

ROLLER COMPACTED CONCRETE FOR DAM CONSTRUCTION

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ABSTRACT. This paper will discuss the advantages of Roller Compacted Concrete (RCC) for use in mass concrete gravity dams as compared to other types of Gravity dams not only from a safety standpoint but from a constructability standpoint, economical and environmental standpoint. The use of RCC has been developing for last 40 years and is now recognized as a most practical solution in the design and construction of major hydropower and water resource projects worldwide. From the time of their inception and designers and constructors alike continue to refine RCC development with new innovative ideas leading to cutting edge technology applied to RCC Dam construction. According to a data base created by Dr Malcolm Dunstan and associates as published in Hydropower & Dams as of 2010 there are approximately 550 RCC Large dams (ICOLD > 15 metres tall) under construction or completed worldwide.

Keywords: Roller compacted concrete (RCC), High cementitious RCC (HCRCC), Low cementitious RCC (LCRCC), Concrete faced rock fill dam (CFRD), Conventional vibrated Concrete (CVC).

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INTRODUCTION

This paper will discuss the history of Roller Compacted Concrete (RCC) dam construction and various applications and advantages to Gravity dam design and construction since its inception when the first RCC dam (Willow Creek) was designed and constructed by the USACE in 1982. Also included in the content is an accurate comparison and realization to the costs, durability during overtopping events while under construction including many case histories as well as other detailed advantages realized over the past 30 years from a practical standpoint as well as a design standpoint. The author would also like to point out that there have been many “lessons learned” and recent trends over the development of RCC dams.

Roller compacted Concrete a brief history

Roller Compacted Concrete (RCC) has been rapidly developing over the past 40 years and is now commonly used for mass concreting operations typically in a Gravity Dam application. With a widely varied methodology of design theories and project specific considerations, RCC is not only extremely practical from a constructability standpoint; it is also, along with other advantages, very cost effective.

Although there have been many applications of a dry mixed concrete in the history of concrete construction and differing opinions of its inception, one of the first known substantial application of Roller Compacted Concrete (RCC) was in the mid 1977 at the Tarbela Dam project on the River Indus in Pakistan (then referred to as “Rollcrete”). Several other applications of Rollcrete were used at Tarbela for various reason until 1980 (E Schhader) (Figure 1 and 2).

The application at Tarbela Dam was for an emergency backfill operation after a malfunctioning gate failure in the powerhouse headrace tunnel released a high volume of water downstream creating a huge cavity in the plunge pool area and immediately downstream of the Earthfill dam foundation. With concerns about the integrity of the newly built Tarbela Dam consuming 127 million cubic metres of Earth and Rock fill material, the Engineers on the project collectively proposed an emergency backfilling operation with a “0 slump dry mix concrete”.. During this application of the Rollcrete backfill operation some 18,000 m³ was placed in a single 24 hr period.



Figure 1 Tarbela earthfill dam

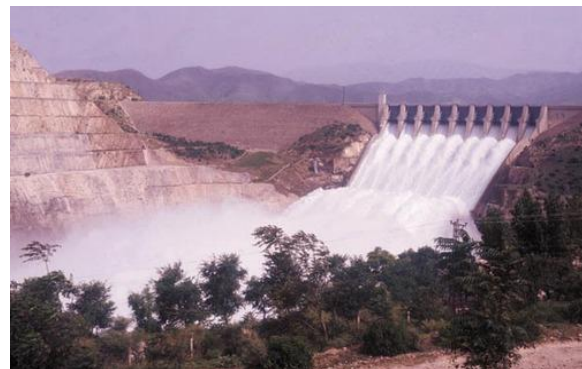


Figure 2 Main spillway Tarbela Dam
Pakistan

The Application of RCC at Tarbela was extremely successful as and became quite significant over the next 40 years and a new age of concrete dam construction was born. Specifically, the Development of Roller Compacted Concrete.

In the early 1980's the first RCC dams were being proposed and successfully built in the US and Australia. By the end of 1985 there had been only 7 large (greater than 15m; ICOLD) RCC dams completed. By the end of 1990 this number had risen to 59 RCC dams completed (Dunstan 1992) and as of last year 2010 over 450 RCC dams have been built worldwide (Hydropower & Dam 2010) with another 50 planned or under construction worldwide. Some now reaching heights approaching 300 m tall.

RCC- A Clear advantage

There are many things to take into consideration when designing a large dam > 15 metres (ICOLD). This paper will not go into the design aspects in detail but when considering a RCC for a project there must be the proper resources available to the site to make it more economical these site specific conditions include the following:

- Adequate foundation conditions
- Adequate aggregate sources in close proximity to the dam site
- Supply of cement
- Supply of a natural Pozzolan or fly ash

Particular and critical resources are the access of Fly ash or natural Pozzolanic material as most RCC dams use considerably more fly ash or pozzolan than conventional concrete (CVC) and in some cases mixes use double the fly ash than cement. This was a tremendous advantage over CVC dams as the use high amounts of fly ash (pozzolantic materials) are in most cases cheaper generate considerably less heat of hydration and promote better workability as well a high past that enables a good bond between layers of RCC placed during rapid construction without the use of a bedding material that further has potential to slow production of RCC construction.

Further advantages from a design standpoint is the strength of the RCC Mass. The amount of cementitious material for a RCC mixture can vary from as low as 100 kg/m^3 to as high as 245 kg/m^3 depending on the design parameters with corresponding compressive strengths of approximately 10 MPa to as high as 45 MPa. Test results for high cementitious mix designs for the recently completed Yeywa RCC dam and the ongoing Nam Gnouang dams in direct tension across the lift joints are as high as 3.0 and 2.21 MPa respectively which is considered excellent. Generally in the industry most RCC dams are now designed using the high past philosophy that is $> 150 \text{ kg/m}^3$ of cementitious material. It should be further noted that several RCC dams have been build with lower amounts of cementitious material with great success including several in North America and as recent as the Taum Sauk reservoir and Saluda dam in South Carolina in the USA that will be further discussed below. Most dams over 100 m tall including the recently completed 134 m tall Yeywa RCC dam (Myanmar),the Kodiat RCC dam (Algeria) and the ongoing 131 m tall Dong Nai 4 (Vietnam) and several others RCC dams in Southeast Asia as well as worldwide are adopting the "High Cementitious" approach (HCRCC). The choice of a mix design is highly dependent the region in which the dam is being built, the height of the dam as well as the resources available.

Another big advantage is the rate of placement for RCC dams is the rate of placement of the 4 RCC as compared with CVC. At Longtan Dam (China) a maximum daily rate of placement

was as high as 18,000 m³ with a corresponding average monthly rate of 144,000 m³ while at Yeywa (Myanmar) the maximum daily rate was 7700 m³ the average monthly rate of placement was 72,568 m³. Maximum monthly rates for the top ten fastest rates range from approximately 130,000 m³ Yeywa (Myanmar) and 425,000m³ Longtan (China). It should be further noted that there have been several RCC dams with monthly rates of placement of between 20,000m³ and 40,000 m³ as the wrong equipment was procured for these projects in an attempt to save initial costs but substantial financial losses in Power generation were lost in the final delivery of such projects. These losses could have been mitigated with the implementation proper expertise in the early development of the project leading to proper equipment procurement and set up as well as effective planning from initial quarry development, aggregate production to RCC batching, delivery and placement equipment.

Advantages of RCC dams as compared to Concrete Faced Rock fill Dams (CFRD) and Earthfill dams

There have been many dams that were designed as CFRD's and changed to RCC as the developments in the designs have proved in many cases that the RCC option proved more economical. One such originally designed CFRD that was changed to RCC was the Al Wehdah RCC dam in Jordan, Figure 3 (See IWP&Dam construction August 2009). Al Wehda still remains in the top ten fastest constructed RCC dams while 1.4 million m³ RCC dam was placed in 19 months.



Figure 3 Al Wehdah RCC dam Jordan

The recently completed Taum Sauk Upper Reservoir Rebuild Project for the pumped storage facility near Lesterville, Missouri. The original dam was a CFRD and suffered a 215 m long breach after being overtopped and was replaced by a low cementitious content (LCRCC) RCC 90 kg/m³ and RCC construction period of just 26 months with an average monthly rate of placement of 88,000m³ with a corresponding maximum daily rate of placement of approximately 14,150 m³.

It should be noted that the original CFRD was completed in 1963 and took 4 years to construct. The rebuild project was constructed by Ozark Constructors with design being done by Paul C. Rizzo Associates.

The project was a huge success and is currently a State of the art “pumped storage” facility as the RCC dam was built in an emergency rebuild operation using nearly all of the existing CFRD material and processing it into RCC for the complete dam structure which includes an emergency spillway.

Another example where a RCC dam was built for an emergency ballast fill behind an earthfill dam was the Saluda project in South Carolina USA where an existing zoned earth fill was deemed unsafe as an intensive investigation was done and within and downstream of the dam (Figure 4). After further analysis, it was apparent that the dam could be subject to Liquefaction and a catastrophic failure could occur during an earthquake event. As a result of the seriousness of the aging structure it was concluded that an RCC dam be build immediately Downstream of the original dam for safety concerns. This project was a huge success containing some 1 million m³ RCC and achieved a rate of placement of 13,000 m³ in a single 24 hr period.

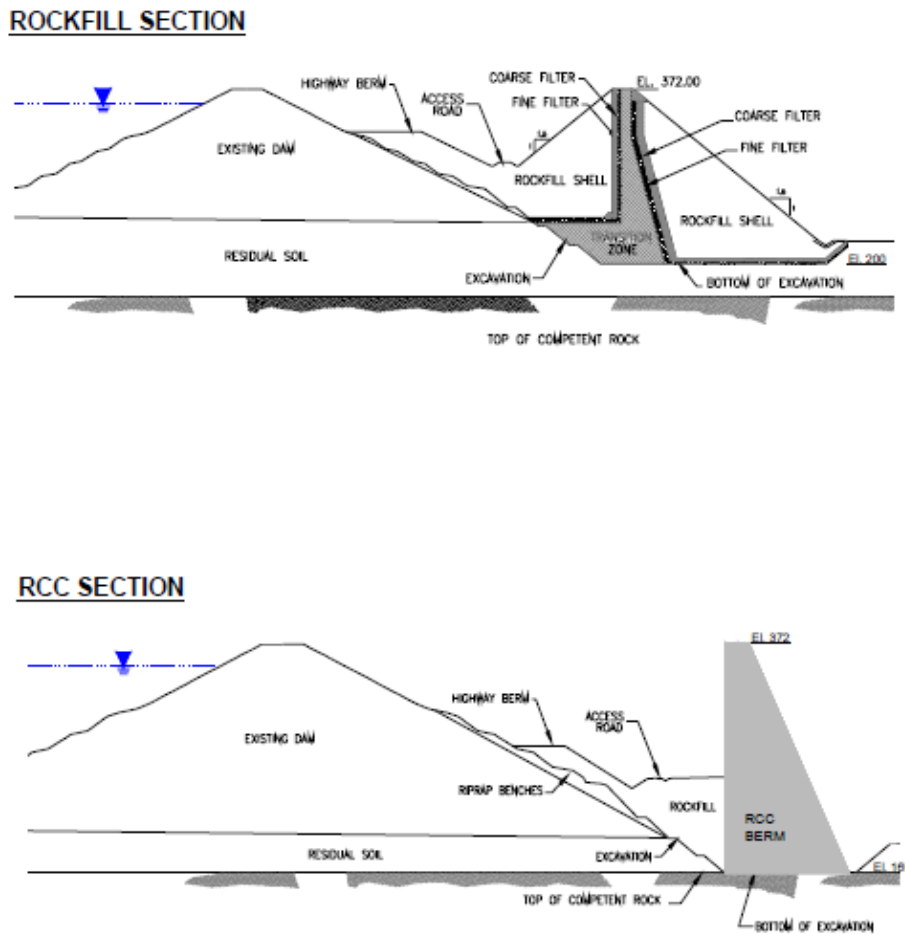


Figure 4 Proposed Saluda RCC dam remediation USA

Another significant advantage is the environmental concerns of the respective types of dam construction. RCC dam have a smaller footprint and require substantially less mass than earthfill dams and CFRD's.

The amount of natural environmental disturbance ie quarries, clearing and large food print excavation as well as substantially larger borrow areas and environmental runoff can be as much as half that of the mentioned counterparts to promote a cleaner and more environmentally friendly construction environment.

Another significant advantage with in the development of RCC dam construction is the fact that the diversion schemes can be significantly reduced in size with further cost savings and reducing the overall construction schedule as the RCC dams can be overtopped during flood stages without any significant damage to the main structure as opposed to their earthen counterparts.

Such overtopping events have happened to several RCC dams during construction. Also cofferdams can be built with a lean RCC mixture to prevent failure during a flood event. Many designers are realizing this and can plan for such events using an integrated (insitu) cofferdam within the structure to prevent downstream scouring of the RCC foundation similar to the massive erosion mentioned at Tarbela. This method was used and properly implemented at the 155 m Ralco RCC dam in southern Chile (see August issue International Water Power and dam august 2009) where the construction of the 60 m tall earth and rock fill cofferdam was nearly complete and was partially destroyed just before the start of RCC (Figure 5). The partially destroyed cofferdam was then rebuilt with RCC to a lower elevation and withstood 3 more overtopping events with no damage to the cofferdam or RCC main dam and only a few days were lost due to these flood events because the proper precautions were made to withstand the wrath of mother nature for three flood seasons during its RCC construction period. Ralco still remains in the top ten fastest constructed RCC dams at average rate of placement of 76,000 m³ / month.

The same design concept was adopted at the Yeywa RCC dam (Myanmar) (Figure 6) as an integrated spillway and cofferdam was implemented into the works to protect the powerhouse. This project was only overtopped 1 time during the first flood season in 2006 during the early stages of RCC construction. below shows the integrated raised upstream spillway, the placing of stage 8 and the longitudinally integrated CVC cofferdam protecting the powerhouse



Figure 5 Second overtopping event 155 m tall Ralco dam (Chile)



Figure 6 134 m tall Yeywa RCC dam (Myanmar)

Another more recent example of an RCC dam with a planned overtopping and integrated spillway is the 70 m tall Nam Gnouang (Figure 7) currently under construction in Lao PDR. The design of the NG dam was for the 50 year return period all of the coffer dam to protect the works were earthen and Rockfill dams.



Figure 7 Nam Gnouang Dam

The first flood event came in September 2010. When the 25 meter upstream cofferdam completely failed as the water in the river rose at a rate of 1 meter per hour after a Tropical Storm engulfed the catchment area and in a matter of a few hours the cofferdam failed sending a large volume of water onto the 140,000 m³ RCC already placed with an integrated spillway similar to the Yeywa project. The Partially built RCC dam withstood a surge of water passing over the dam at a rate of 2000 m³ per second while the diversion was passing some 500 m³ per second. The entire dam construction works was inundated and totally destroyed the downstream cofferdam. It should be noted that was no damage to the partially built RCC dam and the RCC operation continued immediately after the flood waters receded. See Figures 8 and 9 below.



Figure 8 RCC spillway being overtopped after first flood



Figure 9 RCC integrated spillway after river receded No damage to RCC structure

Upstream earthen coffer failure and water inundation the RCC placement operation

A second flood occurred on 15 Sept where the rebuilt coffer dam failed again and the RCC was overtopped with a volume of 2500 m³ per second.

A third event caused another overtopping that cause further erosion downstream and the RCC dam and integrated spillway passed some 3000 m³ per second for nearly 10 day. There was still no damage to the RCC dam other than minor erosion as the RCC was only 10 hrs old when the flood occurred. Total erosion of RCC was negligible at some 10 cubic metres. (Figures 10 and 11). Again the RCC started immediately after the overtopping event receded (Figures 12 and 13).



Figure 10



Figure 11 Nam Gnaoung Dam third overtopping 3,000 m³/sec over dam



Figure 12 RCC production continues during overtopping event



Figure 13 Nam Gnoang dam after third flood RCC resumed

Had this dam been an earthfill or a CFRD as originally considered, major losses of time and damage to the dam would have been inevitable. During the Third overtopping event it was possible to continue RCC production at the left abutment as the dam was designed to overtop and with the integrated spillway within the RCC dam allowed the contractor to continue work at the left abutment while the river was flowing over the spillway. Another significant advantage of RCC dam construction.

CONCLUSIONS

From an owner stand point as well as an a designer and constructor the application of RCC dams is developing as a more economical, safe and practical solution for water storage projects. The applications of Roller compacted concrete and development has gone from the early days at Willow Creek where the first RCC dam was designed and constructed as an RCC dam. Since then many other applications of RCC have been used as a ballast for larger dams, spillways in existing earthen structures as well as Pavements.

The applications in dam design and construction has been extremely significant as there are nearly 500 of these type of Gravity Dams world ranging from 15 metres tall to 243 metres tall under construction or planed by the end of 210. The tallest RCC dam constructed to date is the 192m tall Longtan RCC dam in China. Some of the tallest under construction are the Diamer Basher dam (Pakistan) at 272 m tall, the 220 meter tall Nam Nguam dam in Central Laos, and the ongoing 243 Gibe III project in Ethiopia.

The application of RCC in gravity dams is the clear choice for safe dams worldwide.

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