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Development of design mix roller compacted concrete dam at Middle Vaitarana

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Abstract. The development in roller compacted concrete (RCC) is replacing the conventionally vibrated concrete (CVC) for faster construction of dam during last three-four decades. Notwithstanding, there have been relatively less works reported on the utilization of RCC in dam constructions, especially the dams having considerable height. Further, the Ghatgar dam was the only dam in the tropical country like India constructed using the technology of RCC until two years back. However, with the completion of 102.4 m high Middle Vaitarana Dam (MVD), owned by Muncipal Corporation of Greater Mumbai (MCGM), India, has become the first largest roller compacted concrete dam. The paper traces step by step aspects of the mix design of RCC in respect of the afore-mentioned project besides the construction aspects; and also, demonstrates as to how 12.15 lacs cubic meter of roller compacted concrete was placed within the record duration of 15.2 months, thus, rendering the MVD as the ninth fastest RCC dam in the world. The paper also discusses the various mix proportioning, quality control, constructional features and instrumentation with respect to the high RCC dam such as Middle Vaitarana.

Keywords: Conventionally vibrated concrete (CVC), Roller compacted concrete (RCC), Compaction, Layers, Placement, Zero slump

1. Introduction

Mumbai, one of the thickly populated metropolitan cities in India is the capital city of the Maharashtra state in the country. It is also regarded as the commercial capital of India. Mumbai has the largest inflow of migrants from all over the country. Municipal Corporation of Greater Mumbai (MCGM) is continuously making concerting efforts to cope up with the growing demands for water towards the domestic and industrial consumption. The Vaitarna River, a west flowing river originating from the ranges of the Sahyandri, in Maharashtra state, is one of the major sources of water supply to Mumbai city.

The potential of the river has already been partly harnessed by the MCGM by constructing two storage dams in series across the river, i.e., Upper Vaitarna dam and Lower Vaitarna dam (commonly called as Modak Sagar dam), with combined yield of 986 million liters per day

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(MLD). These existing dams are 42 kms apart. After construction of the proposed Middle Vaitarna dam, releases from Upper Vaitarna Power Station is expected to flow in to Middle Vaitarna reservoir. The city's present population is 14.50 million. The projected population in 2021 is expected to be 17.15 millions, in 2031 the same is expected to be 19.39 millions, and 2041 it is expected to reach the figure of 21.21millions. Consistent water supply is one of the major factors that lead to the development of city. The present supply of water to the city of Mumbai is drawn from four major and two minor sources.

At present available quantity of water at source is 3688 MLD as against the water demand of 4240 MLD. This gap shall go on increasing exponentially in future. Taking this aspect into consideration, the MCGM thought of constructing the dam, referred to as the *Middle Vaitarna Dam*, in between two dams constructed earlier across the river Vaitarana. The research and investigations addressed in this paper relate entirely to the Middle Vaitarna Roller Compacted Concrete (hereinafter referred to be as the RCC) dams. In view of the fact that many of the observations made and the hypotheses presented relate to the nature of RCC as a material and the methods applied for construction, it is considered appropriate to provide some background on RCC in the area of construction of dams. Consequently, the paper presents a background for RCC construction describing the typical compositions of RCC, isolating specifically the 'high-paste' RCC that is of particular interest; the split level methodology applied for construction and RCC placement are discussed.

The 102.40 m high *Middle Vaitarna Dam* mainly consists of a left and right non- overflow section. While the left non-overflow section starts from the record distance (RD) 15 m to 76 m, the overflow section, from RD 76 m to 172 m with the probable maximum flood (PMF) capacity of 6800 cumecs. The maximum ambient temperature ranges from 44 degrees to minimum of 7 degree. Similarly, the right non- overflow section starts from RD 172 m to 565 m. The total length of the Dam at the crest is 565 m with its riverbed level at 186.5 m and top level at 287.40 m. The overflow section is 96 m long with 5 bays of 15m wide and 6 No's Piers of 3.5m width. The overflow section is ogee shaped and designed as high ogee. The overflow section consists of five radial gates (15 m × 12 m) and a trajectory bucket type energy dissipation arrangement (EDA) with sloping apron.

The dam is mainly composed of RCC which is placed in 30 meter thick layers. Both faces are made of Grout Enriched Vibrated RCC (GEVR). The components such as piers, crest and glacis for overflow section was planned to be constructed with the conventional concrete (CVC). Total length of the non-overflow section is 454 m in which left non-overflow section is 61 m and was planned to be constructed with the conventional concrete.

The right non-overflow section is 393 m long and was to be constructed with the RCC. The spillway portion, 96 m long, was planned to be constructed with the RCC up to the bottom level of piers, i.e., up to a level 253 m. With the placement rate of RCC about 134000 cum per month, the *Middle Vaitarna* has become tenth fastest RCC dam having been completed in the World. The total volume of the RCC placed is 12.30 lacs cum within the effective period of 15.2 months.

2. Background

The term Roller Compacted Concrete (RCC) is used to describe a concrete employed in the construction of dams, which combines the economical and rapid placement techniques used for fill dams with the strength and durability of concrete. As a consequence of the application of high capacity plant and equipment, it is most suited to use in large-scale construction and for mass concrete works. Since the early 1980s, the RCC has gained general acceptance as an appropriate material and method for the construction of dams and by the end of 2012, more than 550 large RCC dams have been completed worldwide. The RCC is also being used for pavement construction and rehabilitation works of hydraulic and offshore structures worldwide.

The issues of interest regarding RCC include: design considerations (i.e., seismic aspects and thermal-structural analysis for temperature control), characterization of the materials used in it (aggregates, cementitious materials and admixtures), proportioning of the mixes, construction (transportation and compaction), quality control and performance. The emergence of the concept of RCC as a sustainable construction material, especially in the context of gravity dams, has given the rise for the research on afore-mentioned aspects.

Some of the works reported on the thermal behaviour of RCC dams include that by Luna and Wu (2000), Francisco (2003), Sabbagh *et al.* (2007), Dunston (2009); and Yu *et al.* (2011). Further, the performance and construction aspects including material ingredients have been worked upon by some of the researchers including Schrader and Tatrao (1985), Hansen and Mclean (1992), Hooten (2000), Cervera *et al.* (2000), Schrader (2002), Langan *et al.* (2002), Wieland and Brenner (2004), Cengiz (2005), Pane and Hansen (2005), Schrader (2006), Hong (2011); and Rafaei *et al.* (2011), Shaw (2012). The literature available on the multi-faceted RCC gravity dam is scanty and scattered; most of the literature focuses on the thermo-structural behaviour of RCC gravity dams and relatively lesser work is reported with respect to development of the mix design, performance of admixtures, and construction of RCC dams, especially in respect of high dams in the tropical countries.

In the early days, the RCC was perceived as a low quality and low strength mass material. However, nowadays it has become possible to produce a range of concrete qualities by the compaction of roller, with the most common product being a dense, high quality and relatively high strength concrete.

In principle, the RCC is placed and compacted in 300 mm deep horizontal layers, at rates often exceeding 3000 m^3 per day, allowing construction progress commonly of around 10 m in height per month. The main benefits of RCC for dam construction are increased economy and more rapid implementation. In order to minimize the contents of cementitious materials and take advantage of the fact that the critical zones of a large dams do not generally experience load for an extended period after placement, characteristic strengths for RCC are specified at ages of up to one year and commonly not less than 90 days.

2.1 Modern RCCs

The modern RCCs are primarily designed in accordance with two different approaches, namely- overall approach and separate approach. While the former approach relies on the dam body for water-tightness through high quality concrete and treatment to ensure well-bonded layer and lift joints, the latter relies on an independent impervious barrier, which is usually placed on the upstream face in the form of facing elements, such as CVC layers, geo-membrane, etc.

The majority of the RCC dams contain mineral admixtures, most commonly fly ash, as an active constituent of the concrete. Beyond the basic requirements of strength, a modern RCC mix is defined by the paste/mortar (p/m) and the sand/aggregate (s/a) ratios, the maximum size aggregate (MSA) and the modified Vee- Bee time. These parameters essentially relate to the achievable density (and impermeability as well), the achievable compaction ratio and the tendency of the constituent materials to segregate during handling. Under construction conditions, the afore-mentioned properties determine workability and the difference between permeable and stoney RCC with planes of weakness; and a cohesive, seamless watertight and dense RCC.

For the overall approach, the mixes are designed for maximum density with a paste/mortar ratio of at least 0.37 being required to achieve a density of 98.5% of the theoretical air free density (TAFD). In modern RCC practice, a tendency to use a MSA of 37.5 or 40 mm has developed since larger size aggregates demonstrate a tendency to segregate in RCC mix during handling operations. While early RCC testing suggested that a lower sand/aggregate ratio was optimal for RCC, compared to conventional vibrated concrete (CVC), a practical experience in the interim has demonstrated that quality control and the maintenance of RCC consistency is much more realistically achieved in an RCC with a sand/aggregate ratio exceeding 0.35. The workability of RCC is determined by testing with the Vee- Bee apparatus, which is modified to include a surcharge mass of 19.1 kg. For workable RCC, the modified Vee- Bee time should lie between 10 and 20 seconds. For high-workability RCC, a modified Vee- Bee time of 8 to 15 seconds is usually specified. In the case of lean RCC, the modified Vee -Bee time generally exceeds 30 seconds.

3. General features of RCC dams

The RCC dams are mainly gravity dams, but this technology has also been used for some arch gravity dams with a vertical upstream face, i.e., single curvature arch dams. The stresses in gravity dams due to dead load and water load in the reservoir are relatively small in most parts of the dam. The highly stressed zones are confined to relatively thin layers at the up and downstream faces and at the heel and toe of the dam, where local stress concentrations are present. This allows the use of concrete with a relatively low strength over most parts of the dams. Unfavorable tensile stresses, which are also confined to the up- and downstream surface layers, mainly in the upper portion of the dam, may be caused by the earthquake action.

The main economic advantages result from the following features of RCC dams:

(i) **Speed of construction**: Large volumes of (low or high paste) concrete can easily be placed with the heavy equipment, thus shortening the construction period of these dams.

(ii) **Low unit costs of RCC:** The unit cost of low paste mass concrete is favourable, to reduce the heat of hydration a significant portion of cement is usually replaced by locally available pozzolanic materials or fly ash.

(iii) **Incorporation of the spillway into dam body:** Due to slope of the downstream face of 1:0.8 (gravity dams) to 1: 0.4 (arch gravity dams), the spillway can directly be incorporated into the dam body. This is a major advantage for dams which have to accommodate large floods and which are in need of large spillways.

(iv) **Use of shape of conventional dams:** Because the stresses in gravity type dams are low, the cross-sections of RCC dams are the same as those of conventional dams.

Because of the above advantages, RCC dams are the interesting alternatives to conventional dams in most parts of the world. However, some of the possible disadvantages are the following:

(i) **Water tightness:** Due construction of the dam in thin horizontal layers, in the case of the high hydraulic gradients, water may percolate along the horizontal construction interfaces. Special measures may be needed at the upstream face of the dam to improve the water tightness, i.e., layer of high paste monolithic mass concrete mass concrete.

(ii) **Limited Experience of engineers and contractors:** Few designers and contractors have extensive experience with the design and construction of RCC dams. The design and construction practices are still in development.

(iii) **Limited Experience with safety and long term performance:** No large RCC dam has been exposed to extreme loadings like strong ground shaking during an earthquake or large floods.

(iv) **Galleries:** The placement of RCC around formwork, which is needed for access galleries in the dam body, is tedious and slows down the construction process.

The main weaknesses of RCC dams are the water tightness under high hydraulic gradients, ageing mechanisms and the unknown performance under seismic loading.

4. Emerging concepts in design and construction

With a very significant number of approaches attempted during the early years of development of RCC, three primary concepts seem to have emerged for the design and construction of RCC dams:

- The *lean RCC* dam for which the cementitious materials content is less than 100 kg/m^3. For such mixes, often only Portland cement is used without mineral admixtures or pozzolanic material.
- The *RCD method* (roller compacted dam) unique in Japan for which the cementitious materials content is generally 125 kg/m^3, but only the hearting zone of the dam is made of RCC.
- The *high-paste RCC* dam for which the cementitious materials content is greater than 150 kg/m^3. In the case of high-paste RCC, the RCC material itself provides the watertight barrier and must be designed for an in-situ permeability equivalent to that of traditional dam mass concrete. The RCC and the associated construction methods must further be designed to ensure effective bond between layers. Various facing systems are applied for high-paste RCC dams, but with the simple objective of creating a good and durable surface finish. Transverse joints are induced at pre- determined intervals,15 to 20 m which are generally wider than in the case on a conventional vibrated mass concrete dam.

In early RCC dam construction, a particular problem was recognized as low bond between successive placement layers. Whilst a relatively high shear friction angle could generally be assured between layers under all circumstances, low cohesion and tensile strengths were compounded by high permeability when a new layer was placed on an excessively mature existing layer.

Development in the mix design has included the use of set of retarding admixtures and the use of sloped and non- continuous layer placement methods to ensure the freshness of the underlying RCC layer when the subsequent layer is placed. While such practices are only implemented where required as part of the dam design, the result is a seamless bond between successive RCC placement layers, with joint properties equivalent to the parent RCC properties.

5. RCC mix composition

In case of lean RCC, the material itself is not designed for impermeability and consequently, the requirements for aggregate grading are not necessarily as prescriptive as would be the case for CVC, although density is always important in the case of a dam.

Lean RCC is also often referred to as a dry consistency mix RCC. With similar water contents to high-paste RCC, i.e., 100 – 125 lit/m^3, aggregate contents are obviously relatively high. To ensure consistency and ease of compaction under construction conditions, lean mix RCC often contains a high proportion of aggregate fines (often around 8% of the total aggregate content)(3) that form part of the paste fraction. Ignoring the aggregate fines, the typical lean mix would contain approximately 140 litres of paste per cubic metre of concrete. Including 8% fines in the aggregates, the total paste would be of the order of 200 litres.

In view of the fact that high-paste RCC is designed for impermeability, the maximum density is important and consequently, a continuous aggregate grading is applied. For the latest high-workability RCC mixes, the more restrictive aggregate specifications than required for CVC are applied, with lower compacted void ratios and tighter restrictions in respect of aggregate shaping and flakiness. For all high-paste RCCs, aggregates of suitable quality for use in a concrete corresponding to 30 MPa concrete are required. While it is common to allow relatively high percentages of sand fines in RCC to increase the paste volume, ignoring this component, a high paste RCC would comprise approximately 200 litres of paste and 800 litres of aggregates per cubic metre of concrete.

5.1 Development of RCC mixture proportions for MVD

The design criteria for RCC mix was strength of 15 MPa @ 365 days and target strength of 17.5 MPa. There were four requirements for RCC to be used in water retaining structures of Ghatghar project the first dam (84 m tall) of its kind in India made of RCC. These requirements include impermeability, density, strength and the ability to be transported, spread and compacted without detrimental segregation.

The numbers of mix design trials were carried out at Maharashtra Engineering Research Institute (MERI), Nashik (India) for RCC mix design under the guidance of Dr. Malcom Dunstan, eminent RCC consultant. After observing the mix and the strength development of the cylinders for various combinations of cement fly- ash and aggregates mix was decided with the use of 60 percent of fly -ash. The mix that was suggested by MERI for Ghatghar RCC dam project is indicated in Table 1.

Table 1 Mix suggested by MERI for Ghatgar project

Structure	Mix adopted	Results/Observations
Test section- 1	G-85	Segregation, insufficient strength and weak in joints.
Test section -2	G-85	Insufficient strength and weak in lift joints
Saddle dam	G-85 (C88:F132)	Good strength, proper bonding at horizontal joints, better densities and impermeable structure.
Upper dam	G-85	Similar to Saddle 1 but more adiabatic temperature rise.
Lower dam	G-85	More strength than required, more adiabatic temperature rise and less fines in sand.
	G-75 (C75:F150)	Sufficient strength, comparatively less adiabatic temperature rise, fines increased.
	G-70 (C70:F180)	Sufficient strength, comparatively less adiabatic temperature rise, fines increased.

The above established pattern was retried, in view of the similar prevailing conditions as regards the source of aggregates and climate, with exhaustive trial mixes in the site at the quality control and materials testing facility developed at Middle Vaitarna and the G- 75 was found suitable with slightly modified contents fly ash (C 75: F 145) and was finally adopted at Middle Vaitarna after full scale trials. The main reason for G-85 RCC mix that could not give sufficient strength in test sections was improper gradations and dose of admixture.

5.1.1 Mixer uniformity

The uniform mixing operation is critical for good quality RCC. The development of strength is commonly used indicator of cement contents. Unfortunately, the early age strength of RCC are so low that, using compressive strength as a uniformity indicator is not always conclusive. However, in laboratory *Wash Test* was carried out fortnightly along with the Air entrainment, oven dry and compressive tests. These last three tests were carried out daily in laboratory. However, the temperature of RCC at the time of placement was maintained between 7°C to 23.50°C. In addition, Vee Bee tests hourly and Nuclear Density tests at 150 mm and 300 mm depth was carried out for 500 square meter of surface area. For a batching plant of 240 cubic meter capacity each, two in numbers, the minimum mixing time was 40 seconds.

5.1.2 Aggregate feed system

The aggregates were supplied to the proportioning and mixing plant by using front end loader to feed aggregate to tippers and further to feed bins at the plant. Further, aggregates were batched and they were cooled with the use of sprinklers and brought down to super saturated condition before loading into tippers. All the aggregates were batched and they were discharged in to a mixer. While mixing progress, the mass hopper was recharged with aggregate to continue the process. This batch mixer was coupled to a mixer. The mixture constitute cement, fly ash, water, admixture, ice flex etc. were accumulated in individual mass hopper or volumetric container to be transferred with aggregate to the mixer.

5.1.3 Continuous feed system

The continuous feed system was used to provide a continuous, uninterrupted flow of material. The material was discharged from bins through an adjustable gate opening on to a variable speed conveyor belt. The gate opening and belt speed were varied to achieve a specific rate of aggregate feed. Individual aggregates were often layered on to a single belt feeding the continuous mixer. The feed rate of other constitutes was adjusted in proportion to the rate of aggregate feed. Continuous feed system was used for continuous mixers. Twin horizontal shaft mixer was used for production of RCC which is called as pug mill. They were having the capacity to handle aggregates up to 150MSA. However, in case of Middle Vaitarana Dam, the maximum size of aggregate used was 50 mm. The mixing proportion was based on the feed rate of the material rather than mass per volume. Conveyor system was completely covered and insulated so that none of the cooling of the ice is lost. Chilled water was also used to maintain the temperature of concrete.

5.1.4 Aggregates

The total requirement of coarse and fine aggregate crushed was 32,00,000 MT. Rubble required for production of aggregates was obtained from a quarry located on upstream of the dam around 3 km away from the dam site. Three aggregate processing plants (APP) with total; capacity

Fig. 1 Aggregate stockpiles

of 720 tonnes per hour (TPH), namely- APP-1 having capacity of 320 TPH, APP-2 having capacity of 200 TPH; and APP-3 having capacity of 200 TPH were installed on the downstream side of dam.More than 5 lac MT aggregate was crushed and stockpiled before the start of RCC. Average production of aggregate was around 1.1 lac MT per month. The aggregate processing plant and some stockpiles are shown in Fig.1.

5.1.5 Cementitious Materials

The peak months' placement of RCC was around 100,000 cum. Thus, supply of 7500 MT cement was required. The cement was supplied from Eklahare Thermal Power Station located at Nashik which is 90 kms away from the project site. The delivery of cement was in 50 kg bags and the cement was stored in two silos of 250 MT and also in bags, 3000 MT. The cement for RCC was used from single source only.

The fly-ash was made available from Nashik and Dahanu thermal power plants which are located in the nearby vicinity of approximately 100 kms from the project site. The peak monthly requirement of fly ash was 13500 MT. The delivery of fly- ash had been accomplished in bulker of 20 MT capacities. The total 1500 MT of fly ash supplied was stored in four silos of 250 MT capacities each and one with 500 MT capacity.

6. Steps in proportioning of RCC mix

The process of proportioning RCC mix depends upon the strength and temperature requirement for design, the properties of available materials and the desired workability. Based on the tests performed in site quality control and testing laboratories for developing proportions for a typical mix with target compressive strength of 17.5 MPa at 365 days, following steps were resorted to:

i. Selection of suitable aggregates
ii. Selection of suitable range of trial mixes consisting of various cement and fly ash

contents

iii. Selection of desirable water contents for preparing RCC cylinders for each trial mix
iv. Selection of fines of about 35% by volume of aggregates
v. Preparation of RCC cylinders for strength testing
vi. Preparation of RCC specimen for durability
vii. Selection of mix proportion based on laboratory test results
viii. Adoption of the mix for full scale trial section (FST)

7. Trial mix programme

Trial mix programme was conducted in August 2009. The two retarders were chosen as being the most likely admixtures- Fosroc Conplast- R (as was used at Ghatghar RCC Dam Project) and an admixture from a local supplier, APEX. About seven different types of admixtures were put to trial for their performance.

7.1 Trial mix Nº1

Trial Mix Nº1 was mixed at 1210 Hrs. on 25 August 2009 and had mixture proportions of 75 + 145 + 117 (cement + fly-ash + water including the admixture). The mix contained the APEX retarder. The mixture proportions satisfied all the requirements, such as a coarse aggregate content less than 0.52 m/m^3, a fine aggregate content being in the range of 30 - 40% of the total aggregate and a paste/mortar ratio more than 0.40. The mix had an excess of paste and looked satisfactory after remixing. The Loaded Vee- Bee time was 12 seconds and the Loaded Vee-Bee density 99.3% of the theoretical-air-free density. Overall, this was a satisfactory mix that could easily be used.

7.2 Trial Mix Nº2

Trial Mix Nº2 was mixed at 1440 Hrs on 25 August 2009 and had mixture proportions of 70 + 150 + 117. The mix contained the Fosroc Conplast-R retarder. The mixture proportions satisfied all the requirements. This was a good-looking mix and could, without doubt, be used at full-scale. The Loaded Vee-Bee time was 11 seconds and the Loaded Vee Bee density 97.9% of the theoretical-air-free-density.

7.3 Trial Mix Nº3

Trial Mix Nº3 was mixed at 1710 Hrs on 25 August 2009 and had mixture proportions of 65 + 155 + 117. The mix contained the Fosroc Conplast R- retarder. The mixture proportions satisfied all the requirements specified. This was also a good-looking mix; the ‘ball’ could be formed very easily. There were no signs of segregation and again, this mix could be used in the field. The Loaded Vee-Bee time was observed to be 12 seconds and the Loaded Vee-Bee density was observed to be 97.8% of the theoretical-air-free-density (TAFD).

7.4 Trial Mix Nº4

Trial Mix Nº4 was mixed at 10.20 Hrs. on 27 August 2009 and had mixture proportions of 60 +

160 + 117. The mix contained the Fosroc Conplast R- retarder. The mixture proportions satisfied all the requirements. This was found far less workable than the previous mixes and there was some segregation observed. With the present workability in respect of this trial mix, it would be very difficult to work in the field. The Loaded Vee-Bee time was 25 seconds and the Loaded Vee-Bee density, 95.9% of the theoretical-air-free density. This was less than the specified limit of 97.5% and probably indicates some form of error in the batching/sampling process.

Following the above four trial mixes, it was determined that the workability required using the materials procured for Middle Vaitarna Dam (MVD) project was equivalent to a Loaded Vee- Bee time of between 8 and 15 seconds, with an optimum value being between 10 and 12 seconds.

Table 2 Values of the compressive strengths during various trials taken for the mix design

RCC mix trials	Compressive strength (MPa)					
	7 days	28 days	56 days	91 days	180 days	365 days
G-75 (C75+ F135)	2.91	4.21	7.67	10.52	16.81	22.35
G-75 (C75+ F145)	3.15	4.95	7.89	10.82	17.31	24.50
G-65 (C65+ F155)	1.25	2.54	3.98	5.33	12.85	18.56
G-75 (C75+ F150)	3.46	4.49	8.21	11.24	17.90	25.50
G-70 (C70+ F135)	2.2	4.02	6.58	11.1	18.10	24.20

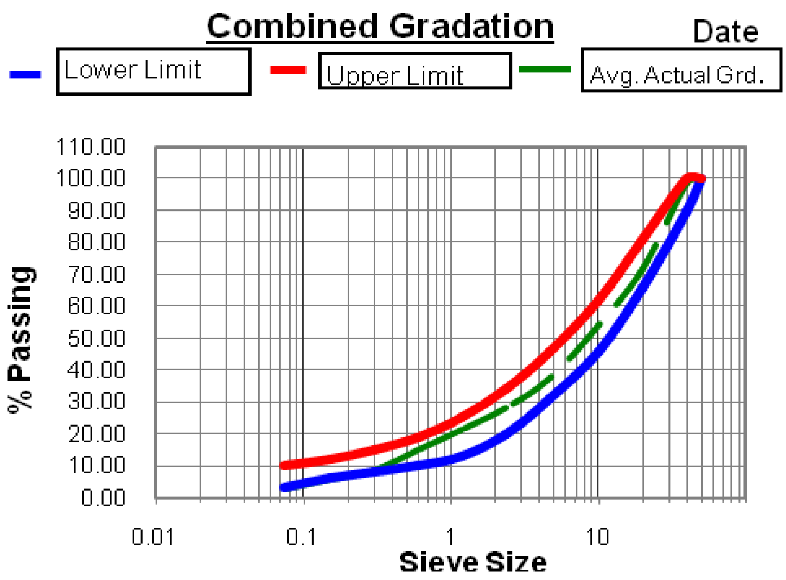

Fig. 2 Combined gradation curve for RCC mix (After Dunston 2009)

8. RCC mix design

An extensive trial mix program was undertaken in the laboratory before the full scale trial. The main objective of the RCC was to design the cohesive mix that would not segregate during transportation, dumping, spreading and compaction within the limitations of the materials available. The design mix of RCC is a developing mix and placement methods which allows the RCC to develop the lift joint strength and permeability characteristics to eliminate the need for a bedding mix except at the infrequent super cold joint which inevitably occur.

The main objective of mix design is to study the initial setting time as per site planning and target compressive strength by using different proportions of cement and fly ash. About 180 trial mixes were tried before arriving at the final mix design. Trial mixture proportion of (C-75 + F-135 + W-115) with admixture Fosroc Conplast 'R' retarder was found to satisfy the requirement. For this mix, loaded Vee- Bee time was 12 second and loaded Vee Bee density, 97.8% of the theoretical air free density. Other mixes were also tried with different admixtures. But the afore-mentioned trial mix proportion was the best proportion observed in all trials. Some of the trials taken are enumerated in Table 2. While the results for 7. 28 and 56, 91, 180, and 365 days' results are indicated in Table 2, the results corresponding to 1000 days are not incorporated. Similarly, combined gradation curve for RCC mix is shown in Fig.2.

Following RCC Mix proportion was finalized:

Cement -75 kg/ m^3, Fly Ash: 135 kg/ m^3, Water: 115 kg/ m^3, Admixture: 1.2%, i.e., 2.52 kg/ m^3, Crushed sand: 768 kg/ m^3, Aggregates: 40 mm- 768 kg/ m^3, 20mm – 420 kg/ m^3, 10 mm- 461 kg/ m^3, Vee Bee time: 8 to 12 seconds, Setting time: 21$\pm$ 3 Hrs., Water cement ratio: 0.52, Placement Temperature: 7^0 C to 23.50^0 C, Paste Mortar Ratio, i.e., Vp/Vm – 0.66.

9. Full Scale trial (FST) section

The full-scale trial (FST) aims at training of all those involved with the construction of the dam. In the present work, the objectives of trial included: Optimization of the methods of spreading and compacting the RCC along with that of raising of formwork, a review of the methods to be used for the treatment of hot and cold joints and also that of performance of set-retarding admixtures retarders; and a review of the assessment of optimization of the method of GVER.

The FST was conducted in December 2009 and January 2010 with G-75 Mix i.e. 75 kg/cu m cement and 135 kg/cu m fly ash. Full scale trial (FST) section comprising of size 50 m long, 10 m wide and 5.4 m height with 30 cm thick layer was planned and constructed in December 2009 and January 2010. The total section was constructed in 18 layers. Table 3 depicts the summary of the joint conditions that was tested during FST.

The mix used in the full scale trial contained 75 kg/cu m cement and 135 kg/cu m fly ash in addition to other ingredients. Admixtures used for full scale trial were produced by using various commercially available admixtures tested during FST stage Fosroc, (complast-R), BASF-Pozzolith 423,Sika- Retarder G1, MYK-Remitard, Apex-Add plast G. Out of these set-retarding admixture produced by Fosroc, Apex and MYK was found to show consistent retardation for the site during FST, as shown in Fig. 3.

Table 3 Summary of the joint conditions for FST

No. of RCC layers	Aims/ Objectives
4	To test the sufficiency of form work
2	To test the hot-joint treatment under normal circumstances
4	To compare the performance of hot and warm joint treatment
2	To compare the performance of warm and cold joint treatments
2	To compare the performance of cold and super cold joint treatment
2	For initial training of engineers and staff

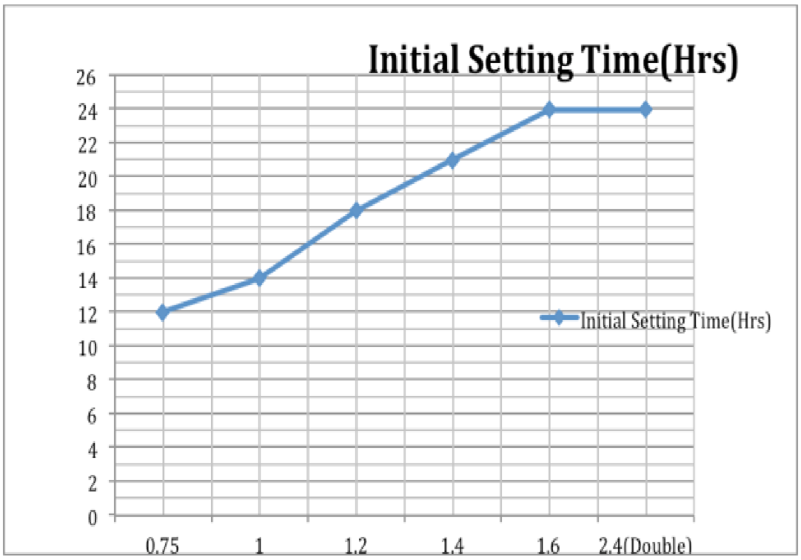

Fig. 3 Improvement in setting time of RCC for various admixture dosages

9.1 Cylinder compressive strength of FST

The values of average strength of the cylinders manufactured during the Full Scale Trial (FST) are observed to be low as compared with those tested during the trial mix programme (TMP). However, the in-situ values of the compressive strengths of core are found to be very reasonable. The average compressive strength of all the cores tested from the FST was 16.0 MPa.

The developments of cylinder compressive strength of the RCC for the seasons (and TMP and FST) at Middle Vaitarna are shown in Fig 3. Also shown is the development of strength of the cylinders at Ghatghar (up to an age of three years). It can be seen that in all the cases the strengths exceed the design strength of 17.5 MPa at the design age of a year. The compressive strengths of RCC cylinders at different ages are shown in Fig. 4. In order to ascertain the in-situ performance of RCC, the cylindrical samples were collected regularly from each RCC layer round the clock and were tested for the compressive strength. The 20- point moving average plot corresponding to different ages is shown in Fig. 5.

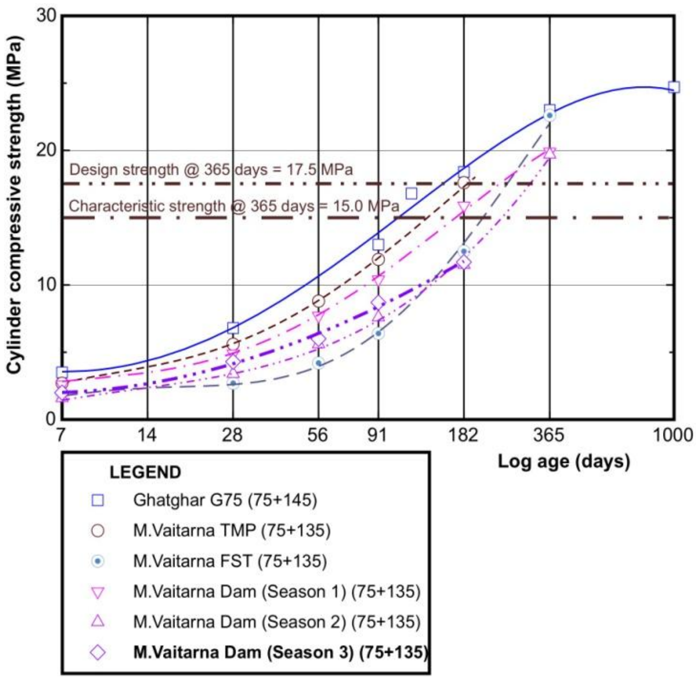

Fig. 4 Development of cylinder compressive strengths with edge

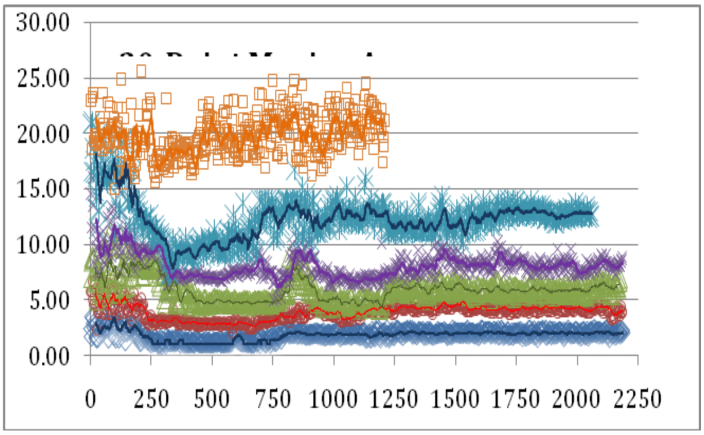

Fig. 5 In-situ compressive strength (MPa) of RCC cylinders corresponding to different ages

Table 4 Summary of the results of FST

Compressive strength (in MPa) for 91 days	14.79
Direct tensile strength (Mpa) for 91 days	2.90
Permeability (91 Days)	Impervious

9.2 In-situ permeability of RCC

Not only did the cylinder compressive strengths exceed the design requirements, all the values of the compressive strengths of cores were found to be even higher. Several permeability tests were undertaken on cores, both in the laboratory at the site and at a Government laboratory. All the tests showed an excellent in-situ impermeability including a significant number at which no permeability could be measured at all. In addition, the cores were taken through the RCC and grout enriched vibratable RCC (GEVR) into the abutments and in all cases excellent bond was observed at the interface.

The cores of 150 mm diameter were extracted from the FST section and these were tested for compression, tension and permeability at testing facility at MERI, Nashik (India). The results in respect of the tests carried out on FST are given in Table 4. It is observed that the in-situ permeability is very low which is expected in high paste content RCC.

10. RCC Construction

A number of different approaches exist for the placement of RCC, but the essential principle is to place and compact 300 mm (compacted) layers as rapidly as practically possible, creating a monolithic mass either by placing successive layers before the first set of the previous layer, or by binding layers together with a bedding mortar, or concrete. The RCC is generally placed continuously between upstream and downstream formwork and the abutments, with no expansion joints and with the induced joints at predetermined intervals to accommodate long-term shrinkage and creep; and thermal contraction due to temperature drop loads.

The surface of the RCC must be “green-cut” and treated with mortar, or grout before placement above is resumed depending upon exposure time and type of joint. The RCC construction operations including transporting, dumping, spreading and compacting is indicated in Fig. 5.

Fig. 5 RCC construction- dumping, spreading and compaction

Fig. 6 RCC surface after compaction at Middle Vaitarna

10.1 RCC compaction

The passage of trucks, etc. can make an impression. While lean or dry consistency mix RCC simply consolidates in the same manner as a fill under compaction, the consolidation causes paste to be squeezed through the aggregate structure and to rise to the surface in high-paste (and particularly high-workability) RCC. The compaction is achieved with 10 to 15 tonne, single-drum vibratory rollers generally applying four passes in either direction to achieve the target compaction. The behaviours of lean RCC and high- paste RCC under vibratory compaction are quite different; with the former consolidating to form a hard and flat surface and the latter producing a 'live' surface, especially when the set is retarded. The development of the paste mortar on top of the layer desirable for interlayer bonding following the compaction is seen in Fig. 6.

10.2 Induced joints in RCC

The joints are induced in RCC at specific cross-sections by de-bonding placement by between 25 and 100% and thereby creating a localized weakness that will concentrate cracking consequential to long term temperature drop shrinkage at a pre-determined location, where it can be isolated with a water stop. While South African practice has to date inserted a de-bonding mechanism in every fourth layer international practice generally applies de-bonding in every layer. The early practice of inserting de-bonding systems into the RCC during placement but before compaction has almost universally been replaced by driving de-bonding systems into compacted RCC.

Although several methods and systems are used for de-bonding RCC to create an 'induced joint', all result in an increased compressibility on the induced joint as compared to the adjacent RCC. While the construction process causes a disturbance of the RCC on either side of the induced joint, the insertion of folded plastic sheeting, geotextile material, or a folded galvanized steel sheet, implies that the aggregate-to-aggregate contact within the RCC is broken. As the presence of the de-bonding system implies that the RCC structure cannot be as effectively redeveloped during the subsequent re-compaction, the increased compressibility is undoubtedly not only the consequence of a compressible joint filler, but also a slightly more open structure within the concrete on either side.

A consequence of the evident compressibility of the de-bonded areas of the induced joints is local exaggerated movement/closure during thermal expansion of the RCC. As the temperature of the RCC rises with the evolution of hydration heat, it will experience expansion, which will be restrained by the continuity of the placement in a direction parallel to the dam axis (left to right bank direction). Due to the fact that joint inducers are only installed in every layer in the dams, their presence will not reduce the overall resistance of the RCC mass to thermal expansion, nor will it cause any perceptible increase in the overall compressibility of the full joint, but it will undoubtedly give rise to increased local compression across the actual de-bonded section of the joint.

10.3 Programme of RCC placement

The total volume of concrete for the dam was 1,550,000 cu m, out of which Roller Compacted Concrete was 1,215,000 cu m and the conventional concrete was 3,35,000 cu m. The planning of placement of the RCC had been based on a 17 month period, i.e. one month before 2010 monsoon,

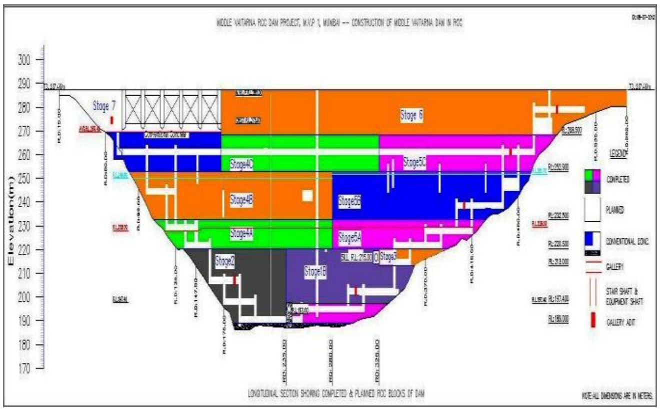

Fig. 7 Construction stages for split level method at MVD

Table 5 Staged placements for Middle Vaitarna

Season	Stage	Volume of RCC placed (cu m)
2009 -10	Stage 1A	63563
2010 -11	Stage 1B	186482
	Stage 3	31129
	Stage 2	183602
	Stage 4A	72463
	Stage 5A	65892
2011-12	Stage 4B/4C	234281
	Stage 5B/5C	227760
	Stage 6	137244

eight months (i.e., October to May) between the 2010 and 2011 monsoon and the eight months between the 2011 and 2012 monsoon (Table 5).

The longitudinal section across the centre line of the dam showing various stages of the placement for split level methodology and gallery layouts is shown in Fig. 7.

Thus 1,215,000 cum of RCC were needed to be placed in 15.2 months at an average rate of 71470 cum/month. The placement at Middle Vaitarna was split into two parts using split level method of construction. The figures mentioned in Table 2 shows the placements of RCC for the Middle Vaitarana.

10.4 Treatment of horizontal joints between layers

These joints are the most controversial and weak zones on RCC Dams, similarly to conventional concrete dams; but the main difference is that in the former the joints are spaced 0.30 m (thickness of layer) and that in the latter, at 1.5 to 2.5 m. The more number of joint in first case demands more attention. Today these joints are classified as hot joint (no treatment needed), warm joint, cold joint (treatment needed), super cold joint (treatment needed). These joints are classified based on the main criteria for determining a type of joint is through concept of Maturity Factor, also called as the Modified Maturity Factor (MMF). It is defined as product of mean hourly temperature, measured on the surface of layers in deg Celcius by the time in hours elapsed between the placing of two successive layers.

MMF = T (hr.) X t (C)

The planning of the construction should be such that numbers of cold joint or super cold joint formed is minimal.

10.5 Exposure times for joint treatment

There are four types of joint treatment used at Middle Vaitarna Dam (MVD). The allowable exposure time between the layers relative to each joint treatment was based on the average monthly temperature estimated for MVD site. These are shown in Table 6.

Table 6 Exposure times for joint movement with respect to monthly temperature at site

Month	Mean temp (^{o} C)	Exposure times for joint treatments (hr)			
		Hot	Warm	Cold	Super cold
January	25.8	< 16	16-32	32-63	> 63
February	27.5	< 15	15-30	30-61	> 61
March	30.0	< 14	14-29	29-57	> 57
April	31.9	< 14	14-27	27-55	> 55
May	33.8	< 13	13-26	26-52	> 52
June	31	< 14	14-28	28-56	> 56
July	26.6	< 16	16-31	31-62	> 62
August	26.5	< 16	16-31	31-62	> 62
September	27.7	< 15	15-30	30-60	> 60
October	29.7	< 14	14-29	29-58	> 58
November	28.8^{o}C	< 15	15-29	29-59	> 59
December	27.6^{o}C	< 15	15-30	30-61	> 61

Fig. 8 Downstream view of the completed dam along with appurtenance structures

10.6 Instrumentation at Middle Vaitarna Dam

The dam is expected to safely withstand the forces created by impoundment of water over longer period. The proper and safe functioning of dam is an extremely important matter of economic benefits and public safety. Instruments are the tools that can monitor the integrity of the hydraulic structures during construction, first filling of reservoir and the long term service operations. The RCC dam is provided with the state –of**-** the**-** art instrumentation works at various levels, such as Electric Thermo-couples (428 numbers) at five sections across dam cross section, stress meters, strain gauges, uplift pressure meters, joint meters, pore pressure meters, etc.

11. Conclusions

Based on the foregoing discussion and with reference to the roller compacted concrete designed and employed in the present investigation, some of the conclusions that can be arrived upon are mentioned below:

- The average compressive strength of all the cores tested from FST was found to be 16 MPa, i.e., more than target design strength of 15 MPa, with the coefficient of variation 18.1% which seems to be reasonable.
- Reduction in cement content beyond 70 kg/ cu m caused reduction in the strength of roller compacted concrete (RCC).
- The in-situ permeability was found to be very low as is expected with well designed high paste content RCC.
- The RCC mix is very sensitive to gradation of aggregates. The percentage passing through 40 mm should be around 80 to 90% to avoid segregation.
- Higher strengths can be achieved for sand – aggregate ratio of 0.35 to 0.36.
- Fineness modulus of sand around 2.8 gives consistent results.
- The mix design was found to achieve the targets, such as initial setting time and the

compressive strength, set for trials.

- The rise in temperature of the roller compacted concrete (RCC) was found to be a function of total contents of cement and fine aggregates in the mix and the compaction factor ratio.
- With partial replacement of cement content up to 40%, the mass concrete structures proved faster and substantially economical than the conventional concrete.
- The admixture could make it possible to achieve initial setting time of fresh RCC upto 36 hours.
- The mixture with Vee Bee time less than 20 seconds showed less segregation than that in mixture having higher Vee Bee time.
- The rise in temperature of RCC was found to be a function of total C+F contents and compaction factor ratio.
- Appropriate treatment in respect of joints between successive RCC layers was observed most important for achieving the interlayer bond between the layers.
- Admixtures performed well initially; but the saturation point reached after adding 2% dose. Further addition of admixtures proved less significant in modifying the properties of RCC.
- Results obtained in respect of the full scale trial section (FST) fall in line and agree fairly with those in respect of the in-situ cylinder tests extracted from the main dam section.
- The placing temperature of RCC and the curing conditions at site needs to be controlled properly in order to minimize the thermal problems.

12. Summary

The total construction period including the initial mobilization for materials and machinery and for preparatory works, in respect of the RCC dam was three and a half years as against the estimated five years which would have required for a traditional concrete dam and seven years for a masonry dam. The early RCC dam completion has allowed the reservoir to be impounded up to 67 % of the total storage during the first 2012 monsoon (the gates on the spillway would not be installed until after the monsoon) and thereafter, for 100% of the storage to be utilized. This has created an additional income for MCGM of an estimated INR 150 Crores (27 Million US Dollars).

The downstream view of the completed 102.4 m high RCC dam constructed with ogee spillway and trajectory bucket type energy dissipation arrangement with radial gate is depicted in Fig. 8.

Not only did the RCC dam allow early impounding, it is estimated (allowing for account escalation and interest during construction) that there was a saving to the tune of 37% cost as compared to other forms of dam construction. Following the great success of the Ghatghar Project, the first RCC dams in India, the Middle Vaitarna dam has been a similar success not only in terms of the speed of construction but also in terms of the quality of the structure. It may be noted that the galleries were bone dry during an overtopping during the 2011 monsoon. This success was, in no small measure, attributed to all parties associated with the project, the owner, the designer, the contractor and the project manager who worked together.

The success of Middle Vaitarna Dam should lead to a further expansion of RCC dam constructions in India. The first two large RCC dams in the country have set a very high precedent. Along similar lines, the RCC application in other areas of civil engineering needs to be expanded.

References

Cengiz, D.A. (2005), “Strength properties of high volume fly ash (HVFA) roller compacted and workable concrete and influence of curing conditions”, *Cement Concrete Res.,* **35** (6), 1112-1121

Cervera, M., Oliver, J. and Patro, T. (2000), “Simulation of construction of RCC dams Temperature and aging”, *J. Struct. Eng.,* **126**(9), 1062- 1068

Dunston, M.R.H. (2009), “SonLa - progress at the largest RCC dam in Vietnam”, *Int. J. Hydropower Dams* ,**1,** 2009.

Dunston, M.R.H. (2009), *Middle Vaitarana Dam (MVD) - Report of the Site Visit,* submitted to Muncipal Corporation Greater Mumbai (MCGM)

Hansen, K. and Mc Lean, G. (1992), “Roller compacted concrete”, *Proceeding of the Conference Roller Compacted Concrete Dams in USA (ASCE), February 2-5*

Hooton, R.D. (2000), “Canadian use of ground granulated blast furnace slag as a supplementary cementing material for enhanced performance of concrete”, *Can. J. Civil Eng.,* **27**, 754-760

Francesco, A. (2003), “Thermal analysis of RCC dams during considerations”, *Proceeding of the 7th ICOLD Benchmark Workshop on Numerical Analysis of Dams,* Bucarest (Romania), 24-26 September

Luna, R. and Wu, Yang (2005), “Simulation of temperature and stress fields during RCC dam construction”, *Jl. Const. Eng. Mngt.,* **125**(5), 362-368

Pane I. and Hansen, W. (2005), “Investigations of blended cement hydration by isothermal calorimetry and thermal analysis”, *Cement Concrete Res.,* **35**(6), 1155-1164

Rafael, A., Noriega, G., Sandoval, A. and Sanz, M. (2011), “Limestone filler used as a cementitious material in the mix for the largest RCC dam in Europe : La Brena II”, *Proceeding of the 31st Annual USSD Conference on 21st Century Dam Design- Advances and Adaptations, San Diego, California, April 11-15,* 259-272

Sabbagh, S.R., Yazdi, and Mastorakis, N.E. (2007), “Galerkin finite volume solution of heat generation and transfer in RCC Dams”, *Int. J. Math. Models Meth. Appl. Sci.,* **4**(1), 261-268.

Shaw, Q. (2012), The beneficial behavioral characteristics of fly ash –rich RCC illustrated through Changuinola 1 arch/ gravity dam:, Proceeding of the International Conference Innovative Dam and Levee Design and Construction

Yu, H., Li, S. , Liu, Y. and Chen, C. (2011), “Study on temperature distribution due to freezing and thawing at the Fengman Concrete Gravity Dam”, *Thermal Sci*., **15** (1), S27-S32

Shrader, E. and Tatro, S.B. (1985), “Thermal considerations for RCC”, *J. Am. Concrete Inst.,* **82**(2), 119-128

Schrader, E. (2002), “Experiences and lessons learned in 30 years of design, testing, constructions and performance of RCC dams”, *USSD News Letter,* **127**, 8

Hong, Y.W., Du, C.B. and Jiang, S.Y.(2011), “Innovative design and construction of high RCC gravity dam in high seismicity intensity region”, *Practice Period. Struct. Design Const.,* **16**(2), 67-72.

Langan, B.W., Weng, K. and Ward, M.A. (2002), “Effect of silica fume and fly ash on heat of hydration of Portland cement”, *Cement Concrete Res.,* **32**(7), 1045-1051

Wieland, M. and Brenner, R.P. (2004), “Earthquake aspects of roller compacted concrete and concrete face dams*”, Proceeding of the 13th World Conference Earthquake Engineering,* Vancouver, BC. Canada, August 1-6, Paper No. 3399

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