The use of concrete in the construction of solid dams

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The Use of Concrete in the Construction of Solid Dams.

Über die Verwendung von Beton beim Bau massiver Staumauern.

Remarques sur l'emploi du béton dans la construction des barrages massifs.

Coyne,
Ingénieur en Chef, Paris.

I.
The Concrete Age.

"Concrete," observed Rabut in 1910, is "a masonry work of small nature composed of materials small enough to reduce the work of shaping, conveying and using to its simplest expression."[1] Compared to previous methods of building, concrete, and reinforced concrete in particular, requires "solutions of disconcerting simplicity in the varied problems of our craft, and assumes countless and often unexpected forms to meet new requirements." From his comparison, Rabut inferred that his generation was experiencing "the most profound revolution ever effected in the art of building."

An invention of the Romans, concrete has become "the modern and most economical form of masonry."[1] Requiring no rare materials or highly trained or skilled labour, adapting itself with marvellous flexibility to the requirements of design and actual construction, and being more durable than timber or steel, concrete has been adopted for all types of building construction — both ground structures and hydraulic and maritime works. "The democratic material," as Rabut familiarly termed it then, probably to signify that its development was bound up with social evolution and the gradual disappearance of the stonecutter (the wealth of another age), has become — the monarch. Its supremacy is, however, still contested by steel, especially for large bridges; but for under-water structures it has gained a veritable monopoly, and we designers or contractors would be considerably inconvenienced now if we had to do without it. In this connection, our age is truly and incontestably the concrete age.

At the present time, there is hardly a dam that is built in any other way, with a few rare exceptions, the most notable of which are the Italian dams built in ordinary masonry, due to the high quality of their workmanship (the celebrated masons of the Alp district). It is by using concrete that designers and contractors have been able to attain the colossal dimensions of certain dams erected in recent years — the largest masonry structures ever put up by the hand of man. Boulder Dam, the huge

[1] *Rabut:* Introduction au cours de construction en béton armé. 1910—1911.

Colorado barrage, actually contains $2\frac{1}{2}$ million m^3, or slightly more than the volume of the Great Pyramid.

Although the conditions governing the use of concrete are constantly evolvine, even at the present time, it seems advisable to make a rapid survey and outling everything that experience has taught us about it.

II.

Ultimate Strength of Concrete.

The Cements. —

The ultimate compressive strengths required in France for dam concretes are, generally speaking, not very high; and even for gravity dams they may drop to comparatively low figures — less than 100 kg/cm^2 at 90 days (8 to 10 times the calculated fatigue figures, which, as we know, are only remotely related to the actual fatigue figures). For arches, the figures vary between 200 and 250 kg/cm^2 at 90 days, or four times the calculated fatigues.

It should be noted that the strength of concrete at 90 days (and, *a fortiori*, the strength at 28 days) is very rarely put under stress in a dam, because, as it takes several years to build, the concrete has begun to harden a long time before it is under water. Again, the newest concretes are the ones usually located at the top of the structure, and these undergo the least amount of fatigue. Consequently, the quick-hardening cements, which have been developed on a very large scale to meet the requirements of reinforced concrete construction, have no place in dams. Their strength only begins to matter after six months or even a year. On the other hand, they set up a considerable amount of heat in the first few weeks after they have set, and thus set up local or extraneous fatigue, especially when expanding, and practical men would like to obviate this.

In certain countries, particularly Sweden and the United States, there is a tendency to manufacture special cements for dams, known as "low heat cements". Generally speaking, these cements differ from the others by containing less tricalcic silicate and aluminate, which are the factors giving rapid hardening and, consequently, excessive evolution of heat. They also have the advantage of shrinking less than rapid-hardening cements and evolving less free lime, and this makes them less soluble in water. Although their initial strength is lower than that of ordinary cements, it is equal too and even higher than the latter after a twelvemonth.

Slag or metallurgical cements are commonly used in France for solid gravity dams. The low strengths necessary in this latter case call for the use of special binders which are very superior to Portland cement from the viewpoint of unreasonable heating and resistance to the effects of clean water. The only trouble with them is that their strength is comparatively low, and their hardening considerably retarded by cold weather.

Influence of $\frac{C}{E}$.

Let us consider a pure cement paste containing a weight C of cement for a weight E of water. Its strength is an increasing function of the ratio $\frac{C}{E}$ (which actually, and very nearly, measures the cement ratio of the voids in the pure paste), and experience has shown that it is connected with this ratio by a linear equation, viz. $R = \alpha\,(\frac{C}{E} + \beta)$.

Now add sand, being careful not to modify the ratio $\frac{C}{E}$ defining the strength of the binder paste, and to fill up all the voids between the sand grains with paste, without allowing air to penetrate.

At first, we suspect that the strength will not be altered, since rupture must take place due to the paste being (generally speaking) much weaker than the sand. Experiment actually shows this to be the case, as the following results prove.

The following were made up:

(1) A very fluid paste, capable of mixing easily with sand.

(2) Three mortars, obtained by adding 3, 6 and 9 volumes of sand respectively to 5 volumes of this paste. The plasticity of these mortars obiously decreased with increase in the amount of sand incorporated, but every attempt was made to get them as compact as possible, by ramming and vibrating. From each mixture, six cubes of 2″ side and six of 2¾″ side were made, and subjected to crushing tests, half of them after 7 days and the other half after 28 days.

Table 1 gives the characteristics of these different mortars at the time they were made, and Table 2 the strength figures obtained after 7 and 28 days respectively. (The mortars have been conventionally defined by the ratio of the volume of *sand* to the volume of *pure paste*.)

Now let us add stone to our mortar, still being careful not to alter the quantity of water incorporated in the cement slurry, and to eliminate, by careful moulding, all the additional voids set up by adding the stone. The strength of this particular concrete may be expected to be the same as that of the initial cement slurry, and this supposition has been verified by making the following tests.

Six cubes of 22 cm side were made up as follows (3 being tested after 28 days and 3 after 90 days):

(1) A mortar M of a very liquid type (or concrete of small mesh aggregate), containing 19% of water.

(2) Eight concretes obtained by adding to the first mortar made 30, 60, 90, 120, 135, 150, 165 and 180 per cent. of stone relatively to the total weight of dry material in the mortar, this being placed in moulds simply with the trowel or by slight ramming. (The fluidity of these concretes obviously diminished with increase in the proportion of water added.)

(3) Six concretes absolutely identical to six of the concretes mentioned above, but rammed or vibrated whilst being placed in the moulds. These concretes contained 60, 120, 135, 150, 165 and 180 per cent. of stone respectively in proportion to the other dry materials. The smaller the degree of liquidity, the more thoroughly they were rammed.

The strengths after 28 days are set out in Table 3.

Whether we are dealing with the cement slurry, or with mortar or concrete, the strength of the several samples (within the limits of error of the tests) is purely a function of $\frac{C}{E}$ and may thus be expressed by the formula: $R = \alpha \left(\frac{C}{E} + \beta\right)$,

Table 1.

Description	Quantities incorporated per Cubic Metre				$t = \frac{\text{Vol. Paste}}{\text{Gaps Sand}}$	Compactness γ	$\frac{C}{1-\gamma}$
	Cement (C) Kilos	Sand (S) Litres	Total Weight of Dry Material	Water (Litres)			
Cement slurry	1365.2	0	1365.2	573.4	—	0.427	0.745
Mortar 3 5	990.5	435.7	1724.7	415.9	4.5	0.584	0.745
Mortar 6/5	775,8	682.6	1926.0	325.7	2.25	0.673	0.741
Mortar 9/5	636.7	840.3	2052.7	267.4	1.5	0.728	0.732

The ratio $\frac{C}{E}$ remained constant at 2.38 (by weight) or 0.744 (by volume).

Table 2.

	Measured Strengths							
	Cubes of 5 cm Length of sides				Cubes of 7 cm Length of sides			
	7 Days		28 Days		7 Days		28 Days	
Cement slurry . . .	233.3		379.2		213.2		282,0	
	243.7	264.9	362.8	379.1	309.2	253.3	365.7	341.5
	317.7		395.3		237.5		376.7	
Mortar 3/5	274.5		416.0		301.5		383.3	
	260.1	256.0	399.6	390.1	231.1	277.3	336.9	366.7
	233.3		354.6		299.3		380.0	
Mortar 6/5	221.0		297.8		202.8		321.2	
	245.7	247.8	359.7	344.9	275.7	234.1	294.8	306.4
	276.6		377.3		223.7		303.3	
Mortar 9/5	247.8		366.9		218.5		309,2	
	233.3	238.1	338.2	343.7	292.7	259,1	347.9	340.0
	233.3		325.9		266.1		380.8	

where α und β only depend on the cement, the method and time of hardening, the mould, and the dimensions of the test samples.

The strength of a *compact* concrete, i. e., one containing no other interstices than the ones in the pure paste, is therefore nothing more or less than the strength of this pure paste.

	Concretes made	Quantities incorporated per m³ of Concrete								Density of fresh Concrete	Fluidity measured at the jig	$t = \frac{\text{Vol. of Mortar}}{\text{Voids in Stone}}$	Compactness γ Factor Concrete		$\frac{C \text{ actual}}{1-\gamma \text{ actual}}$	$\frac{\gamma \text{ actual}}{\gamma \text{ theoretical}}$	$\frac{C}{E}$ (By volume)	Strength at 28 Days	
		Cement C (kilos)	Sand S		Stone P		Total Weight of Dry Materials	Water E											
			Weight (Kilos)	Volume (litres)	Weight (Kilos)	Volume (litres)		% Weight of Dry Materials	Volume (litres)				Actual.	Theoretical				On 3 cubes 22 × 22 cm for Mortar or Concrete	Mean
1	Mortar M *normal*	461,0	1862,5	856,2	—	—	1828,5	19,0	346,5	2,170	non-determined greater than 2,20	—	0,651	0,654	0,416	1	0,416	225,9 — 228,8 — 188,5	207K,7
2	M + 30% *Normal* aggregates	381,9	1128,6	709,8	453,2	306,6	1963,7	14,62	287,0	2,251	non-determined greater than 2 20	6,14	0,713	0,718	0,416	1	0,416	187,0 — 202,5 — 208,8	199,4
3	M + 60% *Normal* aggregates	325,4	961,8	604,9	772,3	522,5	2059,5	11,88	244,6	2,305	do.	3,07	0,753	0,755	0,414	0,997	do.	219,7 — 221,2 — 183,8	208,2
4	do. *vibrated*	325,9	968,3	605,9	773,5	528,2	2062,7	11,88	245,0	2,308	do.	(1)	0,755	—	0,416	—	do.	171,4 — 183,8 — 174,5	176,6
5	M + 90% *Normal* aggregates	284,0	839,2	527,7	1011,0	684,0	2135,2	10,0	213,5	2,349	2,20	2,05	0,784	0,786	0,413	0,997	do.	180,7 — 211,9 — 191,8	195,8
6	M + 120% *Normal* aggregates	250,8	741,3	466,2	1190,6	805,5	2182,7	8,63	188,5	2,371	2,05	1,53	0,807	0,811	0,406	0,995	0,416	202,5 — 188,5 — 177,6	189,5
7	do. *rammed*	252,1	745,1	468,6	1196,5	809,5	2193,7	8,63	189,3	2,383	2,05	(1)	0,811	—	0,416	—	do.	183,8 — 187,0 — 199,4	190,1
8	M + 135% *Normal* aggregates	236,6	699,3	439,6	1263,4	854,8	2199,3	8,09	177,9	2,377	1,92	1,36	0,814	0,821	0,397	0,991	do.	187,0 — 194,8 — 190,1	190,6
9	do. *rammed*	238,6	705,4	43,6	1274,2	862,1	2218,2	8,09	179,5	2,398	1,92	(1)	0,821	—	0,416	—	do.	171,4 — 180,7 — 194,8	182,3
10	M + 150% *Normal* aggregates	228,8	661,4	416,0	1327,8	898,4	2213,0	7,60	168,2	2,381	1,80	1,23	0,820	0,830	0,388	0,988	do.	205,7 — 187,0 - 194,8	195,8
11	do. *rammed*	225,3	665,8	418,7	1336,7	904,3	2227,8	7,60	169,3	2,397	1,80	(1)	0,826	—	0,405	—	do.	215,0 — 187,0 — 194,8	198,9
12	M + 165% *Normal* aggregates	212,1	627,0	394,8	1384,5	936,7	2223,6	7,17	159,4	2,383	1,72	1,11	0,825	0,839	0,379	0,983	do.	201,0 — 191,6 — 185,4	192,7
13	do. *rammed*	218,6	631,4	397,1	1394,3	943,4	2239,3	7,17	160,6	2,400	1,72	(1)	0,831	—	0,395	—	do	216,6 — 199,4 — 193,2	203,1
14	M + 180% *Normal* aggregates	201,5	595,5	374,5	1434,6	970,6	2281,6	6,78	151,3	2,388	1,65	1,02	0,829	0,846	0,368	0,980	do.	202,5 — 191,6 — —	197,1
15	do. *rammed*	208,9	602,6	379,0	1451,8	982,3	2258,3	6,78	153,2	2,412	1,65	(1)	0,839	—	0,395	—	do.	202,5 — 205,7 — 218,1	208,8

(1) *This ratio con Electuale after ramming in the forms; it could not be verified.*

It will be noted that, on the tests, the percentage of cement varied from

100 p. c. (pure paste) to 0.9 p. c.

by weight of the dry materials, and the compactness from 0.427 to 0.839, without affecting the strength.

On the other hand, the strength takes an upwardt tendency from a certain percentage of stone onwards, due to the fact that the pure paste is then reduced to a thin film occupying the very limited space available between the stones imbricated in each other.

At the limit, a masonry of dry stones would be reconstituted, and this would be endowed with strength although it did not contain the slightest trace of binder.

Thus the conclusion to be drawn from the tests would be that the hardness of the concrete varies in inverse proportion to the amount of cement it contains, which is an elegant and unexpected way of reconciling safety with economy.

Practical Considerations. —

These paradoxical conclusions call for explanation. Obviously the most compact of our concretes, and especially the last ones in the list, represent an ideal grouping of the materials, the largest stones making contact with each other and their voids being filled up to just the right extent with mortar.

No building works ever produced such a concrete. It is a work of art, rather like a broken plate or a kind of jig-saw puzzle, the pieces being put together by an expert hand so as to restore the plate and reduce to the minimum the number of gaps in the structure. There is no reason why the pieces put into a concrete mixer and shaken up for any length of time should automatically fall into the place assigned to them by the hand of the artisan. Suppose this were possible, there is every chance of the concrete de-mixing on its journey from the concrete mixer to the place where it has to be used, and the strength would no longer be a function of $\frac{C}{E}$, but of $\frac{C}{E+V}$, V being the voids.

It is very strange to note that the majority of research workers who have claimed to give rules for producing the most compact type of concrete, have overlooked the fact that their concretes were no more capable than our reconstructed plate was, of being transported from the place of mixing to the site without risk of demixing, and that the conclusions derived from their laboratory tests were dependent on very ticklish rules which vary with the skill of the operator.

The foregoing example should be sufficient to prove this. The maximum compactness of a concrete is usually supposed to be obtained, even in the laboratory, by increasing by 30 to 35 p. c. the volume of mortar strictly necessary for filling up the voids between the stones.

Of our concretes, the most compact is the one in which the pieces touch, and the ratio t between the mortar and the voids in the stones is scarcely more than 1, as was expected theoretically.

One necessary conclusion, then, is this: all the laboratory tests made on the compactness of concretes should be accepted with a great deal of reserve, since they have only a very remote connection with the actual conditions under which the materials are arranged at the building sites.

In this particular respect, the concretes differ considerably from the mortars.

Working Properties.

The best concrete for a particular purpose can therefore only be defined at the particular time it is being used, or else by an experiment carried out on a scale large enough to repeat the exact conditions of practice. To improve our knowledge, Bolomey is the first who has given to the practical men really practical advice, based on experience in actual works. His advice will, however, be found to be precisely opposite to the conclusions which we might be tempted to deduce from laboratory tests, so that the latter just be interpreted the other way round to ensure good work.

Before everything, a concrete must be *well prepared* to be compact on the job, especially on a dam where labour or workmanship is necessarily limited owing to the quick rate of working.

Compared to the best laboratory concrete (or to our ideal conception regarded as a basis of comparison), the concrete must include a surplus of water, a surplus of sand, and a surplus of fine sand. But all these things conflict, or seem to conflict, with strength.

The function of the surplus water is to convey and lubricate the materials so as to facilitate their grouping, the excess of sand acts in the same direction and also serves to make up for the local deficiencies which would certainly arise if the quantity of sand were just sufficient to fill up the voids between the stones. But these two precautions would not be sufficient to obtain a compact concrete on the job, for the water has a tendency, whilst moving, to separate from the concrete and to carry part of the cement along with it. It must be fixed by introducing into the mixture a sufficient quantity of fine dust, viz., fine cement or sand, which fixes the water by capillary action and prevents segregation. In this way, a smooth, binding paste is formed — a kind of emulsion in which the stones float, and which only breaks slowly when once the concrete is in place, expelling part of its surplus water by the effect of the pressure exerted by the successive layers.

It is these cautious remarks which have led Bolomey to suggest the "granulometric curve" which bears his name, and regarding which we shall merely make a few observations.

As these are purely practical problems for which it is impossible te give any general solution, Bolomey's curve is only suitable for certain classes of materials and certain methods of working. Generally speaking it needs, for broken materials, to be corrected by increasing the sand and the fine sand, as shown below (Plate 1).

It may, however, have to be departed from considerably for special forms of materials, such as the broken porphyrys, diorites and quartzites. These very "cold" stones break up flabily in all stages of granulation, and include a large number of voids which have to be filled up with large surpluses of sand.

The added Sand. —

In this latter case, the use of added sand — dune or river sand in round grains — is indispensable, because its shape makes it act as a lubricant to allow the broken material to arrange itself properly, and prevents the pieces merely supporting each other.

We have been able to utilise granulometric compositions comparable to the following (Plate 2.), with rich concretes intended for use in a thin-vault dam (300 kg of cement per m^3 of work; maximum diameter of the stone = 70 mm).

The use of large stones (above 10—12 cm) makes the concrete less workable, and it may also probably be necessary in this case to depart from Bolomey's empiric standards. At any rate, wide tolerances are necessary, to make up for the unavoidable variations in the supply of materials, since perfection in this particular respect is impossible.

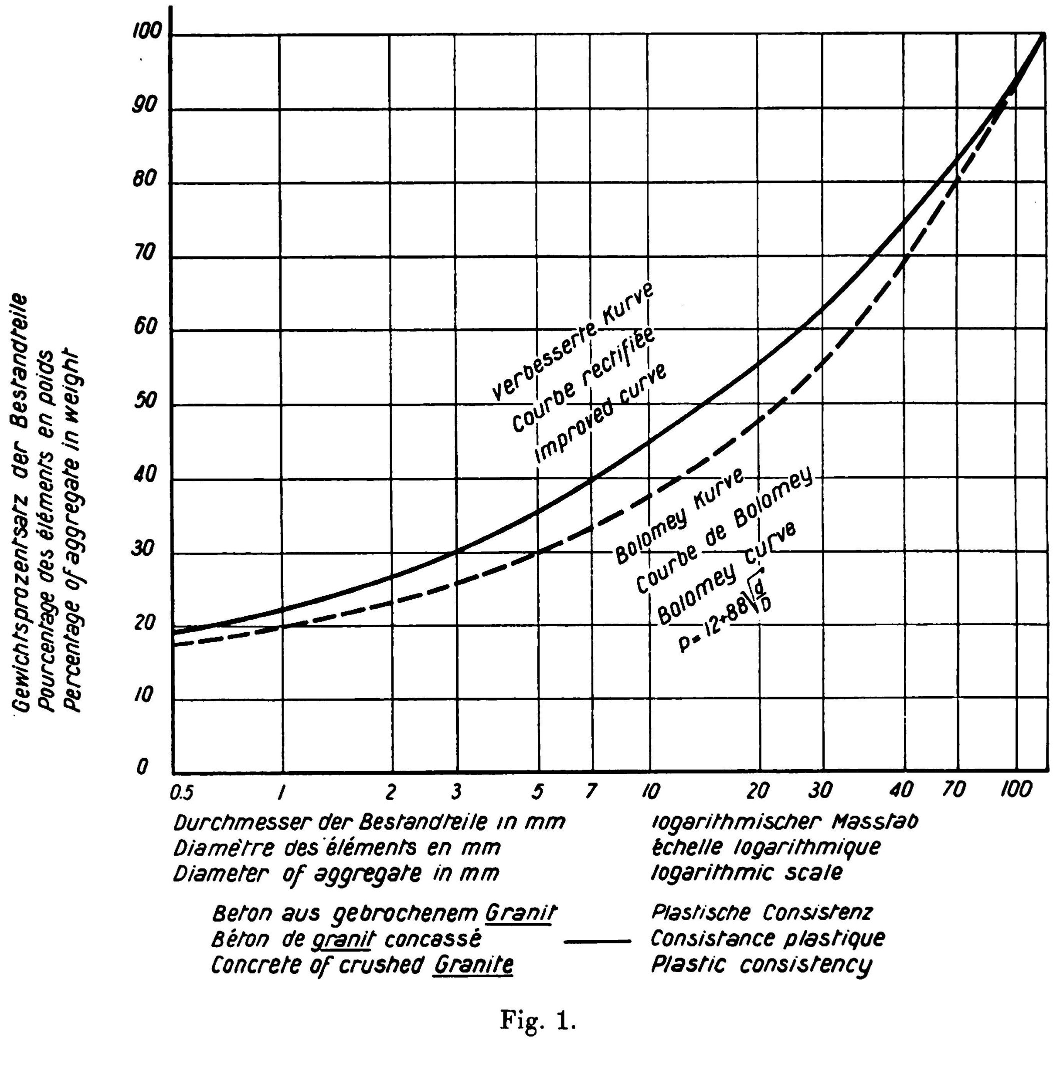

Fig. 1.

It will be seen, then, how difficult are the problems met with on the actual job, and how important it is that these difficulties be properly tackled by the works manager according to the circumstances which arise.

The main thing is that fluidity and grain-composition (grading) should be such as to give the concrete a natural tendency to go properly and automatically into place; and to acquire of itself the requisite homogeneity and compactness, seeing that workmanship is necessarily limited to the rate of working, and reduced to a few detail corrections.

For this reason, the concrete should exhibit no tendency to de-mix (a factor dependent on the way it is put in), and its external friction should be a minimum. This twofold condition in decisive for the handling — previously the attribute of plastic concretes only. Certain products improve it, particularly kieselguhr, or metallic salts incorporated in the mixing water.

It should be noted that, assuming equal fluidity, a "workable" or good handling concrete will be easier to mix than another. An easy way of checking this is to measure the torque at the shaft of the concrete mixer, as is done in America.

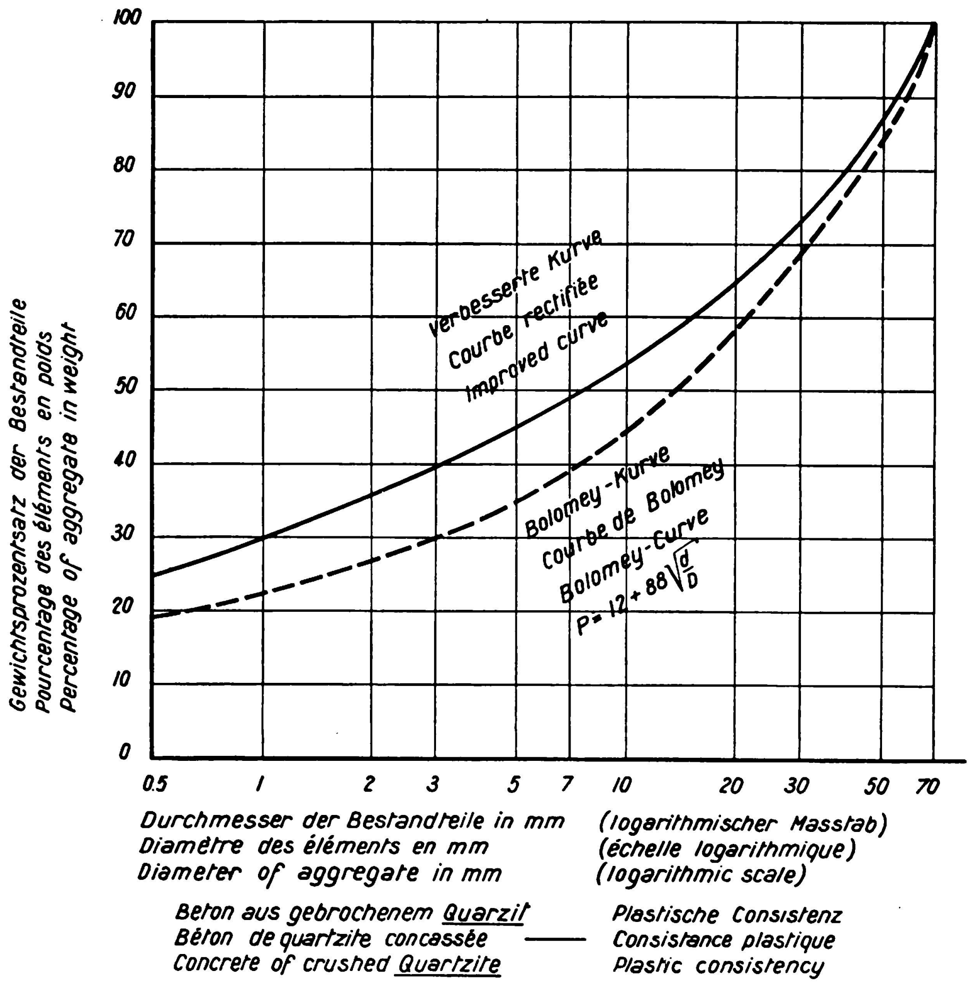

Fig. 2.

Vibrating.

As vibrating is an artificial method of compacting, but one which rightly shows an increasing tendency to be adopted at all building works, it is certain that, for the reasons outlined above, it must call for a special concrete different from the concrete made by ordinary methods. For small parts made of plain or reinforced concrete, it will be noted that the optimum granulometry (grading) of vibrated concrete differs widely from that of ordinary concrete. It is not impossible to obtain in this way concretes which are very dense and contain a high percentage of stones, and which resemble our broken plate or the jig-saw puzzle which we used by way of comparison. The dry concretes, particularly those graded discontinuously and including in their composition a minimum of sand, give very high strengths when vibrated.

On the other hand, ordinary concretes, and particularly cast concrete, desintegrate under the prolonged action of the vibrator which, while assisting the compacting and settling of the concrete, cause the excess of mortar and of pastes to flow up to the surface, thus dividing the mass into alternate layers of very hard concrete and diluted mortar.

Referring to the table on page, it will be noted that concrete No. 4, which is fluid and was vibrated in the test mould, is not so strong as the same concrete which was not vibrated.

Unfortunately, things are very different at a barrage works.

What actually ought to be done is to really vibrate the concrete and to vibrate it everywhere.

Here, again, the rate of working makes the job troublesome, because the vibrators absorb a great deal of power, their scope is comparatively small, and there is a limit to the number of apparatus that can be set to work. The power required is greater, and the radius of action smaller, the less "workable" the concrete.

If too much be expected of vibrators, and it be decided to manufacture a dry and "stiff" (i. e., not very workable) concrete, there is a big danger of disappointment, especially as regards impermeability. Experience almost everywhere has proved this.

In the present state of things, the adoption of the vibration method at a dam construction works can only be regarded as a simple adjunct for compacting the concrete, especially in the outer zones, for increasing impermeability. The grading of the cement will be practically the same as for non-vibrated concrete. At the same time, the quantity of water may be slightly reduced.

Under these conditions, no attempt must be made to vibrate the concrete thoroughly, for fear of disorganizing the mass and causing the liquid constituents to flow back to the surface of each vibrated layer.

The best vibrators are the internal type, and their sphere of action is directly proportional to their frequency, assuming equal power. The most efficient vibrators at present are those revolving at 8,000 r. p. m.

Progress may possibly be made shortly in the vibration method as applied to the construction of dams, but the writer thinks it will always be advisable not to trust exclusively to vibrators and to allow for a certain automatism in operations, f only to make up for the deficiencies of the men.

III.
Technical Control.

Preliminary Tests. —

The foregoing observations show that the preliminary tests are only valuable as a first approximation, and that they must not be relied upon too much for defining in advance the granulometry curve which is applicable on the site of operations.

Control just before Use.

The workability or "handling properties" of concrete, which is an essential element of its compactness, can only be assessed when it is about to be used, and, generally speaking, by eye. No machine can replace the experienced eye in this connection.

The apparatus used for measuring the quantities of the different classes of materials (usually 2 parts of sand, and 2 or 3 of gravel) incorporated in each mixing must be accurate and reliable. Percussion type volumetric testers usuully employed for estimating the material require careful supervision. The automatic weighing machines, which have not been generally adopted in Europe for coarse materials but which are already employed in America, are much more preferable.

Once the plant has been properly adjusted, the chief place where control must be exercised is at the concrete mixers, where it is easy.

The quickest and most practical method of checking the quality of the concrete actually obtained is to measure the *density* of the fresh concrete, and this can easily be done by means of a box of known volume and a simple Roman balance (steelyard). Generally speaking, variations in the density of the fresh concrete will be found to be fairly closely related to variations in the compressive strength. This simple method supplements the visual test of the concrete and enables all defects in composition to be disclosed at once.

Tests on Mortars.

As mentioned by Bolomey, it is possible to check the strength of the concrete by tests on cubes of mortar drawn from the mixing.

The strength will usually be found to be 10 to 20 p. c. higher on the mortars (7 cm cubes) than it is on the concretes (30 cm cubes). This factor appears to conflict with the conclusions of the previous section of this paper, but it is merely due to the fact that part of the water of the concrete is retained by the large stones when the mortar is withdrawn from the mixture.

Under these conditions, the $\frac{C}{E}$ of the mortar is higher than that of the concrete, which explains the increase in strength observed.

Tests on Concrete. —

These tests on mortars, which are very practical (especially for checking uniformity in the quality of the cement), and which can be carried out at no great cost, do not dispense with the need for making compactness and strength tests on the actual concrete. The smallest linear dimension of the cylinders or cubes of concrete used must be at least 2½ times that of the largest stones. The unit strengths appear to increase slightly with the dimensions of the test pieces (for equal $\frac{C}{E}$, of course), probably due to the better compactness of the materials by the effect of their weight.

Concrete must be tested not only for its ultimate compressive strength, but for its tensile strength as well, as the latter is important in view of preventing cracks. The best way of making the measurement is by the bending test at a constant moment.

Crushed sands, so long in disrepute because of their bad workability, give tensile strengths 10 to 20 p. c. higher than the figures obtained with (natural) round sands. Where the latter are only slightly clayey, their tensile strength becomes very low, and this shows how important it is carefully to wash alluvial materials.

The ratio $\frac{\text{compressive strength}}{\text{tensile strength}}$ which measures brittleness, varies from 8 to 12, according to the age and hardness of the concrete. It is higher with increasing age and hardness.

Controlling Concrete on the Job. —

It is no use depending on all these laboratory tests for assessing the actual quality of the concrete on the job. To get an accurate idea in this connection, repeated samples must be taken from the actual mass of the dam even some considerable time after the concrete has set.

For cast concrete, the actual strengths of the finished material are usually found te be much higher than the strengths of test cubes. In one specific case, the test strength was round about 100 kg/cm^2, whereas on the actual job the figure was twice as high at the same age.

This phenomenon is general, and is due to the fact that the enormous surpluses of water in the cast concrete cannot get away before the concrete sets, in the test sample. On the actual job, however, decantation takes place for the first few hours and is considerable compared with the thickness of the layer, with the result that there is a greater amount of heaping due to the effect of hydrostatic pressure.

At the Oued Foddah Dam, concrete mixed in the concrete mixer with 210 litres of water per m^3, had an actual compactness factor on the job of 0.84, a figure equivalent to a maximum of 160 litres of water, which means that 40 to 50 litres, or 25 p. c. of the water fed to the mixer was expelled.

Mixed with 160 litres of water, the concrete would practically have been in a reasonably plastic state but would have taken a great deal of care to put in. The surplus water added to the mixer made it easier to transport and put the concrete in place without reducing its quality.

Influence of $\frac{C}{E}$ *with Time. —*

It should be noted, however, that the effect of surplus water decreases in terms of time, as will be seen from the table below:

Proportions	$\frac{C}{E}$	Compressive Strengths (in kg/cm^2)				Remarks
		7 Days	28 Days	90 Days	1 Year	
Cement 250 kg Water 166.2 Litres	1.504	165.1 *167.2* 166.2	225,1 *226.2* 225.6	248.3 *261.6* 254.9	291.6 *299.0* 295.3	Plastic Concrete
Cement 250 kg Water 215.5 Litres	1.160	103.1 *108.6* 105,8	146,0 *167.2* 156.6	176.9 *183.3* 180.1	227.3 *237.2* 232.3	Cast Concrete

The strengths of cast concrete increase more rapidly than those of plastic concrete. Taking the ratio $= \frac{\text{Strength of plastic concrete}}{\text{Strength of cast concrete}}$ for different periods of crushing, the following figures are obtained:

After	7 Days	= 157%
,,	28 ,,	= 144%
,,	90 ,,	= 141%
,,	1 Year	= 127%

For plastic concrete, even when vibrated, the differences between test samples and concrete as actually laid appear to be much less; and, provided it be not too soft, it is not at all certain that its strength as laid exceeds the strength of cubes taken from the mixing.

Nevertheless, the ultimate compressive strength will generally be higher than what is called for by the coefficients of safety usually adopted for solid dams, which would mean that the proportion of cement could be reduced.

As will be seen farther on, there is great danger in reducing the proportion of cement, especially at the face of the dam, because of attack by water or atmospheric agents.

The high temperatures at which the concrete of a dam is maintained after setting have a definite effect on hardening. They accelerate it in the first few weeks, but this does not imply that they do not retard it afterwards.

The Weak Points: Work joints and cracks. —

The work joints are the weak points in a dam as regards shearing strength and impermeability. Accumulations of stones form there, while leakage through the mass often takes place (in horizontal work joints).

Two precautions are usually adopted: (a) Reopening the surface of the work joints so as to bring away the layer of light constituents which are often very thick in the case of cast concrete, and to expose the accumulation of stones. (b) Spreading a layer of mortar or fine concrete a few centimetres thick over the joint when work re-starts again.

This latter precaution, the author thinks, is indispensible for preventing leakage. If absolutely necessary, and where there is no accumulation of laitance at the surface, method (a) may be replaced by spraying with a jet of water and compressed air a few hours after the concrete has been put in and while it is still soft enough to be defaced slightly.

The shrinkage of dam walls is relatively slight. In the case of one fairly large block, the writer found that it still contained a large proportion of free water even several months after it was cast, and that it was bordering on the state of saturation. This water kept the concrete soaking and so practically eliminated the shrinkage due to drying, or reduced it to a very small amount, 1/10,000 th at most. The thing to do is simply to prevent the faces drying up while the concrete is beginning to harden.

Contraction in dams is therefore almost entirely a phenomenon of heat contraction. The measures adopted to allow for this are known, and actually consist in cutting the work up into separate voussoirs or blocks. Experience shows that these blocks should not exceed 15 metres in length. Unfortunately these precautions are not sufficient to prevent longitudinal cracks developed in gravity dams as shown in the illustration below, and which are the most dangerous.

It also frequently happens that the faces of the blocks in course of construction are subject to cracking in all directions owing to the difference in temperature between the inside and the surface.

Owing to a stoppage at the works whilst the Oued Foddah Dam was being buitl, a large block of concrete 35 $\times$ 35 metres at the base and 12 metres high remained exposed to the air for 18 months. At the end of 6 months the block was found ot

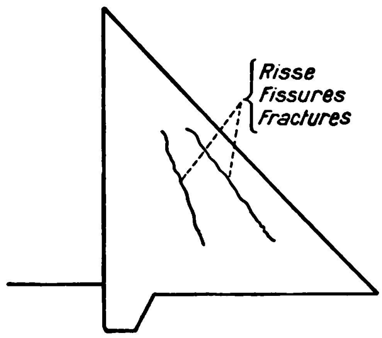

Fig. 3.

be traversed not only by two vertical cro sed fissures, but also by a horizontal fissure encircling the block mid-high. This phenomenon is easily explained. Shrinkage took place more rapidly towards the surface. Since the centre core did not contract to the same extent, it put the outside in tension and caused it to crack.

Hence the interest of the measures adopted at Boulder Dam for cooling the blocks and artificially setting up a thermal state of equilibrium which could only be reached naturally after several decades. Once this state is created, the shrinkage cracks set up in the mass should of ecurse be grouted, and the author thinks it should be possible te regrout them two or three times.

We therefore see how wrong it is to regard the mass of a large dam as a monolith, and the caution that the practical man must observe in trusting to calculations based on the homogeneousness of the mass.

IV.

Impermeability and Resistance to the Action of Water.

Impermeability. —

It is an actual fact that cast concrete is by far the most watertight material that can be used for the construction of a dam. The opposite obtains in the laboratory, where dry concrete is the most impermeable and where cast concrete is worthless. This contradiction once more reveals the fundamental importance of the conditions governing construction.

As was pointed out earlier on, for cast concrete used in large masses, 40 to 50 litres of water per m^3 are automatically expelled, this water having merely acted as a vehicle and lubricant for the concrete and guaranteed it against all local dificiencies.

The reverse is the case with plastic concrete, and, a fortiori, with dry concrete. On the actual job they frequently contain, especially at the work joints, accumulations of pebbles which form waterways.

Another cause is, however, responsible for the impermeability of concretes put in with an excess of water. This has recently been revealed by *M. Mary* of the laboratory of the *Ecole Nationale des Ponts et Chaussees*, Paris.[2] Actually, if a test sample of concrete is subjected to a filtration test at constant pressure, the volume filtered decreases very rapidly with time, even where the water is distilled. This is caused by the concrete swelling in the water — a fact which confirms the very low permeability of concretes kept under water.

Dissolution of Lime. —

The same quantity of filtered water also carries away much less limes in concretes kept under water than it does in concretes kept in air. This fact explains the importance of keeping dam concretes in a state of permanent imbibition, and to a certain extent justifies the surplus water in the cast concrete. The surplus gives a concrete that is less permeable and, for the same permeability, less soluble.

Depositis of Lime. —

Waters containing lime set up a surface deposition of carbonate of lime, which is very effectual in reducing the volume of filtered wâter which, nevertheless, comes out charged with lime. After having deposited its carbonate of lime on the face of the dam, the water is again attacked by the lime of the cement it has dissolved.

This phenomenon only goes on for a certain time.

With pure water, on the other hand, the phenomenon continues, and even laboratory tests have shown it to be aggravated with time, by gradual increase in the filtered discharge, which testifies to a slow dissolution and destruction of the structure of the concrete.

Deposits of Vegetations. —

Very fortunately, phenomena of natural deposition or colmation take place on the dam, due either to matter in suspension in the water, or to the abundance of algae on the walls and even in the fissures of the concrete.

Minimum Proportion of Cement. —

The concrete is much less vulnerable when it contains a high proportion of cement (250 to 300 kg/m^3 at least at the face of the dam, depending on the dimensions of the stones). Very serious decomposition may be expected where the mixture is a "lean" one. There is thus the risk of grave danger in reducing excessively the proportions of cement in the concrete, especially on the upstream side of the dam.

As was pointed out previously, slag and metallurgical cements are much less soluble than Portland cement.

Grain-size of Fine Sand. —

The grade of fine sand used ($e \leqq 0.5$ mm) has a considerable bearing on impermeability, which may be considerable increased by pushing up the proportion of very fine sand, or, better still, the proportion of cement.[4] Above 0.5 mm, the grain size has

[2] See *Annales des Ponts et Chaussées,* May-June, 1933, and November-December, 1934.

no effect on the watertightness of the structures, except that it makes the concrete easy to handle.

Kieselguhr in the proportions usually employed (2 to 3% the weight of the cement) only has an indirect bearing on this particular question, by keeping the concrete compact and casy to handle.

Resistance to Erosion. —

As regards anti-erosive properties, concrete is capable of withstanding, without damage, the contact and even the impact of water moving at very high velocities, say, up to 25 m/sec, provided it is rich in cement, and that its surface is perfectly smooth and free from fissures. In America it has even been found capable of standing up to a much higher speed of flow (up to 50 m/sec.) provided the direction of the streamlets is parellel to the surface of the concrete and that the latter is well finished and very smooth. In that case it will be wise to reinforce the concrete. The discharge galleries of the Mareges Dam are arranged as follows: a steel pipe traverses the dam, forming a strong and watertight element. To prevent it corroding, it was sprayed with a coating of mortar applied with a cement gun, a light metal fitting being welded to the conduit to ensure the mortar adhering properly.

The last few inches of the coating are of carborundum mortar so as to withstand erosion better, and are reinforced by a grillage. The speed of the water is roughly 20 m/sec.

Resistance to Climatic Effects.

Climatic effects, i. e., alternating periods of heat and cold, and especially frost, have been found to cause serious trouble at the faces of dams. Then engineers noticed that similar trouble was experienced in structures erected at places where the climate was mild, and finally realised that such trouble and damage were not caused simply by the rigours of the climate, but also by defects, or bad work.

By "defects" is meant the lack of homogeneity and compactness in the concrete (accumulation of the binders at the work — joints (joints de reprise) in the cast concrete, nests of stones, and, particularly, an insufficient proportion of cement). On the pretext of economy, some engineers have even dropped to proportions of 125 and even 100 kg/m^3 for the body of the work, and barely reached 150 to 200 kg/m^3 for the faces of the dam.

Experience proves that such concretes are very open to attack by the atmosphere and particularly prone to attack by frost. The best remedy for this trouble, in a severe climate, is to include a higher percentage of cement in the concrete for the face-walls. There need be no fear of going up to 300 and even 350 kg of cement per cu. metre = of work if we want to be sure of escaping all trouble of this kind.

It is curious to note that all the damage mentioned has been on solid dams. Reinforced concrete dams (except the Gem Lake barrage, where the concrete was badly made) generally give excellent results, even the Suorva Dam, which is located in Sweden in the polar circle and whose thickness at the face-walls is only a few decimetres. This clearly proves that the trouble is due to errors in the composition of the mixture.

Conclusions.

In the present state of technical progress, the qualities required of a concrete for the successful construction of a solid dam is good handling properties which will enable the concrete to put in almost automatically. This means adopting *"plastic"* concretes.

The quantities of mixing water, sand, and fine sand are therefore fixed to meet this first requirement (depending on the materials available and the method of working), and so give the composition.

Since, however, the composition required to give the necessary strength is fairly low, a composition with a higher percentage of cement must be employed on the faces (walls) so as to guarantee the structure against the risks of leakage, decomposition by water, and attack by atmospheric reagents. This composition will be 250 to 300 kilograms of cement per m^3 of work put in, at least on the upstream wall. It is well to go to 300 or 350 kilograms on the two walls if the climate is severe.

To prevent excessive heating up, a special cement must be manufactured for solid dams, and, for very large sections, artificial cooling.

In the present state of technical development, vibration does not enable good workability to be dispensed with. At the same time, it is a valuable adjunct for working and increases impermeability in the upstream zone. It is to be hoped that its adoption will become general in the form of highpower high-frequency internal vibration.

Special precautions should be taken at the horizontal work-joints (by carefully opening up the work and applying a layer of mortar or fine concrete at the moment when work is re-started again.

The only reliable method of control, both for strength and impermeability, is by controlling the concrete on site, on samples drawn from the actual mass of the dam.

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