) will be displaced towards a corner during concreting. Arrangements to get rid of it should be provided;
- precautions to obviate water inclusions should be taken when components such as piles, reinforcement or precast units have to be concreted in;
- if possible, allowance should be made for placing some extra concrete to obtain a level top surface of the slab. Removal of excess concrete by subsequent hacking is much more expensive than adding concrete;
- for reinforced slabs it is, among other considerations, necessary to take account of the method of construction. If the concrete is placed by tremie or by pumping, suitable apertures must be provided in the reinforcement at the concrete placing points. With the hydrovalve method an aperture in the reinforcement is necessary only at the point of commencement of concreting.

Underwater concrete

1 GENERAL CONSIDERATIONS

1.1 Introduction

The ultimate quality of underwater concrete and its cost will depend on the composition of the concrete and the method whereby it is deposited under water. Only if the relationship between the placing method and the resulting concrete quality is known will it be possible, for each such method, to establish a design based on the attainable quality of the concrete and the functions that the latter has to perform, so that finally the most economical solution can be chosen.

An approach of this kind calls for extensive knowledge of the subject, which is obtainable only by a thorough study of the relevant literature and by carrying out practical tests. The latter are necessary because in this field there has hitherto been an almost complete lack of comparative investigations.

The Committee has endeavoured to make up for this lack of knowledge by compiling the present report, which embodies information derived from:

- a study of the literature concerning various methods of underwater placing of concrete and the results obtained with them;
- an investigation by the Committee of cylindrical cores taken from concrete placed under water;
- an investigation by the Committee of the effect of anti-washout agents on cement washout and the strength of the concrete;
- an investigation of unit prices of underwater concrete placed by various methods;
- calculations to account for the behaviour of concrete which is placed under water by means of a pipe.

1.2 Historical survey

At the very beginning of our era the Romans had mastered the art of constructing foundations under water. This is apparent from Vitruvius's books dealing with architecture and building construction [1].

With a "marvellous powder" obtained from the region of Baiae (probably pozzolana), lime and stones they made mixtures which solidified to a stone-like material under water. The method whereby these mixtures were deposited under water is not reported by Vitruvius.

In 1856, Kinipple [2] carried out experiments with underwater concrete, and in 1885, as reported by Heude [3], concrete was placed under water with the aid of a wooden chute.

In the first applications the concrete was deposited through a pipe (tremie). Major projects dating from that early period in which underwater concrete was used include the Detroit River Tunnel (1906) and a dry dock in Pearl Harbour (1909–1913). In 1911 this method, with some modifications, was patented by a Swedish construction firm named Contractor and has since been known as the "contractor method" in some countries, including the Netherlands.

Besides pouring through tremie pipes, deposition of concrete under water was also carried out with the aid of skips specially devised for this type of work. As far back as the early nineteen-thirties Boonstra [4] conducted an extensive comparative research on the quality of underwater concrete placed by the tremie method and by means of skips. This latter method was already extensively used in the Netherlands at the time. On the other hand, it is hardly mentioned in foreign technical literature.

With the development of pumping technique it became possible to discharge concrete directly under water with the aid of a pipeline from a pump. This is to be regarded as a variant of the tremie method and is now more and more widely applied.

Also of comparatively recent origin are the methods whereby "grouted concrete" is produced under water by the injection of grout into the voids in a mass of gravel deposited in advance. This principle is applied more particularly in the Colcrete method [5] and the Prepakt method [6]. In both of these a patented composition or method of mixing is employed for the grout.

An entirely novel method of underwater concreting was developed in the Netherlands in 1969. It makes use of a collapsibly flexible pouring pipe with a rigid discharging mouth. The whole device is called a "hydrovalve" [7]. So far, only a few projects have been executed by means of this method.

For the sake of completeness it should be mentioned that in special cases "underwater concrete" has been made by injecting grout between layers of textile fabric [8].

The placing under water of bags filled with freshly mixed concrete [9] is an auxiliary method which is used, among other purposes, for the sealing of local apertures.

1.3 Why underwater concrete?

When concrete is placed "in the dry", there is ample scope for attaining high quality. With the aid of compacting equipment it is thus possible to use concrete mixes having a low water/cement ratio. In addition, supervision can be maintained during the concreting operation, so that any mistakes can be corrected. When concrete is placed under water, these possibilities are not available, while there is moreover the hazard that cement and fine particles are liable to be washed out of the concrete.

The decision nevertheless to construct a structure (or a part thereof) by underwater concreting may be based on various considerations, e.g., in order to avoid having to use wellpoint dewatering for placing the concrete "in the dry" and to avoid possible objectionable settlement phenomena resulting from such extraction of water.

If underwater concrete is employed in a sheet-piled cofferdam (a cofferdam is not always necessary, however), such concrete can be considered to have four functions to perform:

- to resist upward water pressure (uplift) after the cofferdam has been pumped dry;
- to ensure a watertight bottom seal so that further construction work can be carried out under dry-land conditions;
- to give lateral support to the cofferdam structure after it has been pumped dry;
- to transmit the loads to piles (driven beforehand) or direct to the subsoil.

1.4 Quality aspects

When concrete is placed under water, differences in velocity at the concrete/water boundary will cause washout of fine particles. The amount of washout will, on the one hand, depend upon how well the freshly placed concrete is able to retain its cement (composition of the concrete) and, on the other, be affected by the magnitude of the velocity differences that occur (method of placing; stagnant or running water) and by the extent to which the concrete/water contact surface increases during placing.

If washout occurs, it will result in concrete resembling that found in so-called gravel pockets and therefore structurally weaker. At its worst, washout is liable to cause the formation of loose layers of gravel, though these are generally quite thin. Such inhomogeneities largely determine the quality of the underwater concrete structure.

1.5 Quality assessment

The strength figures stated in the literature practically always refer to concrete which is free from gravel pockets, which stands to reason. To drill test cores from loose layers of gravel present in the concrete is virtually impossible, while moreover any cores thus obtained are bound to fracture at weak planes, so that the latter are eliminated when the cores are subsequently sawn to form test specimens.

Such figures are actually to be regarded as indications of potential strengths. But what is their practical significance if there are local zones where the strength of the concrete is virtually zero? For a proper assessment of the quality of underwater concrete it is therefore necessary to have information on its strength and homogeneity. In the Committee's investigation of test cores drilled from concrete placed under water, on construction projects in actual practice, the following criteria were accordingly adopted for the quality of the concrete:

- strength: compressive strength, average and standard deviation; splitting tensile strength, average and standard deviation;
- homogeneity: the number of non-coherent layers per linear metre of drilled core.

As will be seen in Chapter 4, the homogeneity of underwater concrete depends greatly on the method of placing adopted. From this it must not be inferred that only those methods whereby a homogeneous concrete can be obtained are acceptable. For instance, if merely a watertight bottom for a cofferdam is required, sporadic gravel layers in the concrete do not matter in the least.

2 METHODS OF PLACING

The possible methods of underwater concreting are summarised in Table 1.

Table 1. Classification of underwater concrete.

place of making the concrete	manner of making the concrete	method of placing	cement washout risk	compaction of the concrete	quality control
above water	- element with final shape (precast and hardened)	- pouring - stacking - assembling		yes	applied to fresh and to hardened concrete
	- plastic element (fresh concrete in bags)	- depositing - stacking	no		
	- grout	- injecting between fabric			applied to fresh concrete or grout before placing or injecting
	- concrete (freshly mixed)	- tremie method - pump method - hydrovalve method - skip method	yes	no	
under water	- grout injected into coarse aggregate mass	- prepakt method - colcrete method			

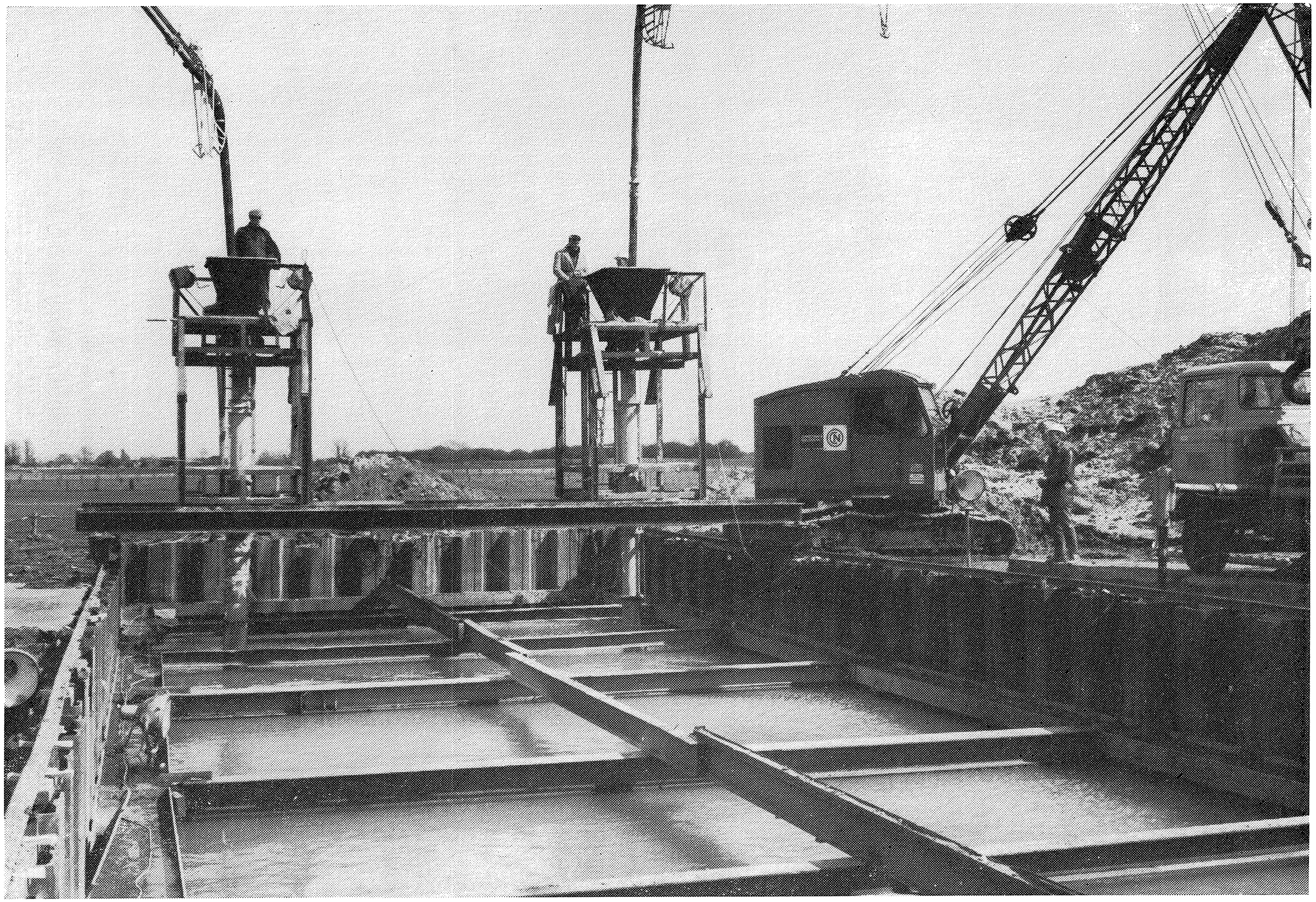
2.1 Concrete mixed above water

2.1.1 *Tremie method*

In the method of placing concrete under water by pouring it through a vertical tremie pipe it is essential to keep the bottom end of the latter embedded in the freshly placed concrete in order to prevent the concrete which flows out of the pipe from coming into contact with the water. In addition, lateral displacement of the pipe is thereby prevented.

During placing, the pipe is moved in the vertical direction only. The movement of the concrete is controlled by gravity and friction.

A tremie pipe is circular in cross-section, usually with a diameter ranging from 250 to 300 mm, though diameters up to 450 mm have occasionally been used. Usually the pipe is suspended from staging and should be so mounted that the pipe can perform the vertical movements necessary for proper execution of the work. The pipe is



Tremie method.

fed from a hopper into which the concrete is deposited by skips, belt conveyor or pumping.

In principle, there are three possible forms of construction for the tremie pipe:

a. Pipe of constant length. In proportion as concreting proceeds, the pipe is raised, so that the filling hopper projects above the staging.
b. Pipe assembled from a number of sections. During concreting, pipe sections are dismantled.
c. Telescopic pipe. Attached to the hopper is a pipe of smaller diameter than the actual concrete placing pipe.

Sometimes the pipe is provided with a foot valve [10, 11, 12] or similar device, which has to perform the following functions:

- to prevent water from entering the pipe at the start of concreting;
- to control the rate of concreting;
- to prevent scour.

Care must be taken to prevent washout occurring while the pipe is being filled with concrete. To ensure this, the first quantity of concrete may be poured onto a "piston" inserted into the pipe. Frequently a plastic ball or sometimes a large wad of paper is used for the purpose.

When the concrete comes into contact with the bottom of the cofferdam in which it is being placed, it spreads out horizontally. While more concrete is fed down through the tremie pipe, the latter is slowly raised, taking care to ensure that the desired immersion depth of the bottom end of the pipe in the concrete is reached as quickly as possible. This minimum immersion depth, which is usually between 1.0 m and 1.5 m, must be maintained while concreting proceeds.

During the actual concreting operation the following flow pattern is found to occur: in the vicinity of the discharge opening at the bottom end of the pipe the concrete advances on a more or less spherical front. The surface of the concrete rises and, in so doing, undergoes a radial displacement from the pipe outwards. Concrete with a slump of about 150 mm can form underwater slopes of about 1:6.

If the immersion depth of the pipe in the concrete is insufficient, a „breakthrough" will occur in the vicinity of the pipe (Prandtl's wedge), associated with relatively large differences in velocity, so that washout of cement and fines from the concrete is then liable to occur.

In general, the tremies are spaced at distances of 4 to 6 m from one another. It should be noted that with closer spacing of the pipes a more nearly level top surface of the concrete will be obtained.

Underwater concrete placed by the tremie method is generally of good quality as regards compressive strength and homogeneity.

2.1.2 *Pump method*

The direct placing of concrete under water by delivering it through pipelines can be regarded as an extension of the tremie method.

In pumping, the concrete is moved along through the pipe by the exertion of pressure. Generally speaking, to produce good concrete by this method calls for the same sort of precautions as those applied in the tremie method, i.e.:

- at the start of concreting a ball or wad in the pipeline should be used to prevent scour;
- during concreting care must be taken to ensure that there is always sufficient immersion depth;
- the outlet end of the pipe must not be displaced sideways while concreting is in progress.

The last-mentioned requirement may be somewhat more difficult to enforce when concrete is placed by pumping.

Just as in the tremie method, an immersion depth of at least 1 to 1.5 m must be ensured. The points of placing the concrete should be spaced at distances of about 4.5 to 6 m.

The concrete used for pumping usually has a smaller slump (100 to 120 mm) than that used for placing by tremie. Because of this somewhat stiffer mix, the concreting points should not – in order to obtain a level upper surface of the concrete – be spaced too far apart. The pumping operation itself may rule out the use of a more plastic consistency with a slump of, say, 150 mm. It is advisable in any case to use concrete with the largest possible slump. Blockages may occur during pumping. They may be caused by incorrect mix composition. As regards the latter, the reader is referred to Chapter 3.

In general, a homogeneous concrete of good quality is produced.

2.1.3 *Hydrovalve method*

A technique first applied in 1969 is the placing of concrete with the aid of a device called a hydrovalve [13, 14].

In this method the concrete is placed under water by pouring it through a flexibly collapsible pipe. The water pressure around the pipe keeps it collapsed, i.e., squeezed shut. When there is only a small quantity of concrete in the pipe, the friction between the plug of concrete and the pipe wall is so great that the concrete undergoes no vertical movement.

When a larger quantity of concrete is fed into the pipe, such big plugs are formed that their weight overcomes the friction with the pipe wall, so that the concrete moves down gradually. The bottom part of the placing pipe is enclosed within a rigid tubular section which (except at the start of concreting) is at the level of the desired surface of the concrete.

While concreting is in progress, the underwater placing unit performs a to-and-fro motion across the width of the cofferdam, and at each change of direction the unit is moved forward in the longitudinal direction of the cofferdam by an amount approximately equal to the diameter of the discharge outlet.

In this technique each successive layer of concrete is placed on the sloping mass of concrete already deposited in position. With correct execution of the job the movement of the concrete is so controlled that no washout occurs. The fresh concrete can suitably have the same consistency as that used in the tremie method, i.e., with a slump of about 150 mm, though stiffer mixes can also be placed by this methode (see also 3.1).

A feature that the hydrovalve method shares in common with the tremie method is that the concrete is poured through a pipe. On the other hand, hydrovalving has features in common with the skip method of concreting in that placing is effected at the actual surface of the concrete, that the placing unit is moved horizontally during concreting and that the concrete is fed intermittently (in successive plug-like masses).

Because of these features the hydrovalve method can be regarded as an intermediate form between the tremie method and the skip method.

Finally, it should be noted that, in principle, concrete can be deposited in a thin layer (e.g., 70 cm) by this method – something that is impracticable with the tremie method and the pumping method because of the required immersion depth of 1 to 1.5 m.

2.1.4 *Skip method*

Underwater concreting with the aid of bottom-dump skips has been frequently employed particularly in the Netherlands. In this method a skip (hoisting bucket) is filled with fresh concrete above water and is then lowered under water and discharged. The skip is lowered onto the bottom of the cofferdam, or onto the concrete already placed, in which latter case the skip should preferably penetrate some way into that concrete.

There are two alternative operating principles:

a. The release mechanism for discharging the concrete is actuated on raising the skip. More particularly with downward-opening discharge doors this will involve a risk of segregation of the concrete.
b. Opening the doors is effected while the skip itself remains stationary in the concrete already in situ. For this purpose, roller doors (or similar) may be used, which are actuated electrically or by some other means.

In the skip method the risk of washout is much greater than with tremie placing or pumping. Although washout cannot be entirely obviated, it can be restricted by applying the following precautions:

- using completely filled skips;
- lowering and also raising the skips slowly;
- building up the advancing front of concrete from below upwards;
- using a concrete mix which does not easily segregate.

As for the consistency of the concrete, a slump of between 100 mm and 140 mm is usually adopted.

With this method, too, concrete possessing high compressive strengths is obtained. In comparison with the methods described in the foregoing, rather numerous non-coherent layers have in practice been found to occur in skip-placed concrete (see Chapter 4).

2.2 Grouted concrete

Grouted concrete is obtained by the injection of grout into a mass of coarse aggregate (more particularly: gravel) which has been deposited beforehand. The gravel should be clean to ensure good bond with the grout. Besides, to ensure good filling of the voids between the particles, the gravel must not be too finely graded. It should be so placed in the cofferdam that there is no risk of fracture and of contamination with dirt. Even gravel which is clean can subsequently become contaminated by algal growth; for this reason, grouting should be done as soon as possible after the gravel mass has been deposited in position.

The grout is injected through pipes (e.g., 35 mm diameter) which extend down to just above the bottom of the cofferdam in order to obviate the formation of water pockets. As grouting proceeds, the pipes are raised at regular intervals. As a rule, the pipes are spaced about 2 m apart. With wider spacing, greater irregularities are liable to occur.

Grouting the gravel is carried out under low pressure. The grout employed for the purpose must possess good fluidity and moreover must not segregate. Various grout mixes may be used to fulfil these essential requirements. Two such mixes are described in 2.2.1 and 2.2.2 respectively, namely, Prepakt grout and Colcrete grout.

The strength of a grouted concrete is determined mainly by the strength of the mortar and its bond to the gravel. As it is not known beforehand how much the voids content of the gravel is, it is advisable to specify the quantity of cement per m^3 of grout.

In the literature the following advantages are claimed for grouted concrete as compared with concrete made in the ordinary way:

- installing top reinforcement and/or other constructional components is a simple matter;
- work can continue without interruption, because much less material has to be deposited in the grouting operation;
- less storage area is needed; the gravel can be put directly into the formwork;
- no shrinkage cracking, since the pre-placed gravel forms a rigid skeleton;
- no cracking due to temperature effects.

The Committee questions the validity of the two last-mentioned assertions. It has also found the following disadvantages:

- lower strength; this has also been noted by Gerwick [15];
- greater porosity because of the higher water/cement ratio and incomplete filling of the voids;
- more expensive.

2.2.1 *Prepakt concrete*

With Prepakt concrete good fluidity of the grout is obtained by the addition of a so-called intrusion aid and by using sand with a suitable granulometric composition.

The quantity of intrusion aid employed is usually equal to 1% of the cement by weight. This (patented) admixture has the following properties:

a. a dispersive action;
b. a swelling action, which is due to the presence of aluminium powder; in an alkaline medium this powder evolves gas in the form of minute bubbles, whereby the concrete may become more impermeable to water;
c. a retarding action, as a result of which the initial set of the cement is delayed by approximately 6 hours.

2.2.2 *Colcrete*

With Colcrete good fluidity of the grout is obtained by mixing the binding agent (cement with the possible addition of fly-ash, trass, etc.) with water in a high-speed mixer, followed by the addition of sand and further mixing. The mixer also pumps the grout and is equipped with an impeller rotating at speeds of between 1500 and 2500 r.p.m.

In this way a colloidal suspension is produced which is stable and moreover possesses good flow properties. It is a patented process.

2.3 Packaged concrete

There are systems whereby washout of cement and fines from fresh concrete is prevented by protecting the latter by "packaging" it in some suitable enveloping material. Two systems of doing this are applied, according as such packaging is done above or below water.

2.3.1 *Concrete packaged above water*

In this method the fresh concrete is put into bags which are then deposited under water. The bags are made of a strong and close-textured fabric, e.g., hessian or canvas, and are of 10 to 20 litres capacity for diver-assisted work [9]. The concrete employed has a slump of between 20 and 50 mm, and the maximum aggregate particle size is about 40 mm. If smaller bags are used (5 to 7 litres), a mix containing aggregate not exceeding about 10 mm in size is used.

The placing of bagged concrete under water is really an auxiliary method intended more particularly for the plugging of holes, e.g., between formwork and the bed or bottom of the water. Sometimes such bags are stacked up to build an enclosure serving as formwork for further underwater concreting in water depths up to about 2 m.

In some instances bags containing 1 m^3 and more have been installed under water with the aid of mechanical handling appliances. An example is afforded by the use of concrete in bags (which were filled on the spot) for underwater protection around the IJmuiden harbour breakwaters [16].

To ensure good interbonding of the bags they must not be completely filled with concrete (approximately 80% full).

2.3.2 *Concrete packaged under water*

This method is used, inter alia, for the construction of "concrete" bank revetments under water (Fig. 1). Textile fabric serving as "formwork" is used to obtain a certain desired thickness of the layer of concrete. It is a nylon two-ply fabric, the two plies being joined together, by interweaving, at regularly spaced points disposed in two mutually perpendicular directions. The space between the plies is filled with grout composed of, for example, 550 kg of cement, 1100 kg of sand and 4 kg of intrusion aid (see "Prepakt concrete", above) per cubic metre.

The interwoven points hold the two fabric plies together during grouting, thus locating them in relation to each other and determining the thickness of the layer formed. Also, when the concrete mat has hardened, these points serve as filters, so that a revetment permeable to water is obtained. This permeability and the weight per unit area of the grouted mat can be varied by appropriately varying the size and the spacing of these filter areas.

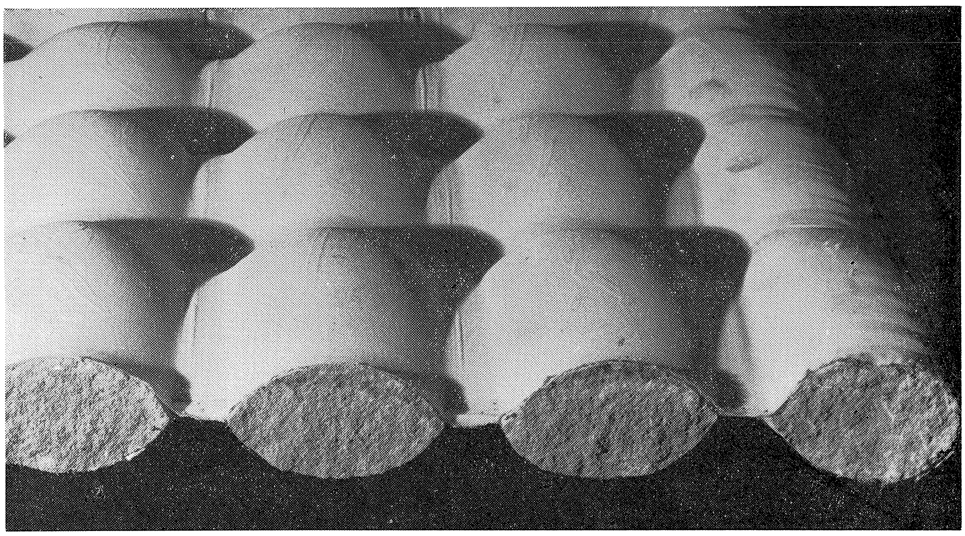


Fig. 1. Concrete revetment.

The mat produced by this method adapts itself to the irregularities of the ground on which it is laid. The fabric envelope prevents washout.

In foundation engineering, too, concrete packaged under water is employed. This technique is characterised in that between the supported structure and the foundation – e.g., piles – bags are placed which, after the air has been extracted from them, are filled with grout (Fig. 2). In this way, by suitable adjustment of the grout pumping pressure and the use of bags of specific known size a predetermined load can be applied to each pile or group of piles. Shrinkage can be compensated by the addition of an expanding agent.

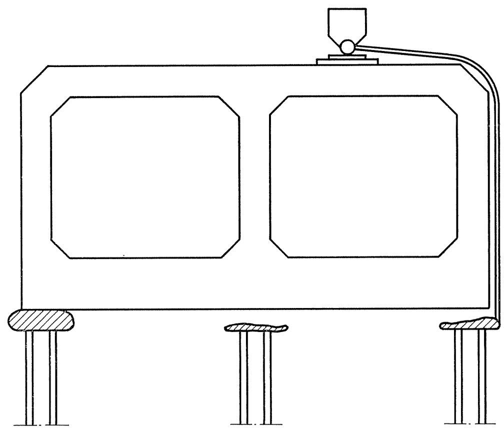


Fig. 2. Concrete packaged under water and serving to connect pile heads to tunnel structure.

In the construction of the submerged-tube tunnel for the Rotterdam underground urban railway system, grouting was not employed for forming the connection of the pile heads to the supported structure, but, instead, movable pile heads were raised and pressed into contact with the tunnel segment which had already been sunk in position [17]. In building the Maracaibo bridge, grout was injected between the toes of the piles and the surrounding soil [18].

2.4 Precast concrete assembled under water

Precast concrete units can be assembled into larger systems under water. Joining the units to one another may, for example, be done by filling the joints with concrete through a tremie.

Underwater concrete will bond efficiently to precast concrete if the following conditions are satisfied [15]:

a. On account of silt deposition, precast concrete surfaces against which the fresh concrete is to be placed should be roughened or be formed with a wavy profile.

b. Underside surfaces of precast units should be given a rounded upward-sloping shape to enable the joint-filling concrete to flow upwards without risk that pockets or inclusions will occur.
c. The joint-filling concrete should not have to overcome minor obstacles (e.g., densely spaced reinforcement) liable to cause segregation.
d. Joints should be closable or closed in order to prevent washout.

2.5 Concrete placed under bentonite slurry

In foundation engineering it is well known that deep trenches can be excavated without danger of collapse if they are filled with bentonite slurry (or bentonite mud, as it is also called). The slurry is of such consistency that reinforcement mats or cages can be installed in the trench and concrete can be placed under the slurry by means of the tremie method. During concreting, the slurry is pumped away and may be processed for re-use.

A concrete mix possessing good workability should be used (150 mm slump). In tests performed in connection with the execution of such concrete structures there was found to be a very definite and practically horizontal interface between the bentonite slurry and the concrete. In general, the quality of the concrete produced by means of this placing method is considered to be satisfactory (compressive strength, bond to reinforcing steel) [19].

A recent development consists in installing precast wall units in a trench in which, before they are installed, a clay-and-cement slurry has been placed under the bentonite slurry [20].

3 COMPOSITION OF THE CONCRETE

Concrete intended for underwater placing should possess a number of specific properties, such as good flow properties (high slump) and adequate cohesion (low susceptibility to segregation).

By segregation of fresh concrete is understood the separation of its constituent components. It is liable to be caused by factors inherent in such operations as transporting, placing, compacting, etc. (external factors). In the fresh concrete the heavier components will tend to settle (sedimentation), causing the lighter ones to be forced upwards.

If water comes oozing out the surface of the concrete as a result of this process, the phenomenon is called bleeding. Sedimentation may occur so intensively that paste with a high water content is forced out of the concrete. Besides cement, this paste may contain very fine sand particles.

The very cement-rich layer (hardened cement paste) often found to be present on the surface of underwater concrete is in part caused by profuse sedimentation, while in this layer moreover cement has accumulated which was washed out of the concrete during placing.

By segregation susceptibility is understood the degree to which fresh concrete tends to undergo separation of its components. This susceptibility depends only on the composition of the concrete, in connection with which the particle shape and grading of the aggregate, the cement content, and the consistency of the concrete are important factors. Much practical information on the composition to be adopted for underwater concrete is given in the literature. With regard to cement washout (a form of segregation) the Committee set itself the task of finding out to what extent currently used practical concrete mixes can be improved by the addition of cohesion-promoting admixtures. The results of the laboratory research carried out for this purpose are reported in 3.4.

The segregation susceptibility of a concrete mix can be investigated by determining the segregation that occurs as a result of external factors, which implies that for each external factor a segregation test is to be devised which conforms most closely to the conditions that occur in actual practice [21]:

- If the only external factor to be considered is gravity, a bleeding test is of interest. Also, the displacement of the centre of gravity which occurs in a vertically concreted prism specimen in consequence of sedimentation may be determined.
- If there is a risk of segregation due to the presence of reinforcement in the structure to be concreted, a test may be performed in which concrete is poured over several layers of reinforcing bars. As a result, a cone of concrete will be formed under the reinforcement; the perimeter of this cone can then, for example, be examined as to the sand/gravel ratio of the concrete there. The deviation from the original sand/gravel ratio in the mix provides a criterion for segregation susceptibility.
- For assessing the washout affecting concrete during underwater placing the Committee introduced a test in which scoopfuls of fresh concrete are deposited into a mould filled with water. A good deal of cement is washed out of the concrete during this operation. After thus being placed under water, the concrete is analysed: the difference between its cement content and the original cement content provides a criterion for washout susceptibility.

Correlations between the results of these various tests were not investigated. It can in general be assumed that with greater cohesion of the concrete the segregation tests will yield more favourable results. In the following sections of this chapter the underwater concrete mixes reported in the literature will be assessed with reference to the results of separate segregation tests which were performed by various investigators. It would appear possible in this way to arrive at more efficient concrete mixes.

3.1 Consistency

In the literature a slump of between 150 mm and 200 mm is usually recommended.

Concrete with such a consistency can flow easily, which is important more particularly when obstacles such as reinforcement, piles, etc. are present. In Dutch practice a slump in the range from 100 mm to 140 mm is often adopted.

In choosing the slump it would appear expedient not to go beyond that corresponding to the most plastic consistency range indicated in Netherlands Standard N 3051 („Directives for the vibrating of concrete") and to take advantage of this lower slump by obtaining a correspondingly higher-strength concrete.

Heaton [21] conducted research on the compressive strength of concrete as a function of plasticity and the degree of compaction. His results are presented graphically in Fig. 3. From this it appears that for concrete with the recommended 150–200 mm slump there is practically no difference between the strength of compacted and uncompacted concrete.

From the investigation of the compressive strength of concrete placed under water and not compacted (see Chapter 4) it has emerged that strengths of 35 to 50 N/mm^2 (300 to 500 kgf/cm^2) are generally obtained.

These compressive strengths are more than adequate, and it would be ill-advised to seek a gain in strength at the expense of diminished fluidity of the fresh concrete and the application of compaction which would be difficult to perform and to supervise.

Conclusion: For underwater concrete a slump of 150 to 170 mm should be aimed

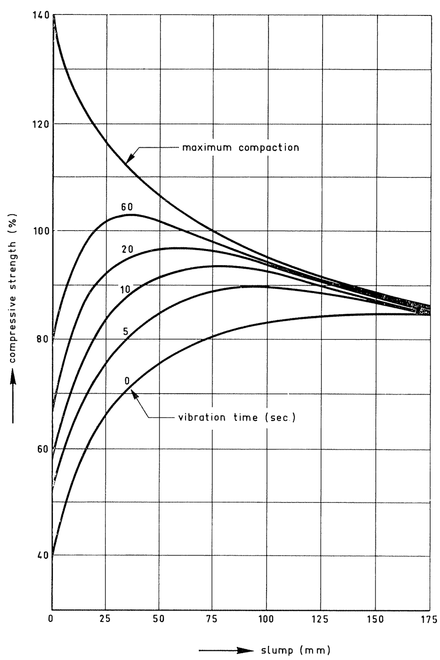


Fig. 3. Compressive strength of concrete as a function of plasticity and degree of compaction, according to Heaton.

at, with 120 and 200 mm as the extreme limits of acceptability. Concrete of such consistency does not require compaction.

With regard to pumped concrete see 2.1.2.

3.2 Aggregate

First and foremost it must be stated that for underwater concrete, as indeed for other methods of concrete construction, the aggregate must not contain substances harmful to concrete.

It is a well known fact that if crushed instead of rounded aggregate is used, more water is needed to give the same workability of the mix. Nevertheless, with crushed aggregate higher strengths can be attained, provided that the concrete is fully compacted. It is likewise well known that concrete made with crushed aggregate requires more compaction energy. In underwater concrete the compaction must be achieved by the dead weight of the concrete itself, and for this reason it appears desirable to use aggregate consisting of rounded particles. Such material is to be recommended also because the concrete made with it has less bleeding tendency (this being due to the lower water demand). To ensure good flow properties of the fresh concrete it is moreover important that the aggregate should not contain too high a proportion of flattish particles.

In the literature it is generally recommended to employ continuous grading; gap grading is considered to involve a greater risk of segregation. In research carried out by Dreux [21] on concrete with continuous grading and with gap grading of the aggregate there was found to be no definite differences in segregation susceptibility. This was established by means of tests in which the concrete had to pass through meshes between reinforcing bars (see also the introductory section of this chapter).

Having regard to experience gained with concrete placed above water, i.e., under dry-land conditions, for which the segregation hazard is greater with gap gradings, it is advisable to use continuous gradings for underwater concrete.

In the literature it is advised that a high sand/gravel ratio be adopted. Gerwick [22] recommends the use of 42 to 45 per cent (by weight) of sand within the total quantity of aggregate. These percentages are considerably higher than the average sand percentage employed in Dutch concrete, which is approximately 35 per cent (by weight). If a higher sand content is used, a more cohesive mix is obtained. This is favourable with regard to segregation and washout. The effect of an increased sand content on washout of cement was investigated by the Committee by means of washout tests. It was found that an increased content of sand (40 instead of 35 per cent by weight) did indeed result in reduced washout (see 3.4). The more favourable result obtained by increasing the sand in the mix is not surprising, since it is in general the fine particles that bring about cohesion.

If more than 45 per cent (by weight) of sand is employed, there is found to be no further reduction in washout. Besides, for achieving the desired workability it then becomes necessary to add more water to the mix, whereby the strength of the concrete is adversely affected. For the above-mentioned sand percentages the material that passes the 2.8 mm sieve (as specified in Netherlands Standard N 480) can be reckoned as sand. With regard to the sand it should be noted that, in the interests of obtaining a cohesive mix, sand from which the finest particle size fractions are absent should not be used. If such sand is nevertheless used, a quantity of fine material (e.g., quartz powder, trass, etc.) will have to be added.

Although some authors report that in underwater concrete (except grouted concrete) aggregate particles up to 50 mm in size have successfully been employed, it is recommended in general not to choose the maximum particle size too large. 20 mm is recommended as the maximum [22].

The deciding factor with regard to this is more particularly the method of placing the concrete (pumped concrete will, generally speaking, require a finer particle size than tremie-placed concrete). The limit imposed upon the maximum aggregate particle size is presumably also linked to the segregation susceptibility of the concrete.

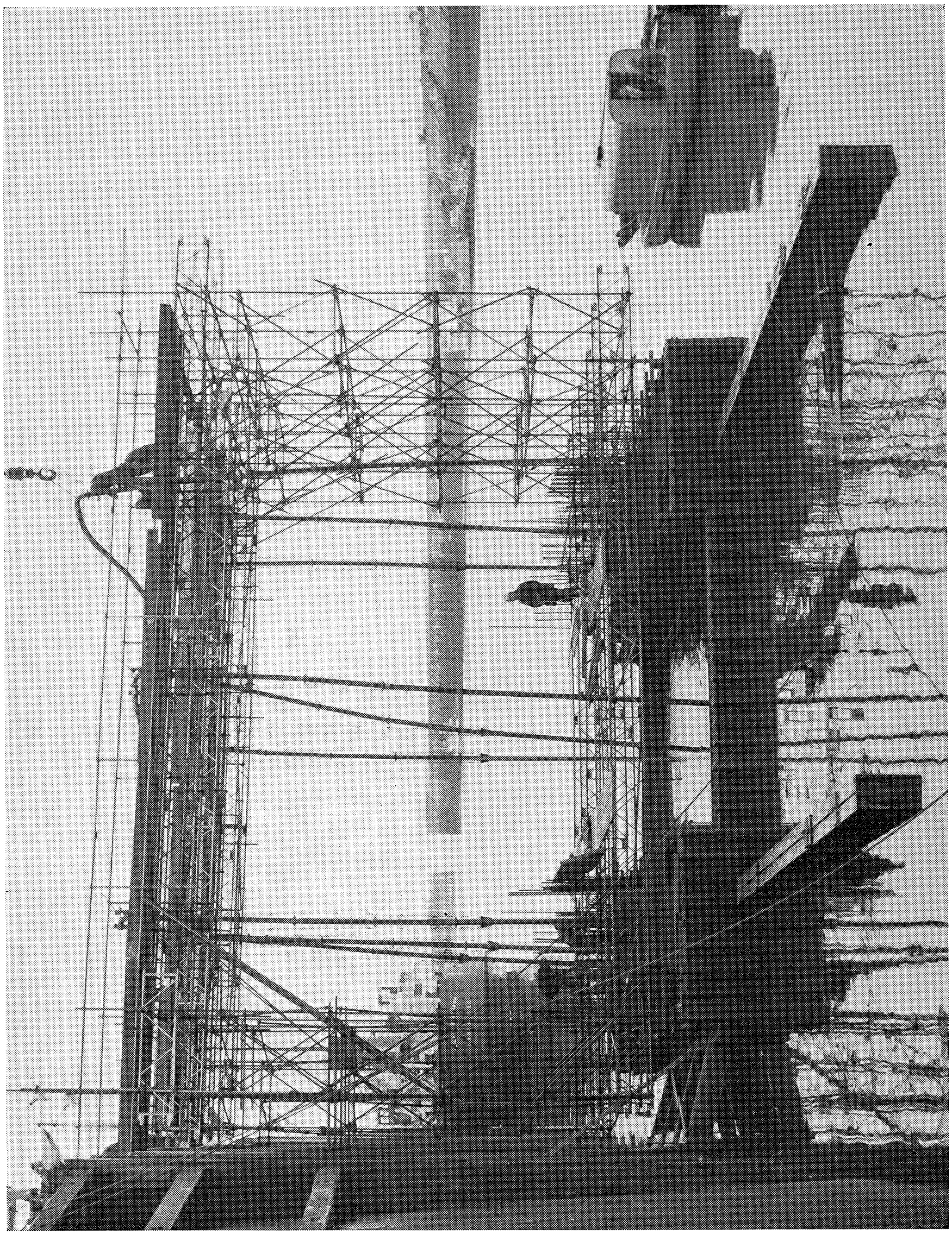
In segregation tests performed by Dreux [21] the segregation susceptibility was found to increase with increasing maximum particle size. Incidentally, his research showed this susceptibility to remain practically constant for maximum particle sizes in excess of about 20 mm.

3.3 Cement

A frequently heard line of reasoning is as follows:

> In concrete placed under water a proportion of the cement is washed out. On pumping the cofferdam dry, this washed-out cement is found forming a layer of hardened cement paste on top of the concrete. This layer is sometimes of considerable thickness. In order to ensure that sufficient cement is retained in the concrete, a higher cement content must be used than in concrete used on dry land. In general, a cement content of approximately 375 to 400 kg per m^3 of concrete is accordingly recommended.

In reality, cement is indeed washed out, but to a much lesser extent than used to be supposed. The top layer consists mainly of paste which, as a result of sedimentation of the coarser aggregate particles, is displaced upwards; it is usually referred to as 'laitance' and is to be regarded as a form of intensified bleeding. The question to be considered is whether a proportion of the cement can be replaced by fine material (e.g., quartz powder, fly-ash, trass, etc.) without involving any significant reduction in the quality of the concrete. If so, the heat evolution due to hydration would be reduced as a result of cutting down the cement content of the mix, thus achieving a direct advantage with regard to cracking. For obtaining the relatively high slump values, from 120 to 170 mm, a relatively large quantity of water is needed in the mix. On the other hand, the water/cement ratio is of decisive importance with regard to obtaining a certain compressive strength. For underwater concrete this means that, in order to



Pump method.

Photo: Miles Cummings, Lancaster

provide a sufficiently low water/cement ratio (and therefore a sufficiently high strength of the concrete), a relatively high cement content is needed. The desired value of this ratio for obtaining a particular compressive strength can be determined with the aid of Fig. 4 [23]. The standard strength required for class A (= ordinary) portland blastfurnace cement (more particularly of the 'Hochofen' type) is 25 N/mm² (250 kgf/cm²). In reality, the average strength of Dutch cement of this class and type is 40 N/mm² (400 kgf/cm²).

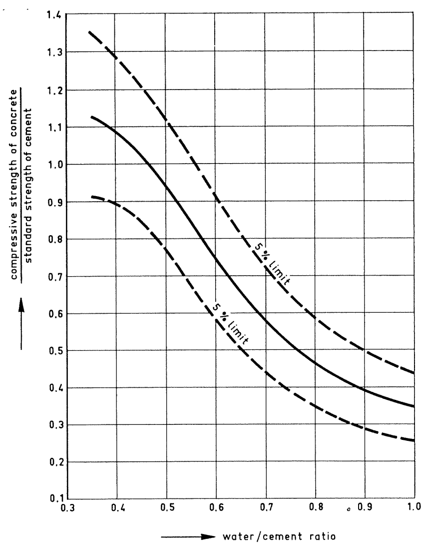


Fig. 4. Relationship between water/cement ratio, standard strength of cement and compressive strength of concrete.

The Committee is of the opinion that adequate strength of underwater concrete can be obtained with 325 kg of cement per m³. This opinion is based on the following considerations.

On a construction job where concrete was deposited under water in four cofferdams by the tremie method the cement content was varied (see also Chapter 4, job V). A number of test cores were subsequently taken from this concrete, for which the following average compressive strength figures were found:

cofferdam	cement content (kg/m³)	compressive strength in N/mm² (kgf/cm²) average	standard deviation
A	400	48.0 (490)	5.4 (55)
B	350	53.1 (542)	5.0 (51)
C	350	50.2 (512)	2.1 (21)
D	325	51.3 (523)	3.6 (37)

On this job no fillers were added to the concrete. The concrete containing 325 kg of cement was found to have even a higher compressive strength than the concrete in which 400 kg of cement per m^3 had been used. On the other hand, the workability (washout susceptibility) is liable to be rather unsatisfactory. This can be improved by the addition of fine material, e.g., fillers such as trass or fly-ash.

Dreux [21] carried out segregation tests on concrete mixes which had a cement content of 350 kg/m^3 and to which various percentages of fillers with particle sizes approximately equal to those of the cement had been added. It was found that minimum segregation susceptibility occurred when 8 to 10 per cent of filler (by weight, referred to the cement) was added to the mix. This means that the concrete is least liable to segregate when it contains about 380 kg of cement (including filler) per m^3. If the fine material of the sand fraction ($<$ 0.25 mm particle size) is added to this total, the requirement as to the fines content laid down in the code of practice for concrete VB 1972 is complied with.

It can permissibly be assumed that with 325 kg of cement per m^3 the concrete will be of sufficient strength and that its susceptibility to cracking will be less than that of concrete with a cement content of 375 kg/m^3 as recommended in the literature (because less heat of hydration will be evolved), but that in order to obtain optimum cohesion of the fresh concrete it is necessary to add about 60 kg of filler to the 325 kg of cement per m^3. It is especially important to use fillers if the structure to be concreted contains reinforcement or has piles embedded in it and if a concrete placing method more liable to cause cement washout is employed.

The requirement stated in ASTM-C593-69 can suitably be adopted with regard to the particle size of the fillers: maximum residue of 2 per cent on sieve No. 30 (595 microns) and maximum residue of 30 per cent on sieve No 200 (74 microns) (percentages by weight).

Since underwater concrete is permanently in contact with water (ground-water or sea-water), aggressive substances present in the water may attack the concrete. In this context sulphates and humic acids call for mention. Concrete with a low lime and aluminate content, more particularly concrete made with portland blastfurnace cement of the "Hochofen" type, is better able to withstand the attack of potentially harmful agents. Hence if it is decided to use this type of cement to obtain better resistance to attack, it will at the same time be the correct choice from the viewpoint of heat evolution, since the hydration of "Hochofen" cement evolves less heat than does that of portland cement.

For the sake of completeness it should be mentioned that practically no "Hochofen" cement is manufactured in the U.S.A. In that country the use of type II cement is recommended for underwater concrete. This cement has a moderate C_3A content (improved sulphate resistance) and moreover evolves only a moderate amount of heat.

It is advisable to use a class A (= ordinary) cement because with a cement having a higher rate of hardening the amount of heat of hydration evolved per unit time in the early stages is larger. Besides, a "Hochofen" cement of class B (= rapid hardening) has a higher content of portland cement clinker and therefore a lower slag content than class A. From the viewpoint of sulphate resistance this latter aspect may be something of a drawback. For more detailed information on temperature effects in massive concrete structures the reader is referred to CUR Report 19 [24].

3.4 Admixtures

A substantial part of the Committee's work consisted in laboratory research in connection with underwater concrete containing admixtures. It was investigated whether the quality of such concrete could be improved by the use of these added substances. As it was assumed that cement washout was the main cause of quality deterioration in underwater concrete, the following criteria were applied in this research:

a. The strength of above-water concrete (i.e., concrete placed "in the dry") made with an admixture must not be significantly lower than that of reference concrete, i.e., the same mix but without admixture, likewise placed above water.
b. The strength of underwater concrete with an admixture must be higher than that of reference concrete likewise placed under water.
c. During underwater concreting there should be less cement washout from concrete with an admixture than from the corresponding reference concrete.

After some preliminary washout tests, it was, in this research, endeavoured to characterise the rheological properties of the cement paste present in the fresh concrete with the aid of a Brookfield viscosimeter and to establish a relationship between cement washout, on the one hand, and the shearing strength of the cement paste, on the other. No correlation was found to exist between these properties. For investigating the effect of admixtures on the quality of concrete deposited under water a primitive skip-and-tremie method for concreting in the laboratory was accordingly developed. In order to have a method of discriminating between the various admixtures, extreme conditions were created, giving results not directly comparable with those obtained under the conditions encountered in actual practice.

This particularly severe test was performed as follows (Fig. 5): For each concrete mix to be investigated two batches, each of about 27 litres, were made. The slump of the first batch was determined. When this was found to be suitable (120 to 150 mm), the bulk density and the air content were determined. Finally, three 150 mm test cubes were made (not under water), which were compacted by standardised tamping.

The following were determined for the second batch: bulk density, air content, degree of cement washout from the concrete, compressive strength determined on three 150 mm cubes made from concrete deposited under water.

For determining the air content the measuring vessel of the apparatus (a cylindrical vessel about 240 mm high and with a capacity of 8 litres) was filled with water to a depth of 140 mm. The concrete was fed through a tube of 60 mm diameter and 500 mm length. The bottom end of this tube was always kept at the level of the surface of the water, so that the concrete fell through about 140 mm of water. The outlet at the

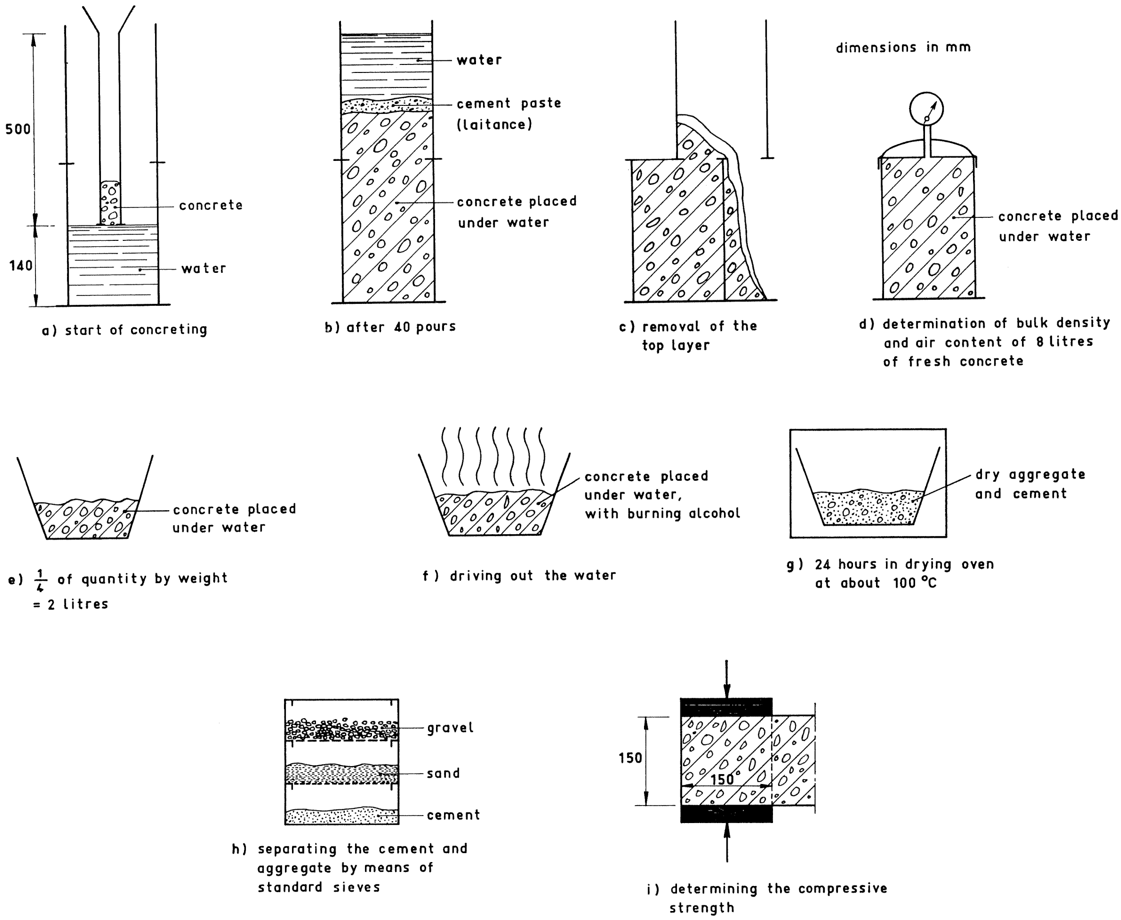


Fig. 5. Diagrams illustrating underwater concreting procedure and determination of cement content and compressive strength.

bottom of the tube was provided with a closable hinged valve which could open by the pressure exerted by the weight of the concrete itself. The quantity of concrete discharged per pour was about $\frac{1}{3}$ litre. To enable concreting to be continued up to about $1\frac{1}{3}$ times the height of the vessel, an upward extension piece to the latter was provided. The desired height of the concrete in the vessel was reached after about 40 pours.

After an interval of time (in which the underwater concrete cubes were made) the extension piece, together with the concrete in it, was removed in one horizontal movement. The top layer containing any washed-out cement (laitance) was thus removed along with that concrete. Next, the bulk density and the air content of the concrete left in the vessel itself, i.e., after removal of the extension piece, were determined.

Then, with the aid of burning alcohol, the mixing water was removed as quickly as possible from one-quarter (by weight) of the quantity of concrete in the vessel. The specimen was next put in a drying oven (100 °C) and, after cooling, the cement content was determined by sieving (Netherlands standard sieve N 480-d-0.150 mm).

Like the above-mentioned vessel, the cube moulds were each provided with an upward extension piece, which was not removed until the cubes were demoulded. The concrete for these cubes, too, was deposited through a water depth of 140 mm from the surface of the water.

In these underwater concreting operations no artificial compaction was applied to the concrete either in the measuring vessel or in the cube moulds. Whenever possible, the cubes were demoulded after 2 days and were kept under water at 20 °C up to an age of 28 days.

At 28 days the compressive strength was determined, for which purpose the cubes were placed between 40 mm thick steel compression platens 150 mm square. The rate of loading applied to the cubes was 0.2–0.3 N/mm² (2–3 kgf/cm²) per second. In the case of the underwater test specimens (because of the extension piece, these were in fact prisms measuring 150 mm × 150 mm × 200 mm) the bottom part was compression-tested in a direction perpendicular to the direction of concreting. It can be assumed that the compressive strength result thus obtained was practically the same as for actual cube specimens of the same concrete.

The reference mix used in these tests, i.e., containing no admixture, was concrete with a portland cement content of 375 kg/m³. The aggregate consisted of dried and screened sand and gravel with a fineness modulus of 5.14 (see Fig. 6).

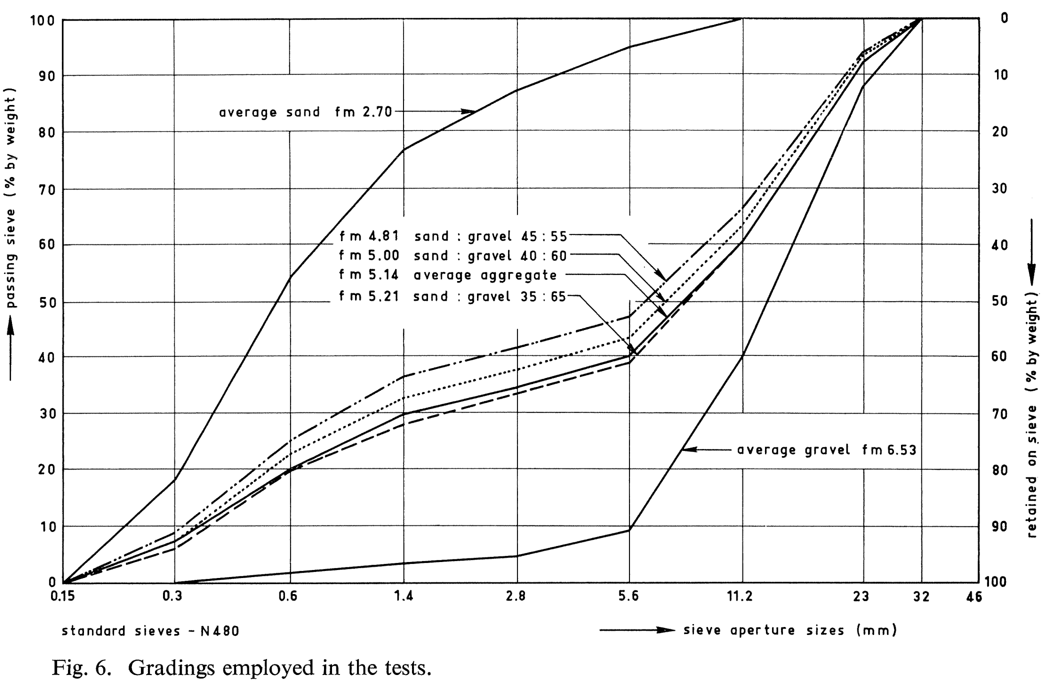


Fig. 6. Gradings employed in the tests.

The consistency chosen corresponded to a slump of between 120 and 150 mm. The amount of admixture to be introduced into the mix was determined by means of trial mixes.

In the case of air-entraining agents the determination of the amount of admixture was based on an air content of 5% in the concrete as placed under water, because with higher air percentages an appreciable loss of strength is liable to occur. For admixtures other than air-entraining agents the occurrence of incipient bleeding was adopted as the criterion for the amount to be used. Finally, for those admixtures for which the above criteria were irrelevant a fairly arbitrary choice of the amount was made, subject to the condition that, for the desired slump of 120 to 150 mm, the water/cement ratio of the mix must remain within reasonable limits.

The Committee was on the look-out for admixtures which, as a result of exercising a "glue-like" effect, would give the fresh concrete better cohesion so that it would be less severely attacked by water. Partly on the basis of experience already gained in other areas of technology, the following main groups of admixtures were first subjected to investigation, for which purpose a choice of substances was made from each of these groups:

a. natural polymers:	arabic gum
	methyl cellulose
	hydroxy-ethyl cellulose
	carboxy-methyl cellulose
b. synthetic polymers:	polyacrylonitrile
	polymethacrylic acid
	copolymer of vinyl acetate and maleic acid anhydride
c. inorganic powders:	silica gel
	bentonite
d. surface-active agents:	air-entraining agent
	air-entraining agent with setting retarder
	plasticiser

The results of this research are summarised in Table 2. The strength of cubes concreted under water and the cement washout were more particularly investigated. If favourable results in respect of these two criteria were obtained, further experiments were carried out with the admixture in question, with the object, inter alia, of finding optimum amounts or combinations of admixtures. It was thus established that optimum strengths for the cubes concreted under water were obtained when 0.5% of bentonite (by weight of the cement) was added, while the strength of cubes made above water in the ordinary way ("in the dry") with this bentonite concrete was much the same as that of reference concrete. As regards cement washout hardly any advantage was gained with bentonite used as an admixture in the above-mentioned amount; but with larger amounts of bentonite (up to about 5%) there was an improvement in this respect, though this was achieved at the expense of the compressive strength of the concrete, both when placed under water and when placed above water.

Table 2. Results of research on admixtures.

admixtures: groupe name	admixtures: general chemical name	amount of admixture per 100 kg of cement	cement washout in %	cube strength at 28 days in N/mm² (kgf/cm²): above water NORM	cube strength at 28 days in N/mm² (kgf/cm²): under water U.W.	compressive strength ratios: $\frac{NORM_t}{NORM_{bl}}$	compressive strength ratios: $\frac{U.W._t}{U.W._{bl}}$	compressive strength ratios: $\frac{U.W._t}{NORM_{bl}}$
reference		–	22,0	44.4(453)	12.5(127)			0.28
concrete		–	21.2	41.6(424)	14.5(148)			0.35
				av. 43.0(438)	av. 13.5(137)	1.00	1.00	av. 0.32
natural	arabic gum	1000 g	22.1	47.5(484)	16.2(165)	1.10	1.20	0.38
polymers	methyl cellulose	150 g.	10.1	25.6(261)	13.9(142)	0.60	1.03	0.32
	hydroxy-ethyl cellulose	150 g	12.4	27.0(275)	13.6(139)	0.63	1.01	0.32
	carboxy-methyl cellulose	1000 g	19.0	24.6(251)	6.8(69)	0.57	0.50	0.16
synthetic	polyacrylonitrile	2000 g	6.8	17.0(173)	10.1(103)	0.40	0.75	0.24
polymers	polymethacrylic acid	3000 g	15.7	9.6(98)	3.6(37)	0.22	0.27	0.08
	polyacrylat	5000 g	15.9	11.8(120)	3.6(37)	0.27	0.27	0.08
	copolymer of vinyl acetate and maleic acid anhydride	500 g	11.1	19.9(203)	8.9(91)	0.46	0.66	0.21
inorganic	silica gel	2000 g	23.6	38.0(388)	12.3(125)	0.88	0.91	0.29
powders	bentonite	2000 g	15.4	32.5(332)	14.0(143)	0.76	1.04	0.33
	bentonite	5000 g	16.6	23.8(243)	11.7(119)	0.55	0.87	0.27
surface-active	air-entraining agent	90 cc	17.0	24.9(254)	11.1(113)	0.58	0.82	0.26
agents	air-entraining agent with setting retarder	30 cc+266 g	11.9	29.0(296)	12.5(127)	0.68	0.92	0.29
	plasticiser	200 cc	14.3	45.4(463)	12.4(126)	1.06	0.92	0.29

Note: percentage of cement washed out $= \frac{\text{cem.cont. NORM} - \text{cem.cont. U.W.}}{\text{0.01 cem. cont. NORM}}$

cem.cont. = cement content
NORM = concreted in the normal way
U.W. = concreted under water
bl = reference concrete
t = with an admixture

Table 3. Results of research on concrete placed above water and under water with bentonite admixture.

		cube concreted above water			cube concreted under water			cement washout		
bentonite in % of cement by weight	type of cement	average compressive strength in N/mm^2 (kgf/cm^2)	standard deviation in N/mm^2 (kgf/cm^2)	number of observations	average compressive strength in N/mm^2 (kgf/cm^2)	standard deviation in N/mm^2 (kgf/cm^2)	number of observations	average washout in %	standard deviation in %	number of observations
0% (blanco)	portland cement	43,5(444)	1.44(14.7)	18	14.7(150)	1.40(14.3)	18	23.8	2.2	6
	Hochofen cement	41.9(427)	1.28(13.1)	9	17.5(179)	1.55(15.8)	9	23.1	0.3	3
0.25% in dry form	portland cement	39.1(399)		3	15.5(158)		3	26.0		1
	Hochofen cement	40.0(408)		6	18.4(188)		6	22.9		2
0.25% in suspended form *	portland cement	51.1(521)		3	18.2(186)		3	21.1		1
	Hochofen cement	39.5(403)		3	18.7(191)		3	20.6		1
0.5% in dry form	portland cement	41.1(419)		3	19.4(198)		3	24.2		1
	Hochofen cement	40.1(409)		6	18.4(188)		6	21.2		2
0.5% in suspended form *	portland cement	42.0(428)		3	16.1(164)		3	20.2		1
	Hochofen cement	40.1(409)		3	17.7(181)		3	20.4		1

* a suspension was used because the effect of bentonite was expected to improve after prolonged contact with water

These improvements obtained by using bentonite – bearing in mind also that this admixture is relatively cheap and does not impair the durability of the concrete – were decisive reasons to confine the final stage of this research to a further investigation of this admixture only. The results obtained are summarised in Table. 3.

From this table it appears that with regard to strength the results obtained with "Hochofen" cement were better than those obtained with portland cement and that addition of bentonite to concrete made with "Hochofen" cement had hardly any effect on compressive strength and washout. With bentonite admixture the results obtained with portland cement came rather close to those obtained with "Hochofen" cement.

In all the tests described here the proportion of sand (material passing the 2.8 mm sieve) was about 35% of the aggregate (by weight), and the fineness modulus was 5.14. Since a sand content of between 40 and 45% is generally recommended in the literature, the effect of the sand content was investigated in a series of tests. Three gradings of average-type sand and gravel as used in the Netherlands were prepared, the sand content being 35, 40 and 45% respectively (see Fig. 6). "Hochofen" cement was used in these tests, the cement content of the concrete being 375 kg/m³; the slump was about 150 mm.

The results were as follows:

sand content	35%	40%	45%
proportion of the mixture retained on 2.8 mm sieve	33.5%	37.5%	41.7%
fineness modulus of the mixture	5.2	5.0	4.8
compressive strength, concrete placed above water	40.7(415)	40.0(408)	39.4(402)
compressive strength, concrete placed under water N/mm² (kgf/cm²)	17.9(183)	19.2(196)	17.1(174)
cement washout	23.9%	18.8%	20.0%

At the higher percentages of sand (40–45%) there was a little less washout than in concrete with about 35% sand, which is in agreement with the recommendations, while the compressive strength remained practically unchanged.

The research relating to cohesion-enhancing admixtures for concrete resulted in only relatively minor improvements. This was in part because – as was subsequently learned from the literature [21] – the concrete used in the tests already from the outset had an optimum content of fine particles, namely, 375 kg of cement per m³ together with the fine sand contained in the mix.

As will be seen in Chapter 4, the method of placing the concrete has a greater effect on the quality than has the use of admixtures.

4 PROPERTIES OF UNDERWATER CONCRETE

Although underwater concrete is, in principle, comparable with concrete placed above water, very little is known about the material properties of the concrete, as it generally remains submerged and is thus not accessible for testing. Accordingly, the figures presented in this chapter are somewhat less reliable than those available for concrete construction "in the dry". For the design of underwater concrete structures it is therefore necessary to proceed with caution.

4.1 Shrinkage and creep

By shrinkage is understood:

- shrinkage due to drying;
- shrinkage due to cooling.

With regard to drying shrinkage it can be stated that, so long as the concrete remains under water, no shrinkage will occur; indeed, swelling may occur instead. When the water in which underwater concrete has been placed is subsequently pumped away, shrinkage will develop only at a slow rate in the case of large and massive concrete structures (such as those concreted under water usually are). Also, since these structures are in continuous contact with water (on the underside anyway), it appears unlikely that they are affected by any appreciable amount of drying shrinkage.

Hydration of cement is accompanied by the evolution of heat which may cause a substantial rise in temperature of the concrete (sometimes by as much as 50 °C) [24]. When the concrete subsequently cools, two phenomena occur concurrently:

- accelerated cooling of the outside in relation to the core; this gives rise to tensile stresses on the outside;
- overall lowering of the temperature of concrete, with accompanying thermal contraction.

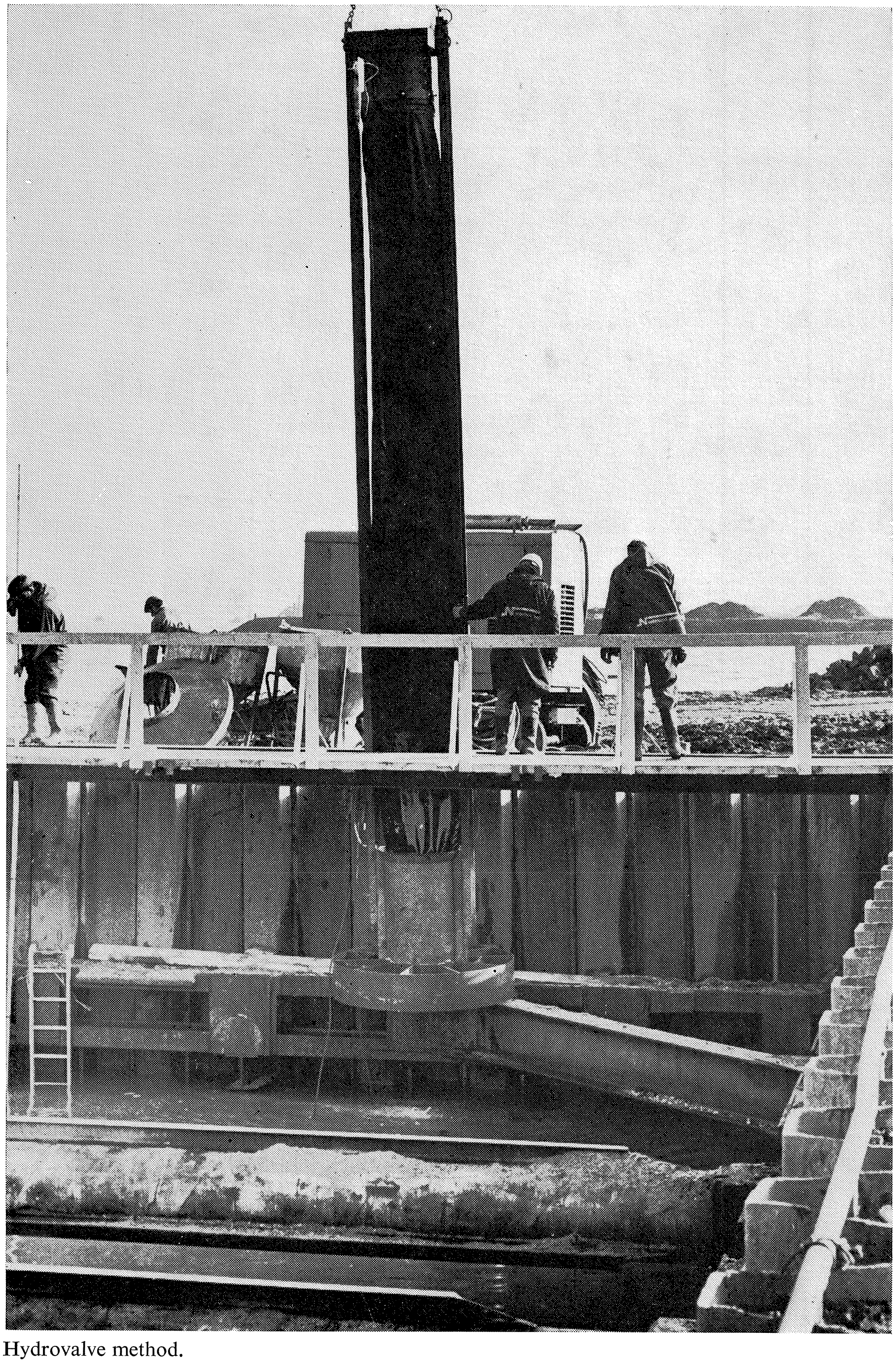
The first-mentioned phenomenon is liable to cause surface cracks which weaken the concrete cross-section. As a result of the second phenomenon, tensile stresses will develop if shortening of the concrete is restrained (subgrade friction, recessed portions in sheet piling, piles, etc.), so that cracks extending through and through the concrete may be formed, more particularly at sections already weakened by surface cracking.

From this point of view it is desirable to use a low cement content, even as low as, for example, 300 kg of "Hochofen" cement per m^3 supplemented by 75 kg of trass, in circumstances where strength is not a major consideration.

No data concerning the creep of underwater concrete are available. The creep deformations are probably never very significant, since the stresses are low.

4.2 Modulus of elasticity

Gerwick [15] gives 28 kN/mm^2 (280.000 kgf/cm^2) as the modulus of elasticity of



Hydrovalve method.

Table 4. Results of research on drilled cores obtained from tremie-placed underwater concrete.

job	IV *	V				VI	IX		
cofferdam No.		A	B	C	D	1	7	5	6
composition of the concrete									
cement content in kg/m³	375	400	350	350	325	400	400	400	400
bentonite in % by weight of cement	–	–	–	–	–	–	–	0.5	0.5
plasticiser (Cerinol BV) in ml/100 kg of cement	–	–	–	–	–	–	–	–	150
fineness modulus of the aggregate	5.4	5.8	5.6	5.5	4.7	5.0	?	?	?
water/cement ratio	0.47	0.48	0.52	0.52	0.50	?	?	?	?
slump in mm	140	?	?	?	100	140	140	140	140
concreting quantity in m³	840	575	475	475	675	70	750	1300	1300
cores									
total length in m		2.15	1.35	1.20	2.80	3.30	3.10	3.10	4.00
number of loose layers		0	0	0	3 **	0	0	1	0
loose layers per linear m of core		0	0	0	1.07	0	0	0.32	0
compressive strength									
number of tests		8	4	4	5	10	11	11	14
average in N/mm² (kgf/cm²)		48.0(490)	53.1(542)	50.2(512)	51.3(523)	43.8(447)	45.7(466)	40.6(414)	46.1(470)
standard deviation in N/mm² (kgf/cm²)		5.4(55)	5.0(51)	2.1(21)	3.6(37)	2.6(27)	3.1(32)	7.2(73)	5.6(57)
coefficient of variation in %		11	9	4	7	6	7	18	12
splitting tensile strength									
number of tests		5	4	3	6	10	10	10	12
average in N/mm² (kgf/cm²)		4.20(42.8)	4.09(41.7)	4.25(43.3)	4.25(43.3)	4.13(42.1)	4.20(42.8)	4.16(42.4)	4.37(44.6)
standard deviation in N/mm² (kgf/cm²)		0.33(3.4)	0.22(2.2)	0.18(1.8)	0.40(4.1)	0.34(3.5)	0.24(2.4)	0.58(5.9)	0.56(5.7)
coefficient of variation in %		8	5	5	10	8	6	14	13

* not included in the research because the execution of the work was not representative of the tremie method: insufficient immersion depth and horizontal movement of pipe during concreting

** loose layers caused by snags encountered during concreting tremie-placed underwater concrete. For the compressive strength of such concrete his figure is 28–42 N/mm² (280–420 kgf/cm²). His figure for the modulus of elasticity appears somewhat low. The Committee has not carried out experimental work in connection with this.

4.3 Compressive strength and homogeneity

Since the properties of underwater concrete are affected by such factors as site, water, method of concreting, etc., the Committee attached much importance to a comparative investigation under conditions as encountered in actual practice. The Committee is greatly indebted to the organisations and authorities that co-operated in this research by granting permission to drill test cores and by supplying valuable information.

Over a period of years, from 1966 to 1972, cores 150 mm in diameter were drilled from underwater concrete in various structures. During core drilling, particular attention was paid to the presence of any loose layers. The splitting tensile strength and compressive strength were determined by testing small cylinders (with height equal to diameter) sawn from the cores.

Table 5. Results of research on drilled cores obtained from pumped underwater concrete.

job	VII		X		
cofferdam No.	1	2	9	14	15
composition of the concrete					
cementcontent in kg/m³	375	375	360	360	360
bentonite in % by weight of cement	–	–	–	–	0.5
fineness modulus of the aggregate	4.3	4.3	?	5.4	?
water/cement ratio	0.46	0.46	?	?	?
slump in mm	100	100	120	120	120
concreting quantity in m³	270	270	3300	3300	400
cores					
total length in m	1.00	1.00	1.35	0.95	1.70
number of loose layers	0	0	0.5 *	0	0
loose layers per linear m of core	0	0	0.37	0	0
compressive strength					
number of tests	3	3	5	3	7
average in N/mm² (kgf/cm²)	40.4(412)	37.9(387)	34.8(355)	39.4(402)	36.3(370)
standard deviation in N/mm² (kgf/cm²)	4.2(43)	2.9(30)	3.5(36)	1.6(16)	4.8(49)
coefficient of variation in %	10	8	10	3	13
splitting tensile strength					
number of tests	3	3	4	3	4
average in N/mm² (kgf/cm²)	3.2(33)	3.6(37)	3.7(37.7)	3.38(34.5)	3.65(37.2)
standard deviation in N/mm² (kgf/cm²)	0.17(1.7)	0.37(3.8)	0.15(1.5)	0.33(3.4)	0.33(3.4)
coefficient of variation in %	5	10	4	10	9

* actually not a continuous loose layer; more a sandy patch

Table 6. Results of research on drilled cores obtained from hydrovalved underwater concrete.

job	XI	XII
composition of the concrete		
cement content in kg/m³	400	325
fineness modulus of the aggregate	5.6	5.35
water/cement ratio	0.38	?
slump in mm	100	80–140
concreting quantity in m³	5250	220
cores		
total length in m	4.50	1.70
number of loose layers	0	0
loose layers per linear m of core	0	0
compressive strength		
number of tests	13	8
average in N/mm² (kgf/cm²)	36.9(376)	31.6(322)
standard deviation in N/mm² (kgf/cm²)	6.9(70)	2.5(25)
coefficient of variation in %	19	8
splitting tensile strength		
number of tests	13	2
average in N/mm² (kgf/cm²)	3.52(35.9)	3.16(32.2)
standard deviation in N/mm² (kgf/cm²)	0.45(4.6)	0.06(0.6)
coefficient of variation in %	13	2

Table 7. Results of research on drilled cores obtained from skip-placed underwater concrete.

job	III	V	VI	VIII
cofferdam No.		E	3	
composition of the concrete				
cement content in kg/m³	375	325	400	400
fineness modulus of the aggregate	?	5.6	5.0	5.8
water/cement ratio	?	0.52	?	0.46
slump in mm	120	?	140	110
concreting quantity in m³	270	900	78	860
cores				
total length in m	1.65	1.65	1.75	1.25
number of loose layers	2	3	4	3
loose layers per linear m of core	1.21	1.82	2.29	2.40
compressive strength				
number of tests	4	6	4	3
average in N/mm² (kgf/cm²)	41.2(420)	41.6(424)	43.6(445)	39.8(406)
standard deviation in N/mm² (kgf/cm²)	2.5(26)	5.9(60)	0.64(6.5)	2.4(24)
coefficient of variation in %	6	14	2	6
splitting tensile strength				
number of tests	5	5	5	3
average in N/mm² (kgf/cm²)	3.8(39,0)	3.37(34,4)	4.18(42.6)	3.38(34.5)
standard deviation in N/mm² (kgf/cm²)	0.46(4.7)	0.51(5.2)	0.27(2.8)	0.30(3.1)
coefficient of variation in %	12	15	7	9

Table 8. Results of research on drilled cores obtained from Prepakt concrete.

job	I	II	IV
cofferdam No.			2
grout			
cement content in kg/m^3	750	750	750
intrusion aid in kg/m^3	5	5	7.5
fineness modulus of the aggregate	1.90	1.95	1.95
coarse aggregate (gravel) particle size in mm	30–80	30–80	30–200
concreting quantity in m^3	700	4500	85
cores			
total length in m	0.90	5.10	1.35
number of loose layers	0	4	3
loose layers per linear m of core	0	0.78	2.22
compressive strenght			
number of tests	4	8	2
average in N/mm^2 (kgf/cm^2)	13.0(133)	14.3(146)	17.9(183)
standard deviation in N/mm^2 (kgf/cm^2)	4.4(45)	3.3(34)	0.9(9)
coefficient of variation in %	34	23	5
splitting tensile strength			
number of tests	0	3	4
average in N/mm^2 (kgf/cm^2)	–	1.79(18.3)	1.02(10.4)
standard deviation in N/mm^2 (kgf/cm^2)	–	0.18(1.8)	0.12(1.2)
coefficient of variation in %	–	10	12

The average results obtained with each concreting method, over the period from 1966 to 1972, are summarised in Tables 4 to 8. The following inferences can be drawn from these data.

The highest average compressive strengths were achieved in tremie-placed underwater concrete (eight cofferdams). Lower average strengths were obtained with pumped concrete (four cofferdams) and hydrovalved concrete (two cofferdams). These lower strengths are probably due to the fact that in these two last-mentioned methods the concrete employed is generally of less plastic consistency and therefore, since it is not compacted, contains a higher proportion of voids.

With all three above-mentioned methods (tremie, pump, hydrovalve) a homogeneous concrete was produced (few loose layers).

High strengths were likewise found in concrete placed by means of skips (four cofferdams). This concrete contained relatively numerous loose layers (about ten times as many as in the concrete placed by the three methods referred to above).

With the grouting methods of concreting the compressive strengths were found to be definitely inferior to those obtained with the non-grouting methods. This lower strength is probably due to poorer bond between the grout and the coarse aggregate. Basing oneself on the mix proportions employed, higher strengths could reasonably be expected. The average compressive strengths determined on structures concreted by such methods in the Netherlands (15.1 N/mm^2) are at any rate lower than Gerwick's [15] for grouted concrete, namely, 18–28 N/mm^2 (180–280 kgf/cm^2).

Table 9. General survey of the results of the research on drilled cores in the period 1966–1972.

method of concreting	number of cofferdams	average compressive strength in N/mm^2 (kgf/cm^2)	average number of loose layers per linear m of core
tremie method	8	47.4(483)	0.17
pump method	5	37.8(385)	0.07
hydrovalve method	2	34.3(350)	0
skip method	4	41.6(424)	1.93
Prepakt method	3	15.1(154)	1.00

In the Netherlands no underwater concrete construction by the Colcrete method of grouting was carried out in the 1966–1972 period. Experience gained with one structure for which this method was used, prior to 1966, indicates that with Colcrete grouted concrete approximately the same quality is obtained as with Prepakt grouted concrete.

4.4 Splitting tensile strength and bond

In general, higher values (3.5–4.0 N/mm^2) were found for the splitting tensile strength of underwater concrete than for that of concrete with the same compressive strength placed above water. This better result for underwater concrete is probably due to good curing (hardening under water).

The Committee did not carry out research on the bond of underwater concrete to reinforcement, etc. In the literature [25] it is reported that tremie-placed concrete adheres well to embedded steel piles and to old concrete. For steel piles a permissible bond stress of 0.15 N/mm^2 (1.5 kgf/cm^2) can be adopted, which figure is based on tests in which bond strengths of approximately 0.4 N/mm^2 (4 kgf/cm^2) were found.

It would appear desirable to use deformed reinforcing bars in underwater concrete, one reason for this being the risk of contamination of the reinforcement with dirt in the cofferdam.

4.5 Watertightness

The watertightness of concrete is determined by the pore distribution in the concrete, the pore width, the presence of inhomogeneities and the presence of cracks.

The (natural) compaction of concrete with a slump of 150 to 200 mm placed under water is good (see 3.1), the more so as the air bubbles enclosed in the concrete are compressed. Besides, in underwater concrete of suitable composition, there is sufficient fine material (cement + filler) to ensure good watertightness.

Thanks to this fine material, too, a concrete mix is obtained with minimum segregation susceptibility – though this does not necessarily guarantee a homogeneous concrete. The method of construction employed (concreting procedure and careful workmanship) is a much more important factor. Loose layers can be pervious and thus allow water to penetrate through the concrete. Continuous cracks extending all the way through the concrete will of course also assist water penetration.

4.6 Evenness of the concrete surface

The evenness of the concrete surface depends on the consistency of the concrete and the method used for placing it under water. With a slump of 150 mm the concrete will repose at slopes of about 1:5. In such circumstances the evenness of the surface will depend only on the spacing of the placing points. Hence it follows that the most even surfaces can be obtained with the hydrovalve and with the skip placing method.

With the other methods the evenness will be less good and will depend, inter alia, on the spacing of the concreting pipes. For slopes of 1:5 and a pipe spacing of 3 m differences in level of about 300 mm can be expected to occur (see Chapter 5).

This aspect must of course be duly taken into consideration when top reinforcement is installed in underwater concrete.

5 FLOW PATTERN OF CONCRETE DEPOSITED THROUGH A PIPE

In order to gain some insight into the flow pattern of concrete placed under water by pouring it through a pipe, calculations were carried out with the aid of the theory of viscous fluids. For this purpose the equations of motion in a model in the shape of a symmetrical surface of revolution with moving upper edge was solved by means of an iterative finite-difference procedure.

From the calculated results it is possible to draw some conclusions as to the method of deposition, the immersion depth of the tube, and the quantity of concrete to be deposited.

Although the calculated results appear reliable, their value must not be overrated. To treat fresh concrete as a viscous fluid in such calculations is a rough approximation.

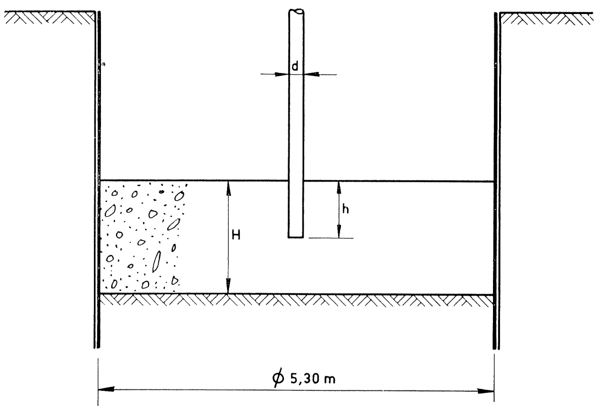


Fig. 7. Model for flow calculations.

The calculations were based on the following model (Fig. 7):

- the cofferdam is circular, with a diameter of 5.30 m;
- at the start of the calculations a layer of concrete is assumed to be already present in the cofferdam; the thickness of this even and horizontal layer is H;
- at the centre of the cofferdam is a vertical concreting pipe with a diameter d (= 300 mm);

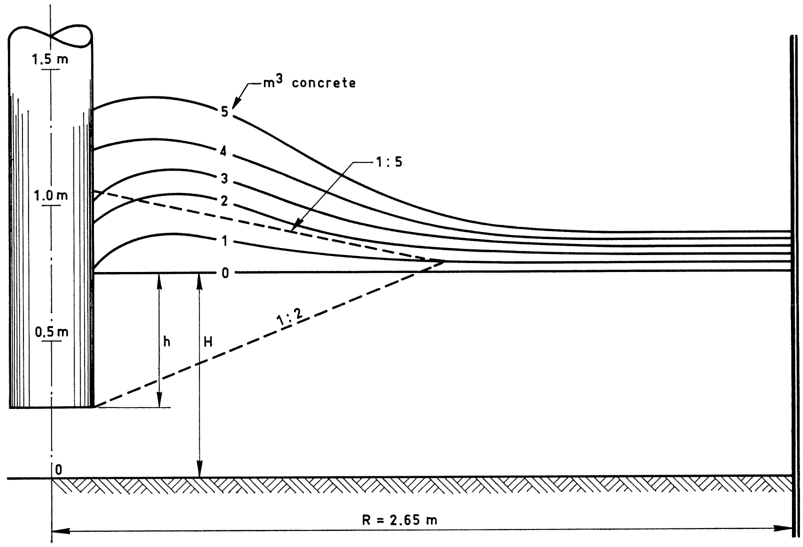


Fig. 8. Results of flow calculations for H = 750 mm, h = 500 mm and d = 300 mm.

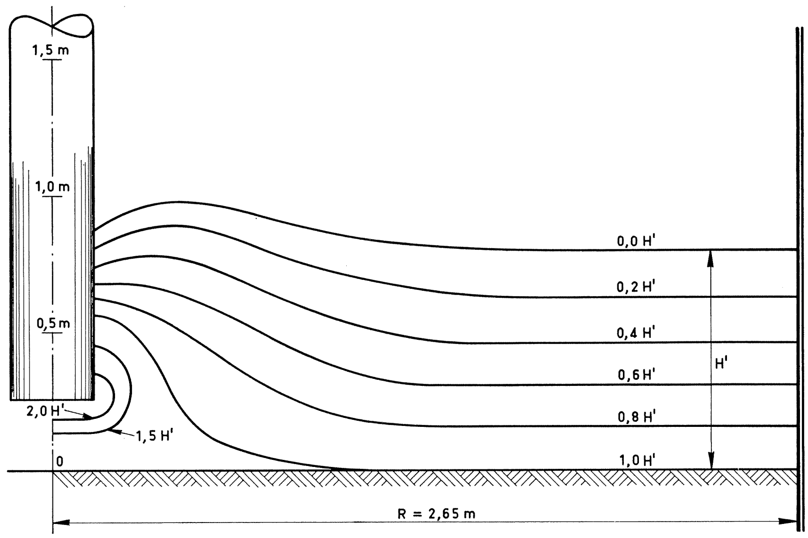


Fig. 9. Lines of equal pressure after placing about 1.5 m³ of concrete for H = 750 mm, h = 500 mm and d = 300 mm.

- at the start of the calculations the pipe is embedded a distance h in the concrete;
- the effect of the dead weight of the concrete is neglected;
- the viscosity of the fresh concrete is 0.1 m^2/s.

Fig. 8 shows, by way of example, the results of the calculations for $H = 750$ mm, $h = 500$ mm and $d = 300$ mm. In fig. 9 the lines of equal pressure are indicated for the situation when about 1.5 m^3 of concrete has been placed.

Around the tube the surface of the concrete bulges up. This bulging extends to a distance equal to about $2h$ measured from the perimeter of the pipe; beyond this distance the surface of the concrete rises but remains virtually horizontal as concreting proceeds. The calculations indicate a similar pattern of behaviour for other pipe immersion depths.

In order to estimate the effect of the distance between the pipe outlet and the bottom of the cofferdam upon the shape of the concrete surface, some calculations were carried out for various values of this distance between 250 mm and 750 mm, for an immersion depth $h = 1100$ mm. The shape of the concrete surface was found to be independent of the distance from pipe outlet to cofferdam bottom. From this it can inferred that a less steep concrete surface will not be obtained by mounting under the pipe outlet a deflector which compels the outflowing concrete to move is a horizontal direction. As an alternative, mounting a baffle plate around the pipe is impracticable because of difficulties in connection with raising the pipe.

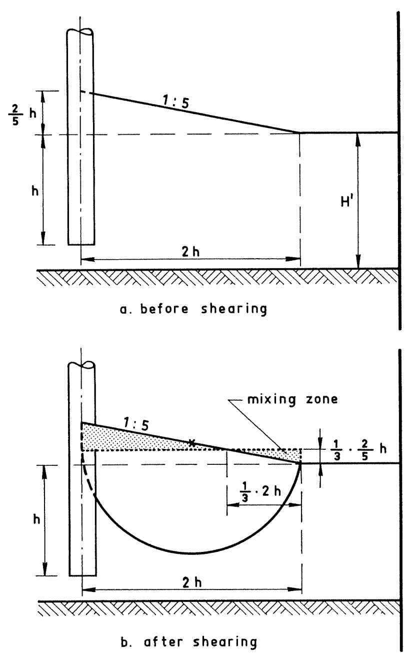


Fig. 10. Shearing of concrete at a 1:5 slope.

If there is sufficient immersion depth, the concrete feed into the cofferdam will take place in such a manner that concrete which is at the surface will remain at the surface (see Fig. 9). From this flow pattern it is apparent that any reinforcement to be incorporated into the concrete should be fixed so as not to undergo any upward movement.

As regards the effect of the dead weight of the concrete it can be inferred from Fig. 8 that the concrete surface in the vicinity of the pipe becomes steeper and steeper according as more concrete is fed through the pipe. As a result, stresses will develop in the concrete and cause shearing within it.

It is assumed that the concrete will shear along a semicircular surface, as occurs also in the sliding of earth masses. This movement will occur when a certain limiting value of the shearing stress is exceeded; this value is taken to be 0.5 to 1.0×10^{-4} N/mm^2 (0.5 to 1.0×10^{-3} kgf/cm^2) [26].

It was calculated that such shearing will occur already when the concrete reaches a 1:5 slope (see Fig. 10). Because of the symmetry of the sliding mass (surface of revolution) the centre of gravity thereof is located farther from the pipe than is the centroid of the semicircle. Mixing of the concrete occurs at a distance $2h$ from the pipe, the depth thus affected being theoretically $\frac{1}{3} \times \frac{2}{5} h = 0.13h$.

From the example illustrated in Fig. 8 it appears that a 1:5 slope, and therefore shearing, will occur already after 1.5 m^3 of concrete has been placed. In this case the immersion depth was $h = 500$ mm. If it were stipulated that no shearing must occur, it would mean that only a very small quantity of concrete could be deposited through each pipe. The occurrence of mixing within the concrete will therefore have to be accepted. In the mixing zone the concrete, so long as it has not stiffened, will be able to coalesce. With sufficient concreting capacity to maintain an adequate rate of feed it will be possible to ensure that this will happen.

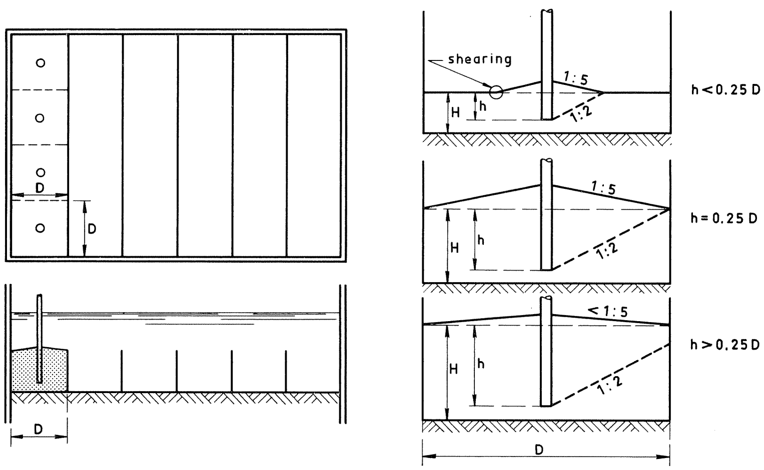


Fig. 11. Schematic subdivision of the cofferdam into concreting bays and sections through a bay at different immersion depths of the pipe.

When a large slab (with a thickness H) has to be constructed under water, it may be subdivided into a number of bays, each with an area $D \times D$ m^2, which are concreted individually (Fig. 11). If one pipe is used to fill each bay, the quantity of concrete that must be fed to each pipe will be D^2H m^3. Shearing of the freshly placed concrete will occur if the immersion depth of the pipe is less than $0.25D$. If the clear space below the pipe outlet is 250 mm this shearing will take place until a slab thickness of $(0.25D+0.25)$ m has been reached. Now if it is assumed that in t hours the concrete has stiffened to such an extent that shearing still just has no detrimental effect upon the eventual quality of the concrete, it follows that the concreting capacity should be not less than $D^2(0.25D+0.25)/t$ m^3 per hour and per placing pipe. Only if H is less than $(0.25D+0.25)$ m does the requisite concreting capacity become D^2H/t m^3 per hour.

For concreting a slab with dimensions of 32 m $\times$ 12 m $\times$ 2 m the following procedure could be adopted:

- the cofferdam is subdivided into bays measuring 4 m $\times$ 12 m $\times$ 2 m;
- in each bay concreting is done through three pipes, therefore $D = 4$ m;
- if the concrete remains workable for 2 hours, the requisite capacity per pipe is $D^2(0.25D+0.25)/t = 4^2 \times (0.25 \times 4+0.25)/2 = 10$ m^3 per hour, so that a total concreting capacity of 30 m^3 per hour will be needed; for a slab which is 1 m thick a capacity of $3D^2H/t = 3 \times (4^2 \times 1)/2 = 24$ m^3/hour will suffice.

It should be borne in mind, however, that better surface evenness is obtained according as the pipe immersion depth is greater. With the pipe spacing of 4 m, as envisaged here, slopes of 1:5 would be formed if an immersion depth of 1 m were used. For the slab thickness of 2 m it is, if desired, possible to increase the immersion depth to 1.75 m, so that much flatter slopes than 1:5 would be formed.

If the cofferdam is not subdivided into concreting bays, the concrete will be placed with an advancing front sloping at 1:5, for example (see Fig. 12). Shearing will likewise occur in this slope. If the condition is imposed that such shearing is not allowed

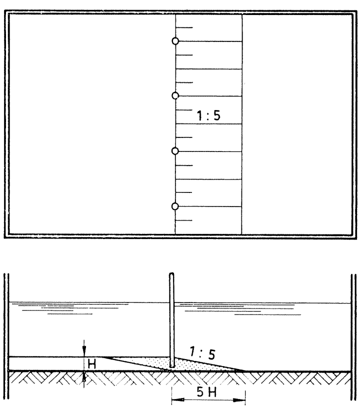


Fig. 12. Placing underwater concrete with an advancing front.

to occur later than t hours after concreting, i.e., after the concrete concerned has been deposited in the slope, this can be satisfied by choosing the rate of placing at least so high that the concrete which at first is at the toe of the slope will, on completion of concreting, have arrived at the final surface of the concrete.

This means that, for a 1:5 slope and a slab thickness H, the concreting capacity per metre width of the cofferdam should be $5H^2/t$ m^3 per hour.

In the above example the capacity would thus have to be $5 \times 2^2 \times 12/2 = 120$ m^3 per hour. But if the slab had to be only 1 m thick, the requisite capacity would be merely 30 m^3 per hour. By using a retarder the available working time of the concrete can be increased and the requisite concreting capacity thus reduced. In practice a concreting scheme will be drawn up, suited to the available capacity.

If high quality of the concrete is required and the slab to be constructed is of considerable thickness, it may be advisable to concrete it in individual bays [27]. This will, of course, necessitate extra arrangements.

If the cofferdam is not subdivided into bays, the concrete obtained is likely to be of somewhat poorer quality unless the concreting capacity is high enough to compensate for this. In the Committee's investigations on core specimens it was found that the tremie methods produced relatively homogeneous concrete possessing high compressive strength. Yet the concreting capacity used on the jobs inspected was substantially lower than the theoretically required capacity.

From this it can be inferred that a subdivision into bays or a very high concreting capacity appear necessary only in cases where very stringent demands are applied to homogeneity.

To ensure proper flow, the depth of concrete in the pipe must be at least equal to the sum of:

- the immersion depth h;
- a certain height $(0.4$ to $2.0)h$ for overcoming the friction of the concrete in the cofferdam; this height depends, inter alia, on the desired placing rates (concreting capacity); to be on the safe side it may be taken as $2\,h$;
- a height z/γ for overcoming the water pressure, where
  z = height of water over the surface of the concrete in the cofferdam, and
  γ = weight ratio of 1 m^3 fresh concrete to 1 m^3 of water;
- approximately 100 mm extra height per metre of concrete column in the pipe for overcoming the friction between the concrete and the wall of the pipe; this value depends, inter alia, on the ratio of cross-sectional area to circumference of the pipe.

The level of the concrete in the tremie pipe will therefore have to be at least $1.10\,(h+2h+z/\gamma) = 3.3h+1.1z/\gamma$ m above the outlet (bottom end) of the pipe.

A watertight base slab will generally have to have a thickness H in order to retain $2.4H$ metres of water. In this case therefore $z = 1.4H$. For the immersion depth h a value of $(H-0.25)$ m can be adopted, so that the height of the concrete in the pipe as a function of the slab thickness can be expressed as follows:

$$3.3 \times (H-0.25)+1.1 \times 1.4H/2.4 = (3.94H-0.83) \text{ m}$$

Since the surface of the water is $(2.4H - 0.25)$ m above the bottom end of the pipe, the level of the concrete in the pipe must then be $(1.54H - 0.58)$ m above the surface of the water.

For slab thicknesses up to 2 m the level of the concrete in the pipe will then be up to 2.5 m above water level. In most cases this will not present any practical problems. However, with thicker slabs the requisite height of the concrete column in the pipe in relation to the water level may be difficult to comply with. This drawback can be overcome in various ways:

- accepting a lower concreting capacity per pipe;
- placing the concrete by pumping;
- reducing the immersion depth h.

6 COST OF UNDERWATER CONCRETE

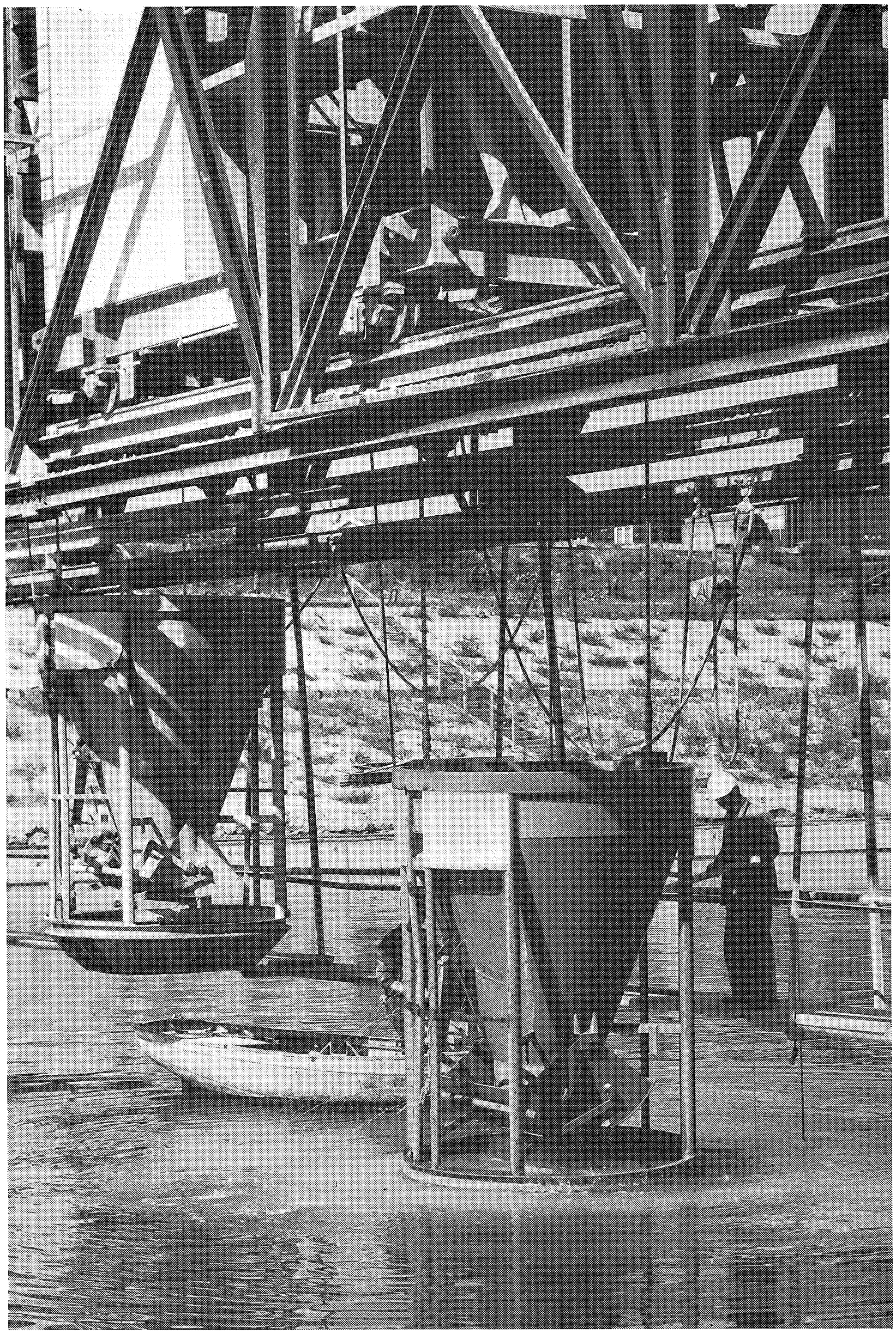
In Chapter 4 it was stated that the quality of concrete deposited under water depends, among other factors, upon the method of concreting employed. The question may be asked whether, besides the said differences in quality, there are also differences in cost. This latter aspect has been investigated for the methods most widely used in the Netherlands, namely, the skip method, the tremie method and the pumping method.

The same concrete mix compositions are, generally speaking, used in all these methods, so that material costs are the same and the cost price therefore depends only on the cost of handling and placing the concrete. The calculation of this last-mentioned cost was based on the following assumptions:

- the concrete is brought to the site in truck mixers;
- the concrete is placed in a foundation slab within a steel sheet-piled cofferdam;
- the final top surface of the concrete is 6 m below water level;
- the ground level is 1 m above water level;
- the water level in the cofferdam is kept constant by means of an overflow outlet;
- the truck mixers travel on a trackway along the cofferdam.

For calculating the cost of concreting (handling and placing) the various concrete quantities listed below were considered:

	dimensions of the slab			
quantity to be placed (m^3)	length (m)	width (m)	thickness (m)	deepest point below ground level (m)
500	50	5	2	9
1000	50	5	4	11
2000	50	10	4	11
3000	50	10	6	13
4000	50	20	4	11
5000	50	20	6	13



Skip method.

Table 10. Equipment for underwater concreting.

concreting quantity (m^3)	skip method	tremie method	pump method
500 1000	skip crane staging=working platform	tremie pipe skip crane staging, also support for pipe	concrete pump staging=working platform crane for holding and handling the pipeline
2000 3000	skip crane staging=working platform	tremie pipe skip crane 2 coupled pontoons with small derrick for holding the pipe and sounding	concrete pump staging=working platform crane for holding and handling the pipeline
4000 6000	2 skips 2 cranes 2 pontoons for sounding	2 tremie pipes 2 skips 2 cranes 2×2 coupled pontoons with small derrick for holding the pipe and sounding	2 concrete pumps 2 pontoons for sounding 2 cranes for holding and handling the pipeline

Depending on the quantity of concrete to be placed and on the method of placing, the equipment indicated in Table 10 was assumed to be used for carrying out the concreting.

For the calculation the cost of concreting was taken to comprise the cost of the preparatory arrangements for concreting, plant costs and manpower costs. The results of the calculation are presented in Table 11.

For the skip method and the tremie method the concreting costs were approximately equal for equal quantities to be placed; for both methods the cost per m^3 decreased with increasing quantity. In the case of the pump method the concreting costs were very nearly constant for different quantities to be placed, because with pumped concrete a fixed cost amount per m^3 of concrete handled must be reckoned with.

The greatest differences in concreting costs are found to exist between the skip method and the pump method for a concrete quantity of 6000 m^3, the cost of the latter being about twice that of the former. However, if the cost of the material is included in the cost comparison, the differences are much less pronounced: 1 m^3 of concrete is thus found to cost about Fl. 95.— when placed by pumping and Fl. 85.— when placed by skip, i.e., the difference is 12%.

Also, it should be borne in mind that, with pumping, concrete can be easily placed in cofferdams which are not very accessible to the other methods.

According to information supplied by the patentee, the preparatory arrangements for concreting by the hydrovalve method cost about the same as those for the tremie method.

Table 11. Cost of concreting for six different quantities of concrete placed by three different methods

quantity in m³	500		1,000		2,000		3,000		4,000		6,000	
cost per m³	Fl.	%	Fl.	%	Fl.	%	Fl.	%	Fl.	%	Fl.	%
skip method												
preparation	1.10	7.6	0.55	4.1	0.84	7.1	0.56	4.9	0.92	8.6	0.61	6.0
equipment	5.72	39.6	5.17	38.7	4.96	41.7	4.85	42.3	4.95	46.5	4.85	47.4
manpower	7.64	52.8	7.64	57.2	6.10	51.2	6.06	52.8	4.78	44.9	4.77	46.6
total	14.46	100	13.36	100	11.90	100	11.47	100	10.65	100	10.23	100
tremie method												
preparation	1.29	9.1	0.65	5.1	1.17	9.9	0.78	6.9	1.28	11.4	0.86	8.0
equipment	4.94	34.8	4.28	33.6	4.19	35.4	4.09	35.9	4.18	37.2	4.09	38.1
manpower	7.96	56.1	7.84	61.3	6.49	54.7	6.51	57.2	5.77	51.4	5.78	53.9
total	14.19	100	12.77	100	11.85	100	11.38	100	11.23	100	10.73	100
pump method												
preparation	1.10	5.3	0.54	2.7	0.99	4.7	0.66	3.2	0.61	2.9	0.40	1.9
equipment	13.05	62.7	13.00	64.5	13.75	64.6	13.75	65.7	13.75	65.9	13.75	66,6
manpower	6.65	32.0	6.60	32.8	6.51	30.7	6.50	31.1	6.51	31.2	6.50	31.5
totaal	20.80	100	20.14	100	21.25	100	20.91	100	20.87	100	20.65	100

Note:
- wages and prices as in July/August 1971 (Fl. = florin or guilder = approx. £ 0.135)
- hire of cranes and concrete pumps from third parties = current rates
- cost of crane includes crane driver
- cost of concrete pumps includes installing and pump operator

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