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THE STATE OF RESEARCH ACTIVITIES ON RCD METHOD



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SYNOPSIS

The RCD Method was first used in the construction of Shimajigawa Dam in 1975, and numerous improvements have since been made on the details of the method. As of May, 1989, placement of RCD-concrete has been completed on 5 dams and is in progress on 8 dams.
This paper presents a outline of investigations and test results from previous projects. This paper describes the features of the RCD method, characteristics of RCD-concrete, mix design, construction of concrete with emphasis on uniformity, construction of joints with emphasis on watertightness, temperature control and economic advantages of the RCD method in comparison with conventional methods.

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1. INTRODUCTION

The RCD (Roller Compacted Dam-Concrete) Method is a new method for construction of concrete dams in which the bulk of the concrete used is extremely dry concrete compacted by vibratory rollers. It was developed by the Japanese Ministry of Construction with the aim of rendering construction of dams more rational by reducing labor and costs. As of May 1989, placement of concrete has been completed on 5 dams under construction by the RCD Method and placement of concrete is in progress on 8 others. Construction of a further 12 dams is planned under the RCD Method and orders have already been made for some of these.

The RCD Method was first used in the construction of Shimajigawa Dam in 1975 and numerous improvements have since been made on the details of the method. The method became established as a technically systematized method by the completion (completion of dam concrete placement) of Tamagawa Dam in 1987 and has received high appraisal worldwide.

There are, however, possibilities for further improvement in the planning and design stage of the RCD Method and we hope in the future to further reduce the amount of labor and costs involved.

2. OUTLINE OF RCD METHOD[1]

2.1. Development of RCD Method

The development of the RCD Method in Japan began with the establishment of "The Committee on Rationalized Construction of Concrete Dams" (chaired by Emeritus Prof. Masatane Kokubu of the University of Tokyo) by the Ministry of Construction. The main points of the background upon which the committee was established were as follows.

1) In view of the rising labor costs, it was thought to be more advantageous to reduce costs by decreasing the unit cost of the dam concrete through improvements in the construction methods than through structural improvements as seen in arch dams and hollow gravity dams.

2) The lack of geologically and topographically favorable construction sites for dams had led to an increase in the dam volume required to ensure the stability of gravity dams, giving rise to a need to search for methods of reducing the unit cost of the dam concrete through improved construction methods.

Upon this background, research was conducted by the committee with the following basic aims.

1) Promotion of mechanization to reduce labor costs

2) Promotion of use of machines which can be adapted to various conditions to raise efficiency in construction

3) Development of construction methods adapted to the characteristics of the dam site and the scale of the dam

As a result of these studies, the method employing extremely dry concrete compacted by vibratory rollers was chosen and through test fills at Okawa and Shimajigawa Dams, it was judged possible to use this roller-compacted concrete in construction of dams.

Placement of dam concrete using a vibratory roller was carried out for the first time in the world at Shimajigawa Dam in September 1978 and a similar method was then used in the construction of the mat base at Okawa Dam.[2] The construction at these sites was successfully completed in 1980 and Shimajigawa Dam, besides gaining the distinction of being the first dam to be constructed with roller-compacted dam concrete, was given the rôle of proving the excellence of the method. The method was named the RCD Method.

The RCD Method was then used in the concrete work for construction of the stilling basin in the work for raising the height of Shin-Nakano Dam and then in 1983 in the construction of Tamagawa Dam with a height of 100 m and volume of 1,150,000 m³. The construction procedure used at Tamagawa Dam was as shown in Figure 1. It was the first time that inclines were used for transportation of concrete.[3] Placement of concrete at Tamagawa Dam was completed in 1987. Use of the RCD Method is planned in a number of high dams over 100 m, including

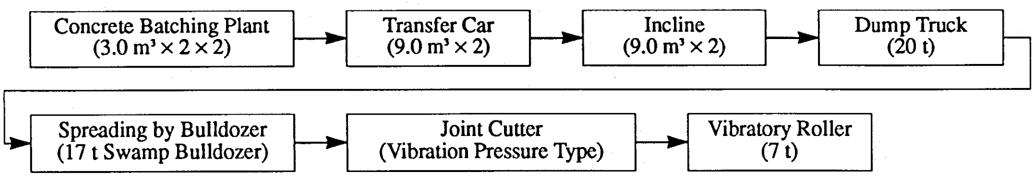


Figure 1 Flow of Concrete Placement at Tamagawa Dam

Table 1 Examples of Concrete Dam Construction by RCD Method in Japan

Name	Jurisdiction	Height (m)	Crest Length (m)	Volume (m³)	Remarks
Shimajigawa Dam	Chugoku Regional Construction Bureau	89.0	240.0	317,000	Fixed Cable Crane (13.5 t) Dump Truck (11 t)
Shin-Nakano Dam	Hokkaido	74.9 Before raising dam 53.0	248.0 Before raising dam 162.0	276,400 Stilling Basin 13,000	Dump Truck (11 t) RCD Method in stilling basin only
Okawa Dam	Hokuriku Regional Construction Bureau	75.0	406.5	1,000,000 Mat Base 300,000	Dump Truck (11 t) RCD Method in mat base only
Tamagawa Dam	Tohoku Regional Construction Bureau	100.0	431.5	1,154,000	Incline (9 m³ × 2) Dump Truck (11 t)
Pirika Dam	Hokkaido Development Agency	40.0	1,480.0 Concrete 910.0 Fill 570.0	560,000 Concrete 360,000 Fill 200,000	Dump Truck (11 t)
Mano Dam	Fukushima Prefecture	69.0	239.0	212,000	Incline (3 m³) Dump Truck (8 t)
Shiramizugawa Dam	Yamagata Prefecture	54.5	367.0	311,000	Dump Truck (11 t)
Asahiogawa Dam	Toyama Prefecture	89.0	252.0	350,000	Dump Truck (8 t)
Asari Dam	Hokkaido	73.9	390.0	506,000	Dump Truck (11 t)
Dodairagawa Dam	Gunma Prefecture	70.0	300.0	348,000	Incline (6 m³) Dump Truck (8 t)
Sakaigawa Dam	Toyama Prefecture	115.0	297.5	626,000	Incline (4.5 m³ × 2) Dump Truck (11 t)
Nunome Dam	WRDPC	72.0	360.0	370,000	Dump Truck (11 t)
Kamuro Dam	Yamagata Prefecture	60.6	257.0	298,000	Incline (4.5 m³) Dump Truck (11 t)
Ryumon Dam	Kyushu Regional Construction Bureau	99.5	618.0 Concrete 378.0 Fill 240.0	1,052,000 Concrete 844,000 Fill 208,000	Incline Dump Truck
Miyagase Dam	Kanto Regional Construction Bureau	155.0	400.0	2,200,000	Incline Dump Truck
Gassan Dam	Tohoku Regional Construction Bureau	122.0	393.0	1,130,000	Belt Conveyer

Miyagase Dam with a height of 155 m. The method has also been adopted abroad at Guanyinge Dam in China and a construction method taking in some of the characteristics of the RCD Dam has been adopted at Elk Creek Dam under construction by the U.S. Army Corps of Engineers, reflecting the favorable appraisal the method has received worldwide.

2.2. Characteristics of RCD Method

The characteristics of the RCD Method are as follows.

1) The unit cement content of the concrete is 120 to 130 kg/m^3 and the unit water content 95 to 105 kg/m^3. The sand aggregate ratio is 30 to 32%.

2) Between the plant and the dam body, the concrete is transported by dump trucks, inclines, fixed cable cranes or belt conveyers, depending on the characteristics of the dam site. Within the dam body, dump trucks are used.

3) The concrete is spread out, using bulldozers, in several layers, each 17 to 25 cm thick, to create lifts 50 to 75 cm in thickness (1 m at Tamagawa Dam).

4) In compacting the concrete, 7-ton class vibratory rollers are made to pass between 6 and 12 times over each lift of 50 to 75 cm.

5) In the whole layer method, the concrete is placed without longitudinal joints. Transverse joints are made with vibrating joint cutters at 15 m intervals after spreading.

6) Conventional concrete is used near the upstream and downstream ends as exterior concrete.

7) The mortar is spread on the surface of the horizontal joints.

8) The strengths, unit weight, watertightness and durability of the RCD concrete are more or less the same as those of conventional concrete.

The dams at which the RCD Method has been or is being used are listed in Table 1.

2.3. Similar Construction Work Abroad

Besides in Japan and the United States, roller-compacted concrete has been used only in a few cases in Brazil, South Africa and Australia.

Roller-compacted concrete was used in the construction of a dam for the first time in the United States in 1982 at Willow Creek Dam (height: 52 m, volume: 330,000 m^3) constructed by the U.S. Army Corps of Engineers. The unit cement content of the concrete at this dam was 67 kg/m^3, of which 19 kg/m^3 was fly ash. This is extremely low in comparison with the unit cement content of 120 to 130 kg/m^3 in the RCD concrete. In this method, called the RCC (Roller Compacted Concrete) Method, numerous measures were taken to raise efficiency in the design and construction by, for example, using dry lean concrete, not applying treatment to the joint faces, not using forms on the downstream faces, not creating transverse joints and not placing structures within the dam body. As a result, it took only 5 months to complete the placement of the concrete and the construction cost was greatly reduced accordingly. The method was named the Roller Compacted Concrete Method (RCC Method).[4]

After filling of the reservoir at Willow Creek Dam, however, it was reported that leakage of approximately 6,000 *l* per minute was observed mainly from the horizontal joints.[5] Despite the improvements made in the construction of dams implemented after this, large quantities of leakage continued to be observed and as a result the Army Corps of Engineers adopted a new method at their Elk Creek Dam. Although the construction of this dam has been suspended for environmental reasons at the moment, the experience gained from the use of the RCD Method in Japan has been reflected in this new construction method.

While the Army Corps of Engineers were using dry lean concrete in their dams, the Reclamation Bureau of the U.S. Ministry of the Interior began to use rich concrete at their Upper Stillwater Dam (height: 87 m, volume: 1,100,000 m^3).[4] This was a method developed in Britain for the construction of Milton Brook Dam but because of the small number of dams constructed in Britain, it came to be used for the first time in the U.S. The unit cement content is 252 kg/m^3, of which 174 kg/m^3 is fly ash. Placement of the concrete at Upper Stillwater Dam was completed in 1987 but it is too early to pass judgement on this method.

3. RCD CONCRETE MIX

3.1. Concept of Design in RCD Method

The RCD Method is a method of constructing gravity concrete dams with extremely dry concrete compacted with vibratory rollers. The design procedure under this method is no different from that for construction of concrete dams using conventional concrete. There is a need, therefore, to carry out investigations at the stage of mix design and in the actual construction to ensure that concrete of uniform qualities with the same strengths, unit weight, watertightness and durability as conventional concrete is obtained, to prevent thermal cracking and to ensure that the construction joints do not become the weak points.

3.2. Concrete Mix Classifications in RCD Method

From the point of their mix, dam concrete can be classified as follows.

1) Internal Concrete (concrete inside the dam body, which makes up the bulk of the dam concrete)

2) External Concrete (concrete used for upstream and downstream faces of the dam)

3) Rock Surface Concrete (concrete used for the part of the dam in contact with the foundation rock)

4) Structural Concrete (concrete used around structures such as the galleries and conduits)

Because of the triangular shape of gravity dams, the width of the upper parts of the dam are narrower. Internal vibrators are used in these parts, because it is difficult to use vibratory rollers in such parts. The mix for the internal concrete will be further subdivided according to need in the case of RCD concrete. The mix of the RCD concrete used as internal concrete is discussed below.

3.3. Mix Design of RCD Concrete

The mix design for RCD concrete is inevitably different from that for conventional concrete because the concrete used in the RCD Method is extremely dry and the unit cement content is low in comparison with conventional concrete.

The mix design method for RCD concrete is discussed in detail in the "Technical Guidelines for RCD Method (Draft)" (March 1989).[6] The main points are as follows.

VC testers are used for measurement of the consistency of RCD concrete. The VC tester and its specifications are given in Figure 2 and Table 2, respectively. In the VC test, after loads are set on the fresh concrete specimens, vibration is applied and the time it takes for the paste to appear at the surface of the concrete specimen is measured. This called the VC value and is used as an index for the consistency of the concrete.

The procedure below is followed in the mix design of RCD concrete.

1) Selection of Unit Water Content Required to Give Appropriate VC Value

The VC value of the RCD concrete is greatly influenced by the unit water content. For this reason, the unit cement content (proportion of fly ash: normally 20 to 30%) and the sand aggregate ratio are set on the basis of past experience and the the unit water content is made to vary until the appropriate VC values are obtained (around 20 seconds on a standard VC tester). When the maximum size of the coarse aggregate is 80 mm, the unit water content required is around 100 kg/m^3.

2) Confirmation of Unit Cement Content

The unit cement content of RCD concrete is normally set at or above 120 kg/m^3, which is understood to be the minimum unit cement content required to ensure that there is sufficient paste in the concrete. Here, confirmation is made as to whether the cement-water ratio obtained from the unit water content determined in 1) will give the required strengths and, if not, the unit cement content is adjusted accordingly.

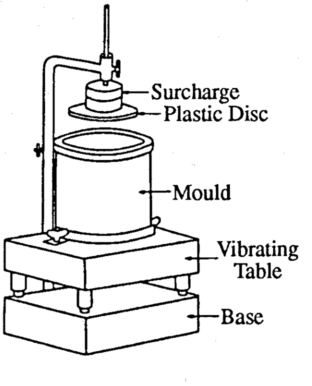


Figure 2 VC Tester (Standard)

Table 2 Specifications of VC Tester

Part	Item	Specification
Vibrating Table	Frequency	3,000 rpm
	Amplitude	1.0 mm
Container	Inner Diameter	24 (48) cm
	Internal Height	20 (40) cm
Surcharge	Mass	20 kg

Figures in brackets for large VC tester

3) Selection of Sand Aggregate Ratio

The sand aggregate ratio is made to vary in relation to the unit water content and unit cement content established in 1) and 2) to determine the sand aggregate ratio that will result in the smallest VC value. The sand aggregate ratio in RCD concrete is generally 2 to 3% higher than that in conventional concrete.

4) Confirmation of Mix

The compactability of the concrete of the mix determined in 1) to 3) above is confirmed through a test in which large specimens of the concrete are subjected to the given vibration energy[7] or through a test fill, and adjustments are made as required. In order to express the mix characteristics of RCD concrete, the ratios of the paste volume to the voids in the fine aggregate and of the mortar volume to the voids in the coarse aggregate have been used as indices in comparison of various mixes at the time of test fill and for comparison with the mixes used at other dams. For the VC value of 20 seconds, the former is around 1.1 to 1.2 and the latter 1.2 to 1.3 in RCD concrete (compared with 1.6 to 1.8 and 1.2 to 1.6, respectively, in conventional concrete).

A typical mix for RCD concrete is shown in Table 3.

Table 3 Concrete Mix at Principal RCD Dams (RCD Parts Only)

Name	Height (m)	Volume (x1000m³)	G max (mm)	VC Value (s)	Air Content (%)	Unit Water Content (kg/m³)	Unit Cement Content (kg/m³) C+F	Proportion of Fly Ash (%) F/(F+C)	Water Cement Ratio (%)	Sand Aggregate Ratio (%)	Type of Cement	Type of Aggregate	AE Agent
Shimajigawa (1980)	89.0	317	80	15±10	1.5±1	105	130	30	80.8	34	Ordinary Portland	Crushed Sand, Crushed Stones	Used
Shin-Nakano (1982)	74.9	(13)	80 150	20±10	1.5±1	95 90	120	30	79 75	34 32	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Okawa (1987)	75.0	(300)	80	15±10	1.5±1	102	120	20	85	32	Moderate Heat Portland	River Sand, River Pebble	Used
Tamagawa (U.C.)	100.0	1,154	150	20±10	1.5±1	95	130	30	73	30	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Pirika (U.C.)	40.0	(360)	80	15± 8	1.5±1	90	120	30	75	30	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Mano (U.C.)	69.0	212	80	20±10	1.5±1	103	120	20	85.8	33	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Shiramizugawa (U.C.)	54.5	311	80	20±15	1.5±1	102	120	20	85	32	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Asahiogawa (U.C.)	89.0	350	80	40±10	1.5±1	94	120	20	78	32	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Asari (U.C.)	73.9	506	80	20±10	1.5±1	103	120	20	85.8	30	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Dodairagawa (U.C.)	70.0	348	80	20±10	1.5±1	100	120	20	83.3	30	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Sakaigawa (U.C.)	115.0	626	80	20±10	1.5±1	100	130	30	76.9	32	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Nunome (U.C.)	72.0	370	150	20±10	1.5±1	95	120	35	79	27	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used
Kamuro (U.C.)	60.6	298	80	20±10	1.5±1	103	120	20	85.8	32	Moderate Heat Portland	Crushed Sand, Crushed Stones	Used

U.C.: under construction as of 1989

Dam Volume: for stilling basin only at Shin-Nakano Dam,
for mat base only at Okawa Dam,
for concrete dam part only at Pirika Dam

3.4. Quality of RCD Concrete

a) VC Value

VC values of around 20 seconds are said to be appropriate for consistency of concrete without coarse aggregate of over 40 mm, when measured using a standard VC tester, under normal ground conditions with lift thicknesses of 50 to 75 cm. (60 seconds when consistency of concrete with full-size aggregate is measured using large VC testers — See Figure 3) VC values above this (e.g. above 50 seconds) will result in the concrete becoming too stiff for compaction with vibratory rollers, while values below (e.g. under 10 seconds) will result in the concrete becoming too soft, making it difficult for vibratory rollers to drive over the concrete and resulting in inconveniences such as surging of the concrete in the adjacent lane.

b) Mix Properties Affecting VC Values

Mix properties affecting the VC values include unit water content, unit cement content and sand aggregate ratio. The relationships between variation in each of

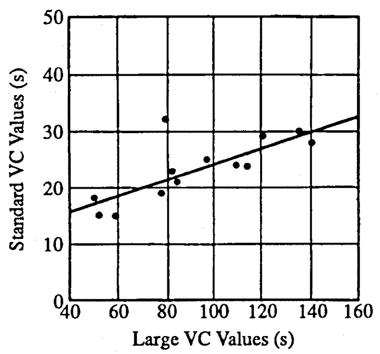


Figure 3 Relationship between Large and Standard VC Values

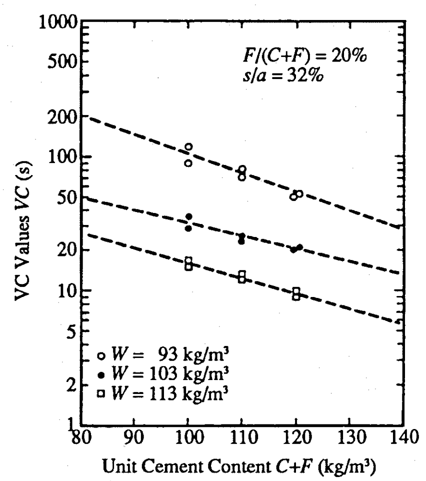


Figure 5 Relationship between VC Values and Unit Cement Content

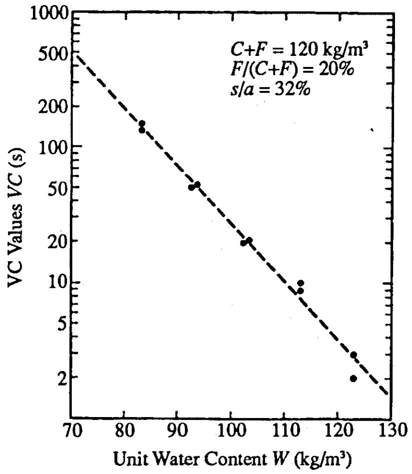


Figure 4 Relationship between VC Values and Unit Water Content

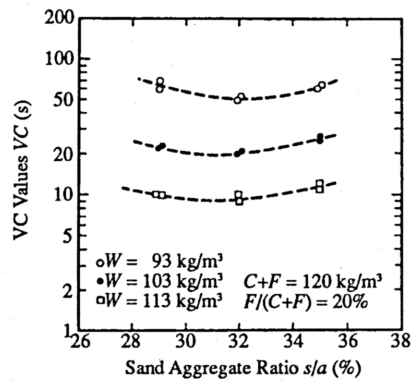


Figure 6 Relationship between VC Values and Sand Aggregate Ratio

these items and the VC values measured using standard VC testers are shown in Figure 4 to 6.[8] The unit water content can be established by implementing VC tests on concrete samples whose unit cement content and sand aggregate ratio are constant. Since the variation in the VC values obtained with the standard VC tester is relatively small in relation to the sand aggregate ratio, it is better to use large VC testers in determining the sand aggregate ratio (See Figure 3).

The VC values represent the time it takes for the cement paste to appear at the concrete surface when vibration is applied to RCD concrete. There is, therefore, a close correlation between the VC values and the the quantities of paste, and, to be more precise, with the ratio of the cement paste volume to the voids in the fine aggregate. (Figure 7)

c) Unit Weight and Compressive Strength of RCD Concrete

Unit weights and compressive strengths are measured using core samples taken 91 days after placement in test containers 50 cm diameter and 45 cm in height and compaction using vibrators to a degree comparable to that in actual construction using vibratory rollers. This series of tests implemented to confirm the validity of the unit water content, originally determined from its relationship to the VC values, by looking at its relationship to the unit weight and the compressive strength, is called the large specimen test and is normally implemented at the final stage of the mix design.[7]

An example of the test results is shown in Figure 8. Both the unit weight and the compressive strength reach maximum values at certain unit water contents but the unit water contents corresponding to the two maximum values are not the same. For reference, the relationship between the cement-water ratio (unit water content) and the compressive strength in a standard specimen of concrete without aggregate larger than 40 mm is shown in Figure 9. The relationship between the VC value and the ratio of the actual unit weight to the the theoretical weight

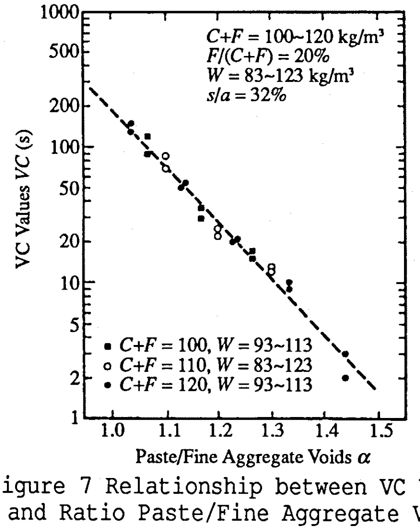


Figure 7 Relationship between VC Values and Ratio Paste/Fine Aggregate Voids

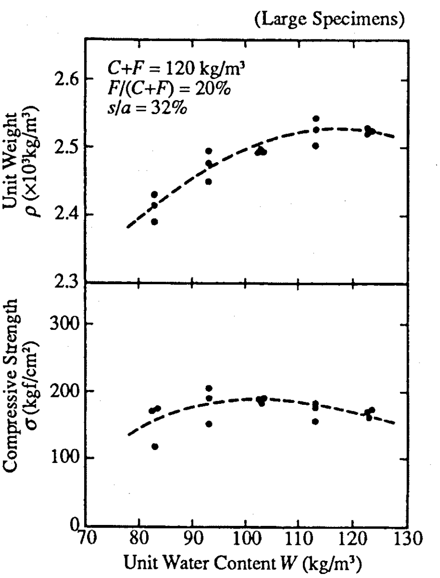


Figure 8 Relationship between Unit Water Content and Unit Weight/Compressive Strength of RCD Concrete Core

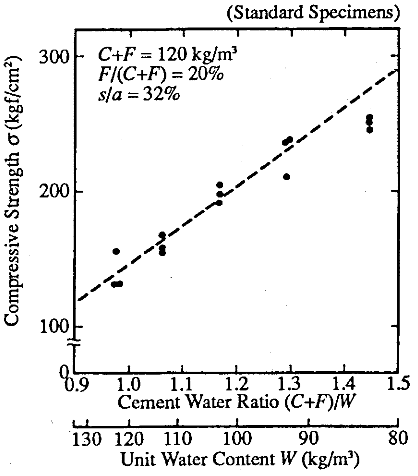


Figure 9 Relationship between Unit Water Content and Compressive Strength of Standard Specimen

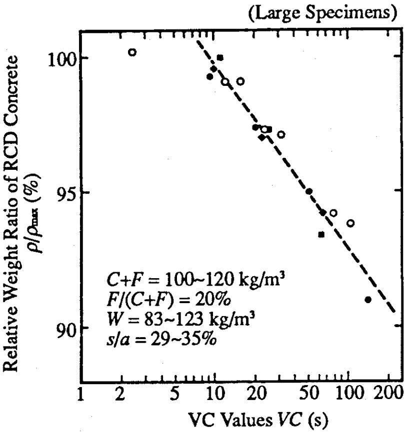


Figure 10 Relationship between VC Values and Relative Weight Ratio of RCD Concrete

is shown in Figure 10. In this example, the unit water content corresponding to the VC value of 20 seconds was 103 kg/m³.

Because of the great variation in the quality of RCD concrete depending on the conditions of vibration compaction, large specimen test or test fill is implemented as the final stage of the mix selection.

4. CONSTRUCTION OF CONCRETE WITH EMPHASIS ON UNIFORMITY

Because RCD concrete is extremely dry and has low unit cement content, there is a need to take adequate care to prevent segregation of materials throughout the process of mixing, transportation and placement.

In particular, special measures are taken in loading and unloading the concrete on to and from trucks to prevent segregation of large-grain coarse aggregate which is liable to occur when the concrete is unloaded. When concrete is spread out in thick layers, this is liable to result in the segregation at the time of removal from the trucks remaining unrectified and, for this reason, each lift is divided into 3 to 4 layers depending on the thickness of the lift and leveled with bulldozers. This leveling with bulldozers is effective also in compacting the concrete and contributes to making the effect of the compaction by vibratory rollers reach below the lift and so to giving the concrete the required strengths and uniform qualities throughout the lifts.[9]

Much research has also been conducted on the vibration compaction of RCD concrete, the mechanism of which is thought to involve not only the effect due to the weight of the vibratory roller but also the reduction of friction between aggregate particles and movement of the mortar due to vibration.

The degree of compaction in the RCD concrete varies according to the capacity of the vibratory roller, the speed of the roller and the number of passes. The vibratory roller normally used is BW-200 Tandem-Shaft Vibratory Roller (total weight: 7 tons, frequency: 2,600 cpm) which is small and has a good performance.

The standard speed of the vibratory roller is 1 km/h. When the lift thickness is 50 cm, a BW-200 Vibratory Roller will be made first to pass twice (i.e. one return trip) over the lift without vibration and then six times or more for vibration compaction. When the lift thickness is 75 cm, it will pass twice without vibration and then 12 times or more with vibration. A finish compaction may be carried out with a tire roller to make the surface smooth and facilitate treatment of joint faces. The validity of this procedure for lift thicknesses of up to 100 cm has been confirmed at Tamagawa Dam.[10]

In earlier cases of construction by the RCD Method, it was observed that the strengths were lower (approx. 75%) in the upper parts of the same lift than in the lower parts. A number of possible reasons were given but it was decided in the end that it was due to the water rising to the upper parts during vibration compaction from above and the problem was solved by selecting appropriate unit water contents (or target VC values) in the concrete mix.

5. CONSTRUCTION OF JOINTS WITH EMPHASIS ON WATERTIGHTNESS

Before placing the next lift, loose aggregate particles and and bits of concrete peeling off are removed from the joint face and the face swept with motor sweepers and cleaned with jets of water.

In the RCD Method, dump trucks inevitably travel over newly placed concrete surfaces to transport concrete to the adjacent blocks. A number of measures (e.g. raising the parts over which the trucks would travel and laying steel boards and sheets on the concrete surface) are taken to protect the surfaces and counter the adverse effects of this traffic such as peeling off of concrete.

After cleaning, water is removed and mortar, around 15 mm in thickness, is spread on the existing surface, immediately before placing the next lift.

It has been confirmed from the results of *in situ* shearing tests (Figure 11) and shear strength tests using boring cores (diameter: 170 mm) that the strengths of the horizontal joints will not fall below the strengths of the concrete so long as care is taken over the quality of the concrete at the joint face and adequate treatment is given to the joints.[12]

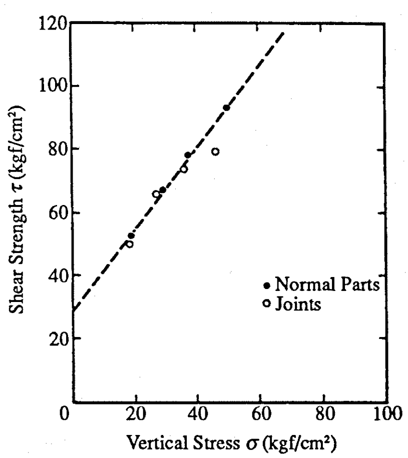


Figure 11 Results of *In Situ* Shearing Test (Dam A)

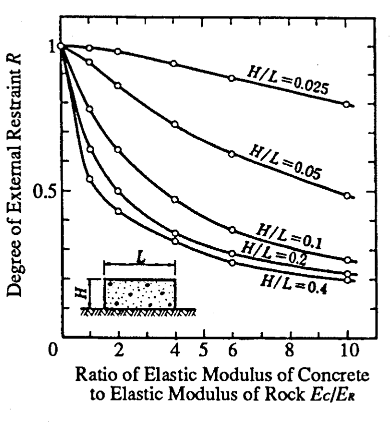


Figure 12 Degree of External Restraint at Rock Face

According to the results of surveys at Shimajigawa Dam, leakage from the dam was minimal at 2 *l*/min. per drainage hole at most and this value is small even in comparison with values at dams constructed by conventional methods.[13]

The high level of watertightness obtained by the RCD Method is thought to be due to motars spreading and the care taken to prevent segregation as mentioned earlier in the construction, as well as the use of external concrete and transverse joints with waterstops.

6. TEMPERATURE CONTROL IN RCD METHOD

As the RCD Method differs from the column method, traditionally used in construction of concrete dams, in that the concrete is placed without longitudinal joints, there arose a need to study new methods of preventing thermal cracking.

Temperature control in the RCD Method was studied by Hirose and Nagayama[14] by adding new considerations to Equation (1) below, an equation traditionally used to express thermal stress. It was discovered that, since the degree of external restraint (intensity of rock restraint) is determined by H/L (Figure 12), concrete can be placed without longitudinal joints even in extremely long layers, if, for practical purposes, the cooling of the dam concrete does not occur until placement of the dam concrete has been completed. (Cooling of the dam concrete is slow because pipe-cooling and other forms of artificial cooling are not used at RCD dams, while the speed of the placement is relatively fast.)

$$\sigma = R E_c \alpha \Delta T \qquad (1)$$

where,
R : Degree of Rock Restraint
E_c : Elasticity Coefficient of Concrete
α : Thermal Expansion Coefficient of Concrete
ΔT : Lowering of Temperature in Concrete

The importance of the thermal stress due to internal restraint which was thought to be relatively unimportant in the column method was pointed out, the temperature in the RCD dam not being uniform at the time of completion of the placement. A thermal stress analysis method using the degree-of-restraint matrix was then developed and a number of discoveries, particularly useful in construction of high dams by the RCD Method, were made from the calculation results, such as that the restraint thermal strain is related to the time of placement (Figure 13) and that the maximum restraint thermal strain and the positions at which it occurs vary according to the heights of the dam (Figure 14). Miyagase Dam, under construction at present by the Ministry of Construction, is one of the largest RCD dams in the world, with a height of 155 m and a volume of 2 million m^3. The thermal stress analysis method using degree-of-restraint matrices was applied to the planning of temperature control in the construction of this dam and investigations were made on such items as the allowable maximum temperature of the concrete, the most advantageous time for commencement of placement and application of pre-cooling.[15]

7. ECONOMIC ADVANTAGES OF RCD METHOD

The RCD Method has the following advantages in comparison with conventional methods.

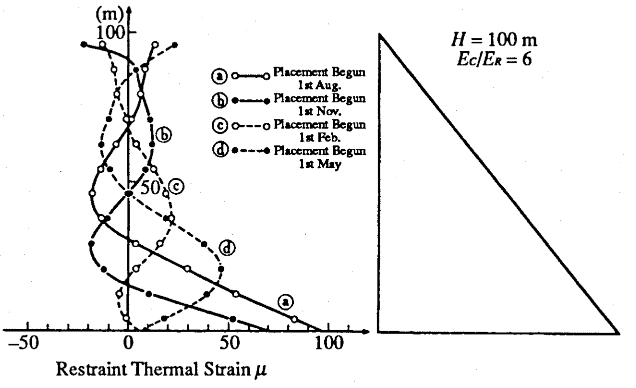


Figure 13 Relationship between Time of Commencement of Placement and Distribution of Restraint Thermal Strain in Dam (Central Part of Each Layer)

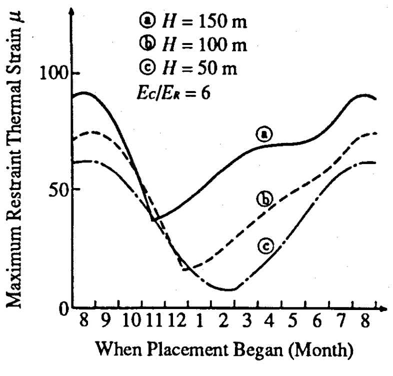


Figure 14 Differences in Maximum Restraint Thermal Strain according to Sizes of Dams (Dam Heights)

1) Reduction of construction costs

2) Increased efficiency of labor

3) Higher level of safety in construction

4) Smaller adverse effect on the environment

5) Adaptability to mass concrete in places other than dams

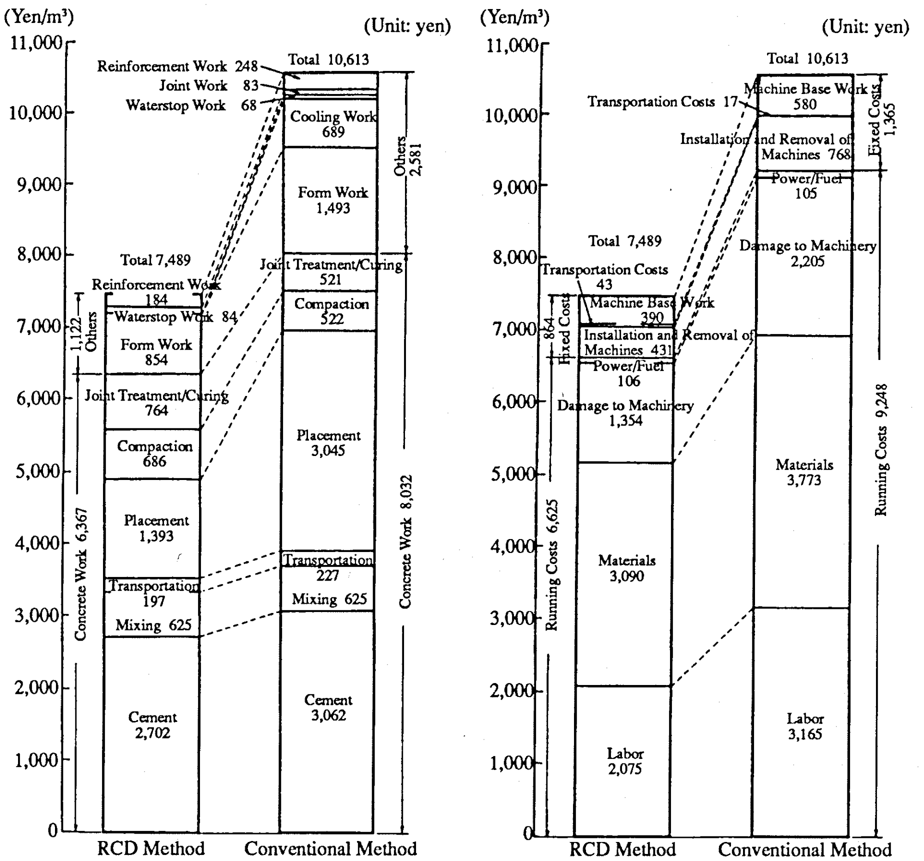
Of these 1) and 2) will be discussed in this section. In making economic comparisons, one needs to take account of the the variation in labor and material costs according the time and place of construction. The costs were, therefore, adjusted using deflators prepared for each year and region. The prices of the aggregate varied according to regions. Investigations below are made without taking account of the costs of aggregate as it is judged that this will not greatly affect the overall conclusions.

Comparative study was made on 5 dams each constructed by the RCD Method and conventional methods. (All of these dams were either completed or under construction in 1986.)

The construction costs were compared using the unit costs per cubic meter of concrete calculated according to types of work and items of expenditure from the design estimates. The averages for the five dams constructed by the RCD Method and the five by the conventional methods are shown in Figure 15.

As far as can be seen from this figure, the construction cost per cubic meter of concrete can be as much as ¥ 3,000 lower in RCD dams. The reasons include the reduction in labor, the reduction in the quantities of cement used, the reduction due to the fact that materials such as cooling pipes and some of the joint forms were not used and the reduction in costs related to machinery due to the use of general-purpose construction machinery. The reduction in labor is because mainly of a) reduction of form work due to the omission of longitudinal joints and lack of form work on transverse joints, b) lack of cooling works due to the omission of cooling pipes and c) increased efficiency due to mechanization of placement and compaction.

The differences in the costs, however, are not absolute as the advantages of the RCD Method may be smaller depending on the shapes and the structures of the dams.



(a) According to Types of Work

(b) According to Items of Expenditure

Figure 15 Composition of Unit Cost of Concrete Excluding Cost of Aggregate (Average of 5 Dams)

The efficiency of the work in the RCD Method, due a) to the fact that the time required for placement of concrete can be reduced to around 80% of that in conventional methods and b) to the fact that the construction machinery can be used more efficiently, allowing for flexibility in the placement work, is also a major factor that needs to be taken into account in assessing the economic advantages of the RCD Method.

The RCD Method has advantages with regard also to safety as there are no dead angles, unlike in the column method, and to environmental considerations as there is no need for large-scale excavations required for installation of large cable cranes.

8. CONCLUSION

Discussed above are the technical merits of the RCD Method and the state of recent research on the method.

The RCD Method was taken up as a major theme in the research for rationalization of dam construction and has been developed jointly by the organizations concerned by overcoming numerous technical problems through laboratory tests and test fills. A large number of problems still remain, however, if the techniques are to be improved further and brought closer to perfection. These include the clarification of the mechanism of compaction by vibratory rollers, further reduction of costs through, for example, raising the efficiency of surface treatment at joint faces and the problems related to spreading of the techniques, such as the investigations on the detailed design of RCD dams.

Finally, the authors would like to take the opportunity to express their sincere gratitude to the members of the "The Committee on Rationalized Construction of Concrete Dams" and all those who contributed to the technical development of the RCD Method by conducting various tests and on site.

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