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Contents

EROSION OF CONCRETE

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Editorial

F. K. Lichtenberg resigned as Editor in Chief of Heron (since 1970) and has been succeeded by J. Witteveen, Deputy Director of the Institute TNO for Building Materials and Building Structures and Professor in the Department of Civil Engineering of the Delft University of Technology.

L. van Zetten has been succeeded as Secretary by G. J. van Alphen of the Department of Civil Engineering of the Delft University of Technology.

Heron continues to be jointly financed by "STEVIN" (the Laboratory of the Department of Civil Engineering of the Delft University of Technology) and "IBBC" (Institute TNO for Building Materials and Building Structures), Rijswijk (Z.H.).

It is intended to continue publishing at least four issues a year.

J. Witteveen

Preface

Partly in response to a request by Rijkswaterstaat (Netherlands Waterway and Highway Administration) the Committee C 37 of the Netherlands Committee for Research, Codes and Specifications for Concrete (CUR-VB) "Erosion of concrete" has been settled up and began its activities in March 1977.

The Committee was constituted as follows:

Ir. W. Stevelink, Chairman
Dr. Ir. J. P. Th. Kalkwijk, Secretary
Ir. P. van den Berg
Ir. J. M. van Geest
Dr.-Ing. H. W. Reinhardt
Dr. Ir. P. Stroeven
Ir. A. P. van Vugt
Prof. Dr. F. H. Wittmann
Ir. J. C. Slagter, Mentor

The following also participated:

Ir. H. L. Fontijn
Ing. M. G. M. Pat
Ir. J. P. van Stekelenburg

Dr. Ir. Y. M. de Haan was closely associated with the first stage of the Committee's activities. Under pressure of other duties he resigned from the Committee at the end of 1977, however.

The research reported in this publication was accomplished in close collaboration between the Laboratory for Fluid Mechanics and the Concrete Structures and Materials Science divisions of the Civil Engineering department of the Delft University of Technology. Ir. H. L. Fontijn has carried out an extensive literature survey the results of which have been used in the present report. The list of references at the end of this report has been taken from his study.

Dr. P. Stroeven has supervised and has analysed the standardized abrasion tests. His results are also incorporated in the present report.

The research has in part been financed by Rijkswaterstaat, for which the CUR-VB wishes to express its indebtness.

This publication is based on CUR-VB Report No. 99 "Erosie van Beton".

EROSION OF CONCRETE

Summary

Within the context of this research, "erosion" is taken to mean the wearing away of a surface by water and the sediments carried along in it. In structures in the sea, erosion may be a phenomenon of attack if water carrying sand and silt regularly flows to and fro past the structure. The construction of the surge tide barrier in the Oosterschelde (Eastern Scheldt) was the direct reason for undertaking this research.

Two testing methods were applied in this research, namely, abrasion testing on an Amsler machine and erosion testing in a specially built circular flume.

The research comprised 15 concrete mixes with the following variables: the cement content, the water-cement ratio, the aggregates, the curing treatment and the addition or absence of an admixture. The 28-day cube strengths ranged from 21 to 48 N/mm^2.

All the erosion tests resulted in a generally similar erosion behaviour pattern: initially (in the first 40 hours) there was considerable wearing away of the outer "skin" of the concrete (a few millimetres), after which the wear increase slowed down and was followed (after 80 hours) by a period of fairly constant rate of wear lasting to the end of the test (240 hours). The latter part of the test appeared most suitable for assessing the behaviour of a structure with an intended long working life.

The following main conclusions emerge:

- The compressive strength of the concrete has a distinct effect. According as this strength is higher the resistance to erosion also increases. A concrete of poor quality, even if only locally so, will be more quickly attacked by erosion.
- The curing treatment is of influence on erosion behaviour, especially in concrete having a low compressive strength. Good curing improves erosion resistance, thus reducing the effect of compressive strength. On the other hand, in specimens made of high-strength concrete there was no demonstrable effect of curing.
- There was no ascertainable effect associated with the addition or absence of an admixture to the concrete mix, apart from the attendant variation in compressive strength.
- There was a slight relation between the quantity of aggregate and the erosion resistance. This trend was clearly manifest for concrete with low cement content (so that the water-cement ratio was higher and the strength accordingly lower). For concrete made with coarse gravel aggregate the results are less clear. If the conclusions are confined to those concretes which have approximately equal strength, the effect of the quantity of aggregate on the erosion resistance is no longer detectable. Coarse gravel concrete then behaves no differently from concrete made with finer aggregate.

Erosion of concrete

1 Introduction

A surge tide barrier is to be built in the last major estuary, the Oosterschelde (Eastern Scheldt), to be dammed under the Delta Scheme of coastal protection and flood prevention works in the south-western part of The Netherlands. It has been decided to construct this barrier in the form of a series of gates installed between piers (vertical supporting members). Under normal weather conditions these gates will be open, allowing the sea water to flow into and out of the estuary, twice a day in each direction, as determined by the tides. At times of dangerously high sea levels the gates are to be kept closed.

According to calculations by Rijkswaterstaat (Netherlands Waterways and Highways Administration) the flow velocity in the openings between the piers of the barrier will range from 3 to 5 m/s, possibly attaining higher values at particularly unfavourable locations. The water carries abrasive material along with it, sand in particular. There are fears that the relatively high velocity of the water, together with its sand load, may cause substantial erosion of the concrete.

These considerations induced Rijkswaterstaat, in collaboration with CUR-VB, to undertake a detailed investigation of the phenomenon of erosion of concrete. For this purpose a study of the literature was carried out, and various foreign organizations such as research institutions and authorities with major water engineering structures under their administration, were asked to communicate their experience. Despite the information obtained as a result of these inquiries, it was not possible to obtain a clear-cut picture of the anticipated erosion attack behaviour of the concrete in the surge tide barrier. This being so, it was decided by Rijkswaterstaat and CUR-VB to carry out research of their own on the subject, the results of which are reported here.

2 The known facts

2.1 *General consideration of the phenomenon*

The phenomenon under discussion comprises the erosive action of water containing an abrasive material, as well as the behaviour of concrete and the methods of testing the damage to structures exposed to such action. Two different forms of attack may occur, namely, erosion and/or cavitation, which can be defined as follows:

- As envisaged in this research, erosion is taken to mean the wear (attrition) that a surface undergoes by the action of water and the sediments carried along in it.
- Erosion by cavitation denotes: The damage suffered by the surface in consequence of the implosion of gas or vapour bubbles, which may give rise to high pressures. Gas bubbles may form in regions of reduced pressure, e.g., where flow velocity acceleration or detachment (separation) of streamlines occurs. Attack due to cavitation is usually local and characterized by circular cavities.

The present research is concerned with erosion by water and the sediments carried along with it, while cavitation will not be considered. This approach is justified in that cavitation usually occurs only at higher water flow velocities than those in the openings of the surge tide barrier in the Oosterschelde. The possibility that cavitation may nevertheless occur in certain localized parts of the structure cannot be ruled out, however.

The action of erosion can be conceived as follows: The solid particles, in so far as they are not in suspension, will be dragged along the surface of the structure, sometimes performing a rolling or leaping motion. At irregularities of the surface the particles will impringe upon the concrete and may dislodge fragments of it at edges or projecting features. Also, at high velocities, turbulence may cause underpressure in the water, so that tensile forces are exerted on the concrete. The rougher the surface, the more likely is such a phenomenon to occur. The loading to which the surface is subjected is therefore of a multiple character: abrasion, impact, tension. Each component of the concrete is subjected to this loading – the hardened cement paste as well as the aggregates. The structure of concrete at a surface which has been in contact with the mould or formwork is different from that in the interior of the concrete: there will be more hardened cement paste and fine aggregate constituents according as the distance to such a surface is less. The outer "skin" of the concrete will consist chiefly of hardened paste and fine particles.

The probability of the presence of small cracks due to shrinkage and cooling is greatest in this outer zone. The progress of erosion in course of time may then be as follows: Since the strength and density of the matrix (hardened cement paste plus fine particles) are inferior to those of the aggregate, the outer skin can be expected to wear away more rapidly than a specimen of concrete taken from the interior of a structural member and exposed to similar conditions. Once the outer skin has been removed, the further erosion will (for constant conditions of erosion load) proceed at an unvarying rate. On the other hand, the surface of the concrete is at first smooth, thus offering few points of attack to the erosive action. After a time, however, the surface will become roughened and the aggregate exposed, so that the gravel particles carried along by the water will have more opportunity to impinge upon the aggregate, with the result that the erosion is intensified.

To what extent the erosive attack to which an actual structure is subjected in the sea proceeds in this same manner as the erosion of test specimens is a question that cannot be answered with certainty. Since the particles carried along in sea water are much smaller in size (and therefore in mass and inertia) than those used in the tests, the action exercised by them will be largely abrasive in character, much less impactive. Edges and corners of exposed aggregate particles will therefore probably not be chipped off, but they will be gradually worn away. The amount of wear that occurs, and indeed the question whether a process of wear gets started at all, will thus depend largely on the hardness of the abrasive material and on that of the material subjected to the abrasive action thereof. Hardened cement paste can be presumed to be less hard than the material particles carried along in the sea, whereas the aggregate in the concrete (quartz) is likely to be just as hard as those particles. This was also the case in the flume tests, only the size of the particles was different. On the assumption that in both cases the hardened cement

paste is the more easily attacked material, under the conditions encountered in the sea the attack of the hardened paste would continue to proceed more rapidly than that of the aggregate because only abrasive action occurs, whereas in the flume it may be that the hardened paste and the aggregate wear away at the same rate because the impactive action developed here causes the aggregate particles to wear away more quickly than abrasive action alone.
Before the test results can be reliably translated into reality as regards the magnitude and time-related behaviour of the phenomenon, it will be necessary to make a closer study of the erosion mechanisms. At the present time the results allow only a relative classification, assuming the mechanisms in the test and reality to be approximately similar.

2.2 *Literature study*

For the sake of readability, the reference numbers of the literature consulted have not been included in the following summary. The complete list of references is given in Chapter 6, however.

- Experience with existing structures as regards the erosion of concrete by running water (carrying sediment) is of a rather fragmentary character; reports are confined to special cases, more particularly those associated with (serious) damage, which are difficult to generalize. For the determination of abrasion resistance, laboratory tests are in general superior in so far as they are (more) systematic, but as they are performed on a reduced scale and generally with increased erosion intensity, they can only very imperfectly reproduce the phenomenon "abrasion by scouring action of solids transported along the sea bed".
- The properties of the abrasive material such as hardness, shape, weight, are important.
- The dynamic behaviour of the attack also causes differences in erosive effect. A distinction is to be drawn between impactive and abrasive action.
- There is a difference in further attack between smooth concrete surfaces and those which have already been eroded.
- Recommendations for achieving good erosion resistance are: The cement content of the mix should not be too high. Higher compressive strength makes for better erosion resistance. The concrete mix should be homogeneous and contain only the minimum of fine constituents. It is desirable to use coarse and hard aggregates.
- The use of streamlined shapes is recommended.
- Transition from rolling transport of abrasive material to transport in suspension reduces erosion.
- High-strength concretes and/or concretes strengthened with plastics have higher erosion resistance. Coatings or facings of other materials applied to concrete also have a favourable effect.
- The laboratory tests included tests with sandblasting, rolling and impactive actions, both under wet and under dry conditions.
- The cases of attack reported in the literature relate mainly to dams, more particularly

in stilling pools. The amount of erosive removal of concrete ranged from a few millimetres to 2 metres after about 2000 hours.

2.3 *Foreign contacts*

In order to supplement the information derived from the literature with additional recent experience, contacts were established with West Germany, Britain, France, Austria, the U.S.A., the U.S.S.R. and Switzerland.

From Switzerland came information on erosion tests which inspired the testing procedure adopted in our own experimental research.

Furthermore, research at Stuttgart has shown that a function of the form $s = at + btv^c$ suitably describes the wear due to erosion. In this function: a is the proportion assignable to rolling or abrasive action and b is the effect due to impact against the particles, while v is the flow velocity of the water and t denotes time. The results obtained with concrete of class B 37.5 are presented in Fig. 1.

Further information from abroad did not shed any fresh light on the subject, but merely confirmed the experience reported in the literature.

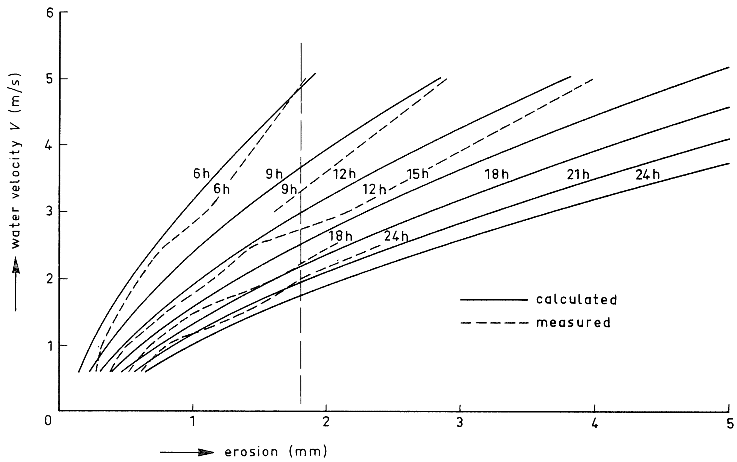

Fig. 1. Erosive wear of concrete. Results of Röhnisch and Vollmer [45].

3 Testing methods

3.1 *Erosion by running water with abrasive material*

This test endeavours to simulate reality as closely as possible by subjecting the concrete test specimens to water together with abrasive material (sand and gravel) flowing over them. The choice of conditions involves intensified erosive action, so that the results can be compared with one another, but translation of the results into reality as regards the time-related behaviour of the phenomenon is not possible. This testing method is very similar to that employed by Gardet and Dysli [6].

Experimental set-up and procedure:
Twelve segment-shaped specimens, each with an area of about 0,5 m^2 and provided with adjustable feet, are placed horizontally on the bottom of a circular flume (open channel) with an outside diameter of 4 m and a rectangular cross-section, as shown in Figs. 2 and 4. The joints between the specimens range in width from zero to a few millimetres. After testing, the water used in the test can be discharged through these small gaps and via a circulating system. When the water is at rest, the top surface of each specimen is 0,30 m below the surface of the water.

To facilitate measurements with a measuring frame, each specimen is provided with three reference points, each in the form of a pointed stud in a cylindrical pocket covered by a plug whose upper face is flush with that of the concrete.

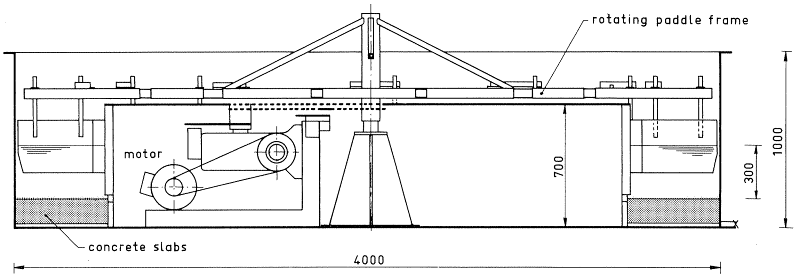

Fig. 2. Section through flume apparatus.

Three series of specimens are tested, i.e., 36 specimens in all, made from different concrete mixes. With regard to the differences between them the use of a plasticizer (as an admixture for lowering the water-cement ratio), the maximum aggregate particle size and the manner of curing the specimens are important factors.

The object is to find out for which concrete mix, and possibly for which manner of curing, the abrasive action of the material carried along with the water is least severe, so that the least erosion-susceptible type or grade of concrete can be chosen for use in civil engineering structures exposed to erosion.

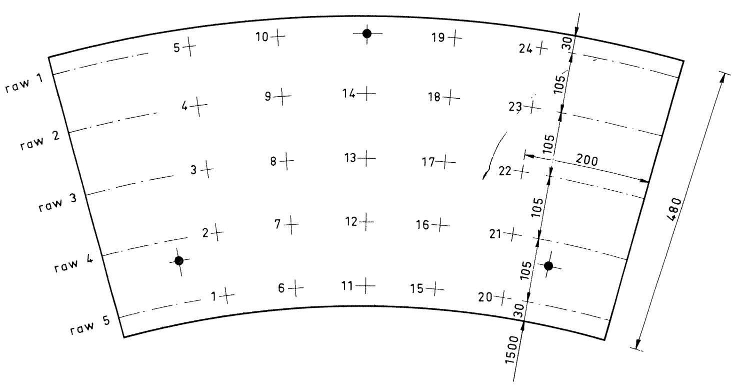

Fig. 3. Location of measuring points on each specimen.

Measurements of differences in level:
These measurements are performed with the aid of a steel measuring frame designed to obtain measurements at 24 points in each operation. The locations of the measuring points are shown in Fig. 3.

Vertical paddles mounted on a rotating assembly extend to a depth of 0,15 m below the surface of the water. The speed of rotation, and therefore the flow velocity of the water in the flume, can be steplessly controlled by means of an electric motor and gearbox. The revolutions are counted, thus providing a check on the speed at which the paddles travel. The motor runs at 18 r.p.m. The average speed of the paddles is 3,5 m/s. They are all set a an angle of 30° in relation to the radial direction in order to reduce the high water level that would otherwise develop at the outer perimeter in consequence of centripetal forces. With this system of water in the flume performs a helical motion and carries along a total quantity of 50 kg of river gravel as abrasive material. Thus there is about $\frac{1}{4}\pi(4^2-3^2)\times 0{,}30 = 1{,}65$ m^3 of water over the specimens; its gravel content is $50/2{,}65\times 10^3 = 0{,}019$ m^3, i.e., a ratio of water to gravel of 87 : 1.

The results of each set of measurements, together with the date and a measurement reference number, are recorded on punched tape. On completion of all the measurements the tapes are processed in a computer.

The reduction in mass due to erosion of the test specimens is determined by weighing under water.

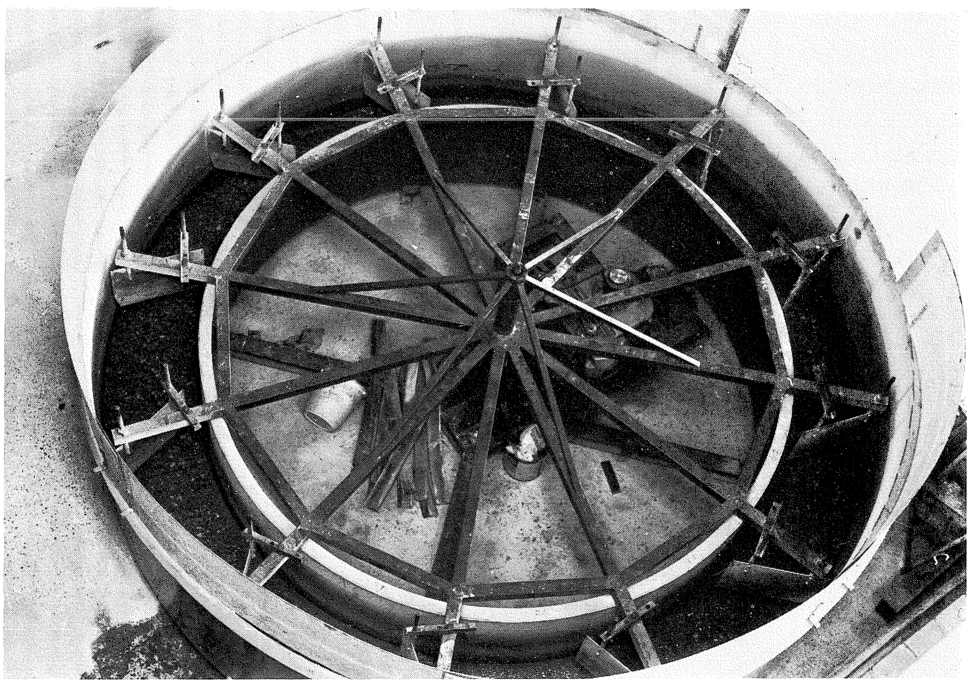

Fig. 4. Test flume viewed from above. The direction of rotation is anticlockwise.

3.2 *Erosion due to uniform abrasion*

In these tests the resistance to abrasion was determined by means of the Amsler test (Netherlands Standard N 502 and German Standard DIN 52108). This method is used for, among other purposes, the determination of the wear resistance of brick, concrete flagstones, natural stone, etc.

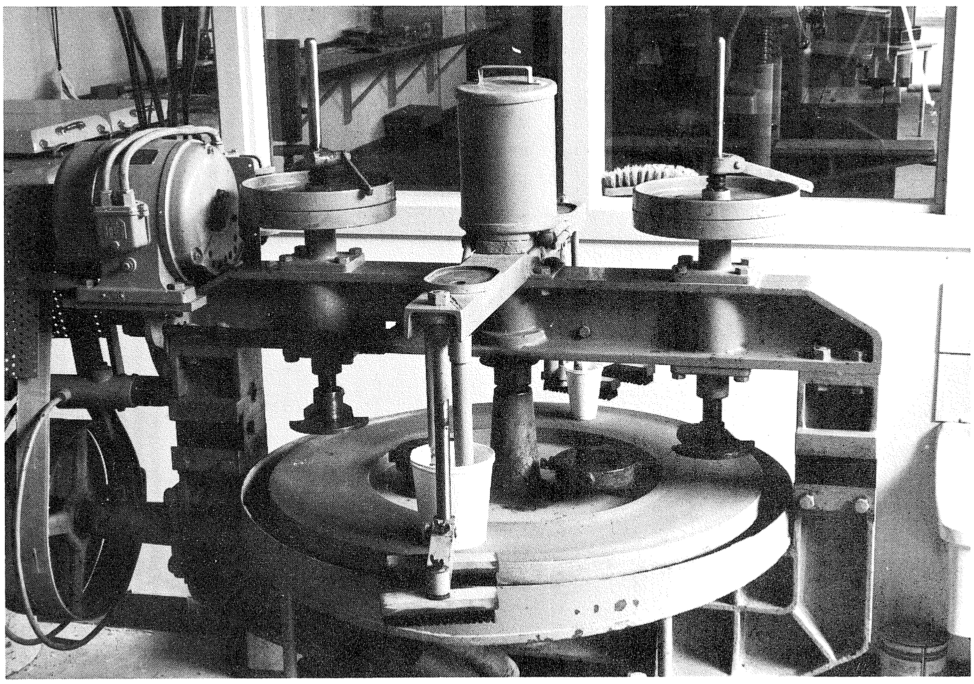

Fig. 5. Abrasion test apparatus.

After being subjected to a number of revolutions corresponding to an abrasion distance of 500 m the specimens, with an area of about 5000 mm^2, were rinsed in water and measured.

4 Experimental research

To date, 15 concrete mixes have been investigated in the erosion flume and by means of the abrasion test. In addition, the associated check tests on the fresh and on the hardened concrete have been performed. The results have been plotted in graphs which give information on the amount of wear occurring in course of time, the effect of the quality of the concrete, and the effect of curing upon the wear [50].

4.1 *Material data of the various concretes*

The first six mixes are closely similar to those which could be considered for use in the

Oosterschelde and were designed in accordance with all available knowledge from the literature and from our own experience. In the next three mixes it has been endeavoured to obtain a low and a high concrete strength in order to obtain, by interpretation of the results, two extremes for reference, thus enabling various influencing parameters to be more clearly identified.

On examination of the results yielded by these two series of erosion tests, the differences in the various concretes under investigation turned out to be too small. It was accordingly decided to carry out a third series of tests in which both the cement content (portland blastfurnace cement "A") and the water-cement ratio of the mixes were varied within wider limits.

The data for the various concrete mixes are listed in Table 1. The average grading curves of the normal as well as those of the coarse gravel mix are presented in Fig. 6.

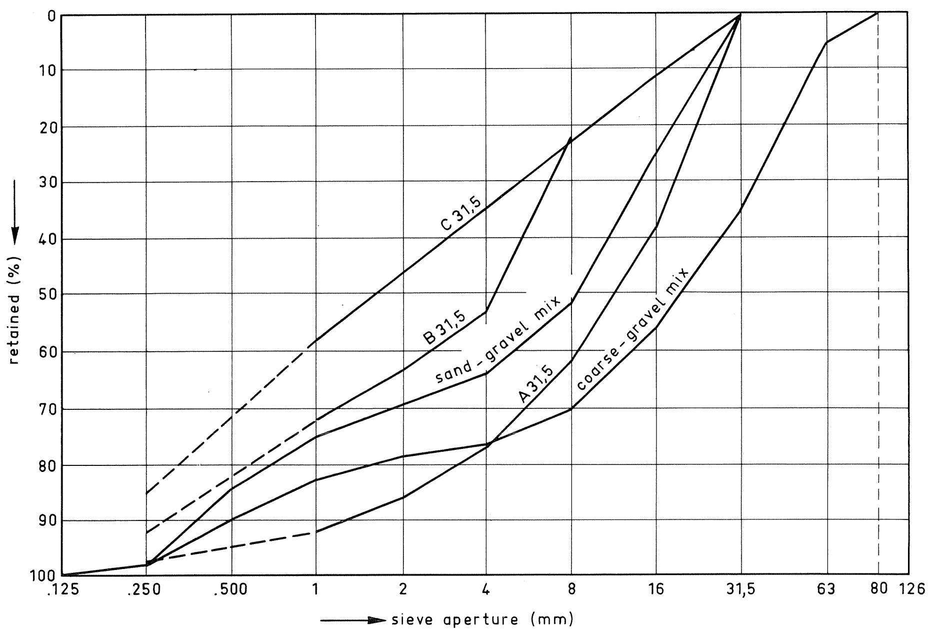

Fig. 6. Grading curves of the various concretes, lines A, B,C according to Dutch standard VB 1974.

Curing:

The specimens of the mixes 1–6 and 10–15 were covered after casting so as to prevent drying of the fresh concrete. After 1 or 2 days they were demoulded and were then stored for at least 2 weeks at 20 °C and 99% relative humidity. Next the specimens (12 in number) were taken to the Laboratory for Fluid Mechanics, where they were stored under water. During transport to the laboratory and during the measurements the specimens were subject to drying.

In the case of the specimens made of the mixes 7–9 six casting batches were likewise produced, each comprising two specimens, one of which was subjected to the same subsequent treatment as described above. The other specimen was not covered after

Table 1. Sumnmary of the various concretes.

mix	cement content (kg/m^3)	type of cement	water-cement ratio	% plasticizer	quantity of aggregate (kg/m^3)	compressive strength (N/mm^2)	slump (mm)	compaction index	air content %	nominal maximum particle size (mm)	aggregate-cement ratio
1	281	HA	0,55	-	1935	37,2	0	1,14	0,8	32	6,89
2	296	HA	0,48	0,40	1926	37,9	45	1,10	1,4	32	6,51
3	307	HB	0,50	-	1918	43,1	5	1,08	0,8	32	6,25
4	303	HB	0,50	0,85	1897	41,3	190	1,00	1,7	32	6,26
5	308	HA	0,37	0,85	2014	48,0	-	(1,25)	1,2	80	6,58
6	368	HB	0,37	0,85	1826	47,7	100	1,08	3,2	32	4,96
7C	266	HA	0,63	-	1938	31,2	80	1,08	1,2	32	7,27
7N	266	HA	0,63	-	1933	24,1	150	1,11	1,1	32	7,27
8C	335	HA	0,42	0,85	1825	39,2	120	1,05	4,0	32	5,43
8N	335	HA	0,42	0,85	1813	40,1	100	1,08	3,8	32	5,43
9C	384	HA	0,43	0,85	1782	44,4	140	1,04	3,2	32	4,63
9N	384	HA	0,43	0,85	1776	39,1	200	-	3,6	32	4,63
10	303	HA	0,38	0,85	1999	46,3	-	(1,21)	1,2	80	6,60
11	263	HA	0,63	-	1948	22,7	100	1,11	1,0	32	7,41
12	334	HA	0,41	0,85	1850	40,5	120	1,07	3,2	32	5,54
13	380	HA	0,43	0,85	1790	35,4		1,01	3,1	32	4,71
14	266	HA	0,63	-	1922	21,0	-	1,01	1,3	32	7,23
15	225	HA	0,63	-	1999	21,9	-	1,13	1,7	32	8,88

HA = portland blastfurnace cement class A
HB = portland blastfurnace cement class B
Plasticizer = Cretoplast SL (superplasticizer)
Mixes Nos. 5 and 10 are so-called coarse gravel mixes with nominal maximum aggregate particle size of 80 mm
The sand/gravel ratio was 35/65% for the mixes 8, 9, 12, 13 and 15 and was 38/62% for the mixes 1, 2, 3, 4, 6, 7, 11 and 14
The designation "N" appended to a mix number indicates "not cured" while "C" indicates "cured"

casting and was, up to the time of its removal to the laboratory (about 4 weeks after casting), stored in the casting shed at approx. 20 °C and 40–50% relative humidity.

As a result of this procedure a new parameter is introduced, namely, the curing treatment. This investigation would have to show whether the amount of erosion is affected by whether or not the structural members concerned are carefully covered or kept moist.

4.2 *Erosion of concrete surfaces in running water*

On account of the severer attack at the outer edge of the circular concrete test surface formed by the specimens, the erosion at that edge was greater than at the inner edge. The measuring ponts were disposed in five rows; there were 48 of these points in all (24 on each specimen). The distribution of the erosion across the specimens for mixes 1–6 has been plotted in Fig. 7.

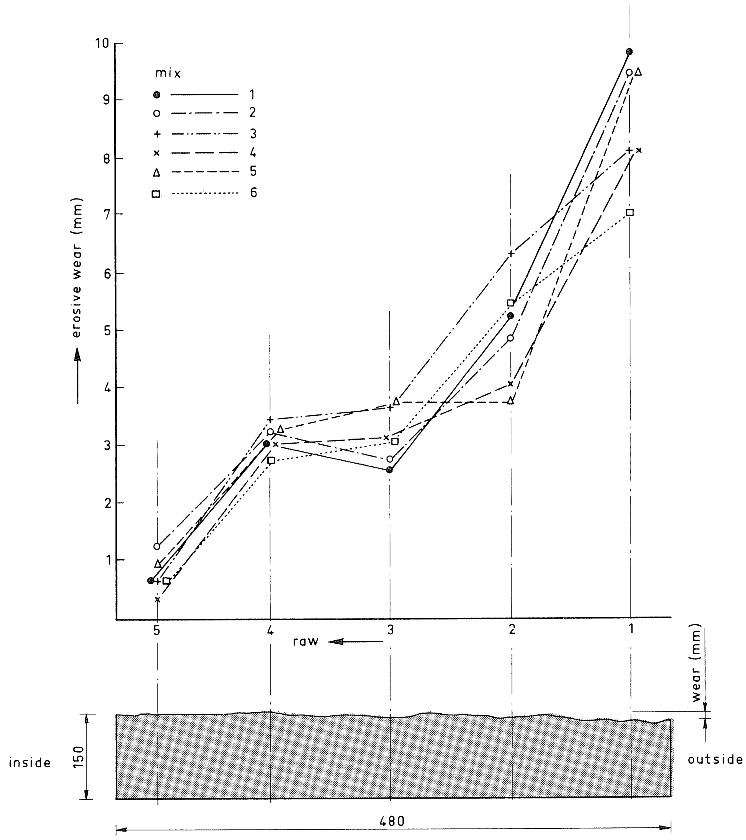

Fig. 7. Distribution of erosive attack across the specimen.

This figure shows that the area between the rows 2 and 4 is the most stable. Therefore it was decided to draw conclusion in regard to the magnitude of erosion of the specimens from the measurements of the rows 3 and 4.

The total average erosion is calculated from all 48 measuring points and, as a function of time, at first displays a non-linear behaviour (see Fig. 8) which later, after about 40 hours, changes into a steady rate of increase. For the purpose of mutual comparison of the specimens it appeared meaningful to calculate the hourly rate of erosion (increase of erosion per hour) for this linear part of the curve in the case laboratory testing under these artificially severe conditions.

Table 2 indicates the compressive strength of the concrete and the quantity of aggregate per m^3 for the various mixes. It also gives the values for the total erosion over a period of 240 hours, results of rows 3 and 4 the increase in erosion per hour, and the amount of erosion calculated from the reduction in weight. The results of the mixes 1 through 6 are calculated by lineair interpolation because the test duration of these tests was 260 hours.

The designation "N" appended to a mix number indicates "not cured" while "C" indicates "cured".

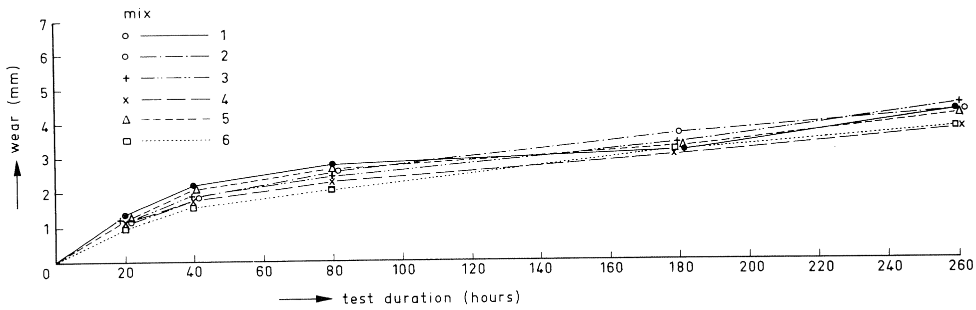

Fig. 8. Total average erosive wear per mix (approx. 48 measuring points per mix).

Table 2. Summary of data for erosion due to running water and abrasive material.

mix	compressive strength (N/mm^2)	quantity of aggregate (kg/m^3)	total erosion (mm) after 240 hours	erosion increase (mm/ 1000 hours)	erosion determined by weighing
1	37	1935	2,75	4,38	5,76
2	38	1926	2,81	5,57	4,00
3	43	1918	3,38	8,39	4,79
4	41	1897	3,00	7,24	4,65
5	48	2014	3,38	6,85	3,93
6	48	1826	2,86	6,36	4,80
7C	31	1938	3,49	6,91	7,51
7N	24	1933	5,36	10,45	7,60
8C	39	1825	2,81	7,56	4,42
8N	40	1813	2,57	7,10	5,55
9C	44	1782	2,07	4,41	5,37
9N	39	1776	2,23	4,88	3,57
10	46	2002	3,27	10,98	5,85
11	23	1947	3,60	10,33	4,54
12	41	1892	3,44	10,30	8,79
13	35	1765	3,49	11,50	5,47
14	21	1921	3,97	7,90	8,58
15	22	1997	5,66	18,95	6,03

4.3 *Loss of thickness due to abrasion of standardized specimens*

The results of the abrasion tests in terms of average values and standard deviation, together with strength data and mix composition data, form the set of basic data [48] which were subjected to various statistical procedures such as the determination of averages, standard deviations, check values, regression comparisons and confidence limits, with as parameters the abrasion value, compressive strength, water-cement ratio, aggregate-cement ratio and quantity of aggregate.

4.4 *Comparison of the results of the various tests*

In order to obtain a proper comparison of the mixes with one another, the influence of

Table 3. Comparison of results.

mix	erosion after 240 hours	erosion increase	abrasion after 500 m	erosion after 20 hours	erosion determined by weighing
1	2,75	4,38	1,45	1,35	5,76
2	2,81	5,57	1,38	1,07	4,00
3	3,38	8,39	1,49	1,10	4,79
4	3,00	7,24	1,45	0,98	4,65
5	3,38	6,85	1,44	1,03	3,93
6	2,86	6,36	1,27	0,85	4,80
7C	3,49	6,91	1,47	1,45	7,51
8C	2,81	7,56	1,35	0,71	4,42
9C	2,07	4,41	1,36	0,80	5,37
10	3,27	10,98	1,35	0,71	5,85
11	3,60	10,33	1,67	1,09	4,54
12	3,44	10,30	1,79	0,90	8,79
13	3,49	11,50	1,66	0,98	5,47
14	3,97	7,90	2,17	1,47	8,58
15	5,66	18,95	1,95	1,41	6,03
unit	mm	mm/1000 h	mm	mm	mm

variations in the method of testing per series must be eliminated. To achieve this, the average per series has been calculated and always reckoned as 100% (the first series comprises the mixes 1-6, the second comprises the mixes 7-9, and the third comprises the mixes 10-15). These figures are summarized in Table 4. They were subjected to a regression analysis with the aid of the method of least squares. The abrasion was in all cases taken as the dependent variable, i.e., as the ordinate.

Table 4. Comparison of results (percentages per series).

mix	erosion after 240 hours	erosion increase	abrasion after 500 m	erosion after 20 hours	erosion determined by weighing
1	90,8	67,7	103,0	127,0	124,0
2	92,7	86,2	97,6	101,0	85,9
3	112,0	130,0	105,0	103,0	103,0
4	99,0	112,0	103,0	92,2	99,9
5	112,0	106,0	102,0	96,9	84,4
6	94,4	98,4	89,9	79,9	103,0
7	125,0	110,0	106,0	147,0	130,0
8	101,0	120,0	96,9	72,0	76,6
9	74,2	70,1	97,6	81,1	93,1
10	83,7	94,2	76,5	64,9	89,4
11	92,2	88,6	94,6	99,7	69,4
12	88,1	88,3	101,0	82,3	134,0
13	89,4	98,6	94,1	89,6	83,6
14	102,0	67,8	123,0	134,0	131,0
15	145,0	163,0	110,0	129,0	92,2
unit	%	%	%	%	%

The results show the best correlation to exist between the erosion testing method (flume) and the Amsler abrasion test for the measurements obtained after 20 hours' erosion in the former and for those obtained after 500 m abrasion distance in the latter. In view of the time-dependence of erosive phenomena the erosion testing method gives a better picture of the progress of the erosion than the Amsler abrasion test does. This is attributable to the difference in the attritional loading applied to the concrete. In the abrasion test the concrete is subjected uniformly to wear, whereas in the erosion test it may occur that, after a time, whole aggregate particles are dislodged from the concrete over certain areas thereof.

The rate of erosion increase per hour would be a better basis for assessing the expected future erosion than the measurement of the amount of erosion that has occurred after 20 hours, but the correlation with the Amsler abrasion value is then not good.

In view of the mechanism involved in the test, it would appear preferable, for the design of concrete structures which are intended to have a long working life and for which the best concrete mix has to be found, to adopt the erosion test in the flume as the most appropriate method.

Next, linear regression analysis was applied, for which purpose the concrete quality (28-day compressive strength f'_{28}), the water-cement ratio, the aggregate-cement ratio, and the quantity of aggregate were introduced as independent variables. The results are contained in Table 5. The equations obtained are of the type $y = ax + b$, where y denotes the erosion or the abrasion test results and x denotes the independent mix characteris-

Table 5. Relation between erosion and mix characteristics of the type $y = ax + b$

	b	a		correlation coefficient $\lvert r \rvert$	$a \cdot \bar{x}/\bar{y}$
erosion after 240 hours	5,380	−0,055	compressive	0,66	−0,62
erosion increase	15,07	−0,177	strength	0,46	−0,78
abrasion (500 m)	2,306	−0,020	N/mm^2	0,76	−0,48
erosion after 20 hours	1,813	−0,020		0,74	−0,71
erosion determined by weighing	8,190	−0,069		0,42	−0,46
erosion after 240 hours	1,150	4,495	water-cement	0,56	0,65
erosion increase	3,833	9,528	ratio	0,26	0,54
abrasion (500 m)	0,820	1,488		0,59	0,46
erosion after 20 hours	− 0,003	2,167		0,85	0,99
erosion determined by weighing	3,133	5,095		0,33	0,44
erosion after 240 hours	0,118	0,507	aggregate-	0,74	0,99
erosion increase	− 1.189	1,529	cement ratio	0,48	1,17
abrasion (500 m)	0,872	0,107		0,49	0,45
erosion after 20 hours	0,032	0,162		0,73	0,99
erosion determined by weighing	4,191	0,227		0,17	0,29
erosion after 240 hours	− 7,087	0,005	quantity	0,52	2,86
erosion increase	−20,112	0,015	of aggregate	0,31	3,36
abrasion (500 m)	0,336	0,001	kg/m^3	0,19	1,23
erosion after 20 hours	− 1,899	0,002		0,46	3,59
erosion determined by weighing	17,112	−0,006		0,30	−2,27

tics. These calculations are based on the actual results presented in Table 3. It is to be noted that the relation between the erosive or abrasive attack and the compressive strength of the concrete is negative. However, in order to detect comparable influences the factor *a* must be divided by the average magnitude of attack and be multiplied by the average independent parameter. This has been done in the last column of Table 5.

The following example is given to help clarify this: The average compressive strength of the concrete is 37.1 N/mm^2 and the average 240-hour erosion is 3,31 mm. The factor *a* can then be transformed into:

$$\frac{-0{,}055 \times 37{,}1}{3{,}31} = -0{,}62 \text{ (last column in Table 5)}$$

In this way these factors are made mutually comparable.

The correlation coefficient, here expressed as an absolute value *r*, is an indication of the reliability of the relation. It is presupposed that for a value of the correlation coefficient larger than 0,7 there is at least a reasonably good relation between the values obtained.

The following conclusions can be drawn:

a. A higher compressive strength of the concrete will increase its resistance to attack.
b. The quantity of aggregate in the mix is seen to have the greatest influence. With more aggregate there is more wear.
c. Associated with a higher compressive strength is a lower water-cement ratio, and here too the relation to emerge is that a lower water-cement ratio means better quality and higher resistance to attack.
d. The aggregate-cement ratio is also of major influence. The greater the quantity of aggregate, the lower the resistance to attack.

5 Summary and conclusions

Within the context of this research, “erosion” is taken to mean the wearing away of a surface by water and the sediments carried along in it. In structures in the sea, erosion may be a phenomenon of attack if water carrying sand and silt regularly flows to and fro past the structure. The construction of the surge tide barrier in the Oosterschelde (Eastern Scheldt) was the direct reason for untertaking this research.

In the literature consulted in connection with the present research the well known testing methods are described, with which the resistance of concrete to erosive action can be determined. Without going into details it can be stated that all these methods have one feature in common: they are accelerated tests, i.e., the erosive action developed in the test is many times more intensive than will occur in reality. If the same magnitude of erosive loading were applied in the test as in reality, the test would take far too long to perform or otherwise the amounts of wear that occurred would be too small to measure.

This speeding-up of the erosion process in the test procedure is the reason why the results are hardly suitable for making predictions with regard tot the quantitative magnitude and the time-related behaviour of erosion affecting an actual structure. However, it is, on the basis of the test results, possible to compare various materials with one another, which can be useful in making a choice of materials and construction techniques to be applied in actual practice.

Two testing methods were applied in this research, namely abrasion testing on an Amsler machine and erosion testing in a specially built circular flume. Although the flume tests have many points of similarity with reality (water in motion, with abrasive material), it is nevertheless to be noted that more particularly the abrasive material causing the erosion is different from that found in the sea. In the accelerated erosion test, gravel with 31,5 mm maximum particle size is used as the abrasive, whereas the average particle size of the abrasive solids carried in sea water is about 150 microns. It may well be that the mechanism of erosive attack differs in these two cases. In the research reported here it has been presumed, however, that the classification of the various type of concrete on the basis of the test results will be valid in actual practice also.

As for the abrasion tests on the Amsler machine, it is to be noted that this standard test in no way resembles the actual conditions of running water carrying an abrasive material. From the statistical processing of the results it emerges, however, that in the first stage of erosion there is a distinctly demonstrable correlation between the results of these two testing methods respectively.

The research comprised 15 concrete mixes with the following variables: the cement content, the water-cement ratio, the aggregates, the curing treatment and the addition or absence of an admixture. The 28-day cube strengths ranged from 21 to 48 N/mm^2.

All the erosion tests resulted in a generally similar erosion behaviour pattern: initially (in the first 40 hours) there was considerable wearing away of the outer "skin" of the concrete (a few millimetres), after which the wear increase slowed down and was followed (after 80 hours) by a period of fairly constant rate of wear lasting to the end of the test (240 hours). The latter part of the test appeared most suitable for assessing the behaviour of a structure with an intended long working life.

The conclusions drawn from the abrasion test results are the same as those from the erosion test results, though there were quantitative differences.

It should be pointed out, however, that there was considerable scatter in the results, so that the conclusions cannot claim to be very soundly based.

The following main conclusions emerge:

- The compressive strength of the concrete has a distinct effect. According as this strength is higher the resistance to erosion also increases. A concrete of poor quality, even if only locally so, will be more quickly attacked by erosion.
- The curing treatment is of influence on erosion behaviour, especially in concrete having a low compressive strength. Good curing improves erosion resistance, thus reducing the effect of compressive strength. On the other hand, in specimens made of high-strength concrete there was no demonstrable effect of curing.

- There was no ascertainable effect associated with the addition or absence of an admixture to the concrete mix, apart from the attendant variation in compressive strength.
- There was a slight relation between the quantity of aggregate and the erosion resistance. This trend was clearly manifest for concrete with low cement content (so that the water-cement ratio was higher and the strength accordingly lower). For concrete made with coarse gravel aggregate the results are less clear. If the conclusions are confined to those concretes which have approximately equal strength, the effect of the quantity of aggregate on the erosion resistance is no longer detectable. Coarse gravel concrete then behaves no differently from concrete made with finer aggregate.

These conclusions are in agreement with the information found in the literature. There, too, the *compressive strength* is reported as the main factor with regard to erosion behaviour.

As for the *composition* of the concrete, there is no concurrence of views in the literature: some authors advise the use of coarse aggregates (crushed stone concrete), whereas others consider that the maximum particle size should be kept low for the sake of better homogenity of the concrete. The results of the present research cannot resolve this divergence, because with the cube strengths of about 40 N/mm^2 there was no ascertainable influence of the maximum aggregate particle size. Good curing is recommended in the literature, and in this reseach it was likewise found to have a beneficial effect.

The range of the research was too limited to enable fundamental pronouncements to be based on it. Nor is it possible - in connection with the problems of translating the accelerated test results into reality - to indicate an optimum concrete composition. It should be pointed out, however, that concrete with a cube strength of 21 N/mm^2 often displayed a greater amount of wear as well as greater scatter in the results than did concrete with a cube strength of 40 N/mm^2. The research shows a good quality of concrete to be desirable for high erosion resistance.

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