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Seepage Mitigation in Hydropower Dams by Optimization in Roller Compacted Concrete Interlayer (Monoliths) Joint Bonding Technology

Junjie Jin[1], Qingguo Zhou[2], Yuanguang Liu[3], Shuncai Ning[4]

[1]Kafue Gorge Lower Hydropower Station, Sinohydro Bureau No.11 Co. Ltd, Zhengzhou, China
[2]Kafue Gorge Lower Hydropower Station Project, Sinohydro Bureau No.11 Co. Ltd, Zhengzhou, China
[3]Kafue Gorge Lower Hydropower Station Project, Institution of Engineering and Technology, Sinohydro Bureau No.11 Co. Ltd, Zhengzhou, China
[4]Expert Team of Sinohydro Bureau No.11 Co. Ltd, Zhengzhou, China
Email: jinjunjie@sinohydrohenan.com

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Abstract

Roller Compacted Concrete (RCC) has gained favorable recognition in hydropower and water resource dam construction. With optimization in construction technology and materials used for RCC Dams, cost is no longer a major disadvantage as compared to environmental impact, that is, wildlife habitat disruption. In as much as it has become optimal for investment in hydropower dam construction, the scourge for dam failure is still eminent, which is as a result of excessive seepage compromising the integrity of the mechanical properties of the dam. The aim of the paper is to highlight successful application methods in joint bonding to avoid excessive seepage and reduce the autogenous healing to a few years of operation. In view of optimization, this paper presents a comprehensive study on the influences of interlayer joints bonding quality from RCC mix performances and how it consolidates the RCC layers to withstand the shear strength along the interface, especially on the high dams. The case study is the RCC dam at the 750 MW Kafue Gorge Lower Hydropower Station. The scope of the study reviews the joint type judged by Modified Maturity Factor (MMF) with joint surface long time exposed in regions with dry and high temperature, technical measures of layer bonding quality control under condition of long time joint surface exposure, effects of joints shear strength and impermeability of the RCC layers when under the conditions of plastic and elasticity. The subtle observations made during the dam construction phases were with respect to the optimal use of materials in relation to RCC mix designs and the basis for equipment calibration for monitoring important data that can be referenced during analysis of shear forces acting on the RCC dam over time.

Keywords

Seepage, Roller Compacted Concrete (RCC) Mix, RCC Joint Exposure Time, Modified Maturity Factor (MMF), Dry and High Temperature Area, RCC Joint Bonding Quality, Control Measures, Impermeability, Shear Forces

1. Introduction

Roller Compacted Concrete (RCC) dam construction technology has been widely popularized and applied in hydropower and water resource construction around the world merely due to its low cost and short construction period. Since the first RCC dam in the world was built in Japan in 1981, up to now there are nearly 1070 RCC dams have been built in the world [1]. Through engineering practice and technological improvements in the past 40 years, the technology of RCC dam construction has exhibited exponential growth. However, there are still many challenges to research on and fathom regarding RCC dam construction technology, hence the consideration of dam construction to be the most expensive civil engineering projects [2]. In as much as natural disasters such as earthquakes and over-standard floods are found to be major cause of dams collapsing, the probability of dam failure has increased drastically in recent years with global climate changes, furthermore, through experience and research, the gradual failure of dams is as the result of the exponential growth of unplanned incipient seepage passages [3].

This paper presents and provides on feasibility basis, the implementation and successful application of RCC interlayer joint bonding technology with interlayer joint surfaces exposed in regions with dry and high temperature site conditions.

1.1. Project Description

The Zambia-Kafue Gorge Lower (750 MW) Hydroelectric Project (herein referred to as the KGL Project) is located on the Kafue River, a primary tributary of the Zambezi River, some 55 km upstream from the confluence of the Kafue River and the Zambezi River. KGL is located some 17.3km downstream from the Kafue Gorge Upper Hydropower Project (herein referred to as KGU) and some 5.9 km downstream from the KGU tail-water outlet. The catchment area upstream the Dam Site measures 153,000 km^2. The annual average inflow is 268.8 m^3/s, the main purpose is for power generation. At FSL of 579.00 m, the reservoir capacity is 83 × 106 m^3, and the active storage is 61 × 106 m^3. The main Dam is of RCC gravity-type, with a maximum height of 130.5 m tentatively, 374.5 m in length.

Dam crest is 8 m wide and footprint width with 120 m. The upstream slope of the dam is designed by 1:0.2 (V: H) and emerging to vertical at EL530m, while the downstream slope is designed by 1:0.75 (V:H) and emerging to vertical at EL569. 5m. The dam is divided into 19 monoliths, **Figure 1**, in which 7 monoliths of non-overflow section at left bank and 4 monoliths of over-flow section (spillway) and 8 monoliths of non-overflow section at right bank [1].

In general, the Zambian weather is subtropical continental. Rainy season starts in November through to March, occasionally it rains in September and October [4]. In Zambia, there are four seasons: the weather is cold and dry in winter from April to August with temperatures as low as 7.5˚C; the temperature rises and the weather becomes hot and dry from September to October with temperature reaching as high as 40˚C, according to site monitoring, raining usually starts in November, it is humid and stuffier at this time; the temperature drops from February to March, it is humid and cool with occasional rains. For meteorology data see **Table 1**.

1.2. Problem Statement

According [2], seepage through a dam is a slow discharge or escape of liquid that is supposed to be retained in the reservoir, through conduits (fracture/fault lines) to the flank of the dam. Excessive uplift pressure not accounted for in the design can be as a result of increased seepage through earth dams based on pervious

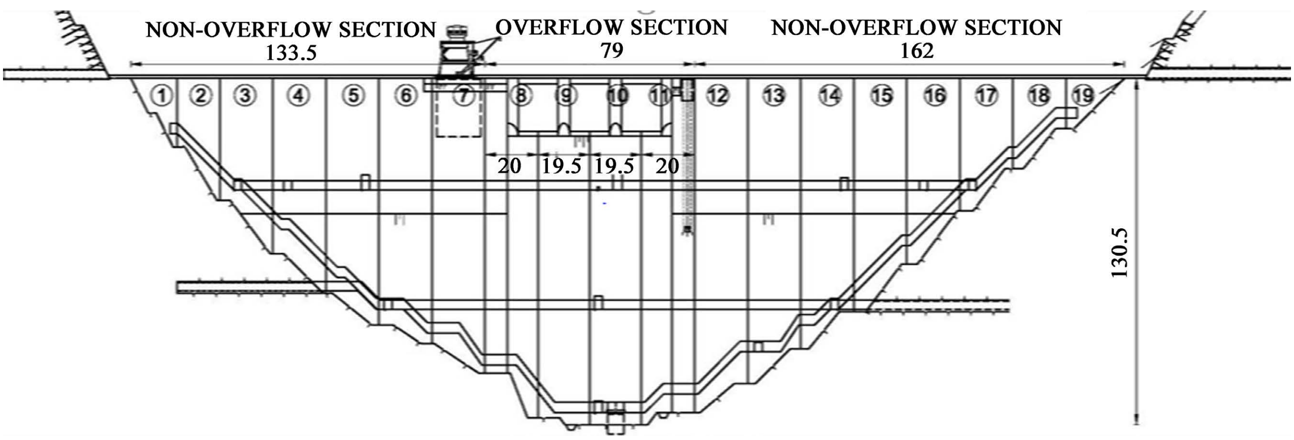

Figure 1. View at up-stream of dam.

Table 1. Meteorology data of Kafue gorge lower area.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year Aver.
Average Rainfall	205	153	68	26	2	0	0	0	1	19	81	210	766
Average Temperature	26.4	26.1	25.7	24.5	22.1	20.1	20	22.5	26.1	28.5	28	26.8	24.7
Average Evaporation	149	133	160	166	163	144	158	195	232	259	202	159	2120
Relative Humidity	78	80	77	68	63	62	57	50	43	44	56	73	62.6
Average wind velocity	1.6	1.6	1.8	2	2.1	2.2	2.5	2.7	3	2.9	2.5	2.1	2.2

layer [5], also permitting the loss of excessive amounts of water from reservoir.

As well known, RCC dam seepage often occurs in between the interlayer joints, hence, it is imperative to consider the quality of interlayer joint's bonding during construction of dam [6].

In addition, considering the fact that the curing temperature determines the strength gain rate and the value of compressive strength for cement-based materials, shear strength along the interface between RCC layers is an influencing factor, especially on high dams and those with steep downstream slopes [7]. Compressive strength is generally not a controlling factor except for its influence on shear strength and for very high dams where compressive stresses may be large.

Based on the comprehensive capacity of the batching plant production, transportation and site placement progress etc. [8], the interlayer joint surface maximum exposure time is set to be at least 16 hours which does not consider the conditions such as the malfunction of batching plant or other equipment. In order to ensure the quality of interlayer joint bonding, the project technician implemented and advocated for optimization in the following guiding topics: a) Optimizing of RCC mix proportion. b) Study of characteristic of joints under different exposure time and treatment. c) Establishing the control standard of Maturity degree at the placing site. d) Site quality control system.

2. Optimizing of RCC MIX

KGL project adopted one type RCC mix with 12 MPa @ 365d in full section of the dam, so that simplifying the placement procedures and improving the site placement rate. The technical requirement of RCC mix is as shown in **Table 2**. The concrete materials and final selection of RCC mix and its properties are discussed below. During KGL dam RCC construction peak period, the maximum placement block area was at circa 14,000 m^2 from EL470 to EL.510. The single layer (30 cm thick) RCC maximum volume reaches at 4250 m^3 (see **Figure 2**).

2.1. Properties of Raw Materials

2.1.1. Cement

The Lafarge Cement in Zambia was chosen as the main supplier. The Lafarge Cement Plant is relatively close to the site, and its output can reach 4000 t/day. It can be supplied steadily during the peak period of dam RCC construction. Type CEM-I 42.5N cement is selected for RCC mix design [9]. The cement complies with BSEN 197-1. The test results were as shown in **Table 3**.

Table 2. Performance requirements of RCC mix.

Compressive strength (Cylinder), MPa	Tensile strength (MPa)		Age (day)	Impermeability coefficient (cm/s)	M.S.A (mm)
	Indirect	Direct			
12	≥1.99	≥1.14	365	$\leq 10^{-8}$	63

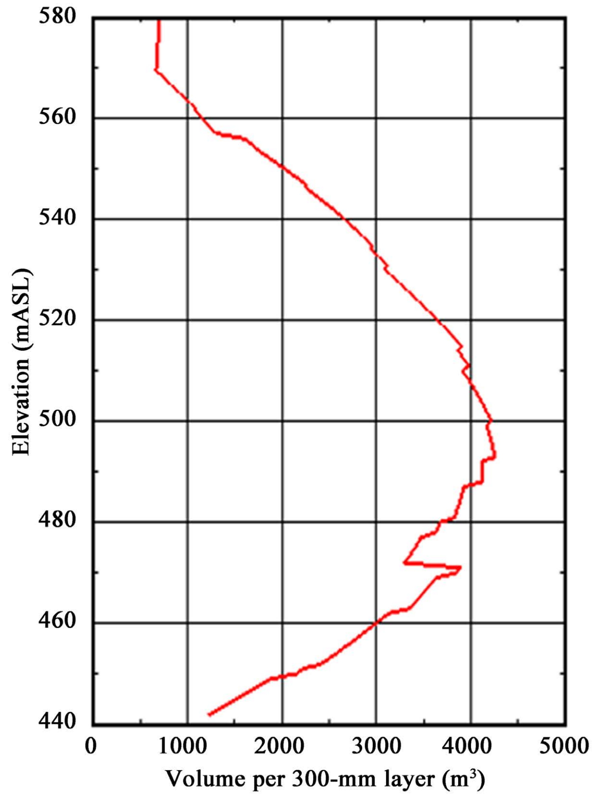

Figure 2. Single layer (30 cm), RCC volume, m^3.

Table 3. Cement test results.

Item	Density (g/cm^3)	Soundness (mm)	Fineness (%)	Setting time (min)		Compressive strength, (MPa)	
				initial	final	2d	28d
Results	3.11	1.0	1.5	163	216	28.4	54.9
BS EN 197-1	/	≤10	≤10	≥60	/	≥10	42.5 ≤ f ≤ 62.5

2.1.2. Fly Ash

After surveying, the maximum demand of dam RCC construction peak period was 500 tons per day, hence, Mamba thermal power plant in Zambia (300 MW) with production of 2000 t/day fly ash qualified as the main supplier. The fly ash is collected by electrostatic collection system. The fly ash met the requirements of ASTM C618 class F. The test results are shown in **Table 4**.

2.1.3. Aggregates

The aggregates were made of artificial aggregates produced on-site crushing plants. Previous exploration confirmed that there was no potential alkali aggregate reaction in quarry rocks, and quality met the technical requirements of ASTM C33, EM1110-2-2006 and ACI 207.5R-2011. The test results of artificial sand are shown in **Table 5**. The coarse aggregate was divided into three groups: 4.75 - 19 mm, 19 - 37.5 mm and 37.5 - 63 mm. The technical properties of the coarse aggregate were in accordance with ASTM C33 and EM1110-2-2006. The test results are shown in Table 6.

2.1.4. Admixtures

The admixtures used for RCC mix are type SN-2 super plasticizer and SN-GH retarder produced by the Additive Factory of Bureau No.11 of Power China, China. The admixtures performances meet the technical requirements of ASTM C494. The test results are shown in Table 7.

Table 4. Fly ash test results.

Item	Density (g/cm^3)	Soundness (mm)	Loss on ignition (%)	Fineness (0.045mm sieve), %)	Water requirement (%)	Activity index (%)		
						7d	28d	90d
Results	2.34	0.5	3.79	17.7	104	85.3	93.7	113
ASTM C618	≥2.0	0.8	F, C: ≤6 N: ≤10	N, F, C: ≤34	F, C: ≤105 N: ≤115	≥75	≥75	/

Table 5. Test results of artificial sand.

Item	Density (g/cm^3)	Absorption (%)	Fineness modulus	Soundness (%)	Light Materials (%)	Organic matter	Clay (%)	<0.075 mm
Results	2.61	2.2	2.73	5.8	0.1	0	0.3	12.8
EM1110-2-2006	>2.5	/	2.1-31	<12	<0.5	No allowed	<3.0%	/

Table 6. Coarse aggregates test results.

item	Density (g/cm^3)	Absorption, %	Los Angles abrasion,	Soundness	Flat & Elongation	Clay lump	Light matter	<75 μm
4.75 - 19 mm	2.62	0.8%	25%%	5.0%	3.7%	0.30%	0.08%	0.8%
19 - 37.5 mm	2.63	0.6%	27%	5.8%	2.5%	0.25%	0.08%	0.6%
37.5 - 63 mm	2.64	0.3%	28%	7.0%	8.8%	0.20%	0.06%	0.3%
ASTM C33	>2.5	/	<50%	<12%	<30%	<3%	<0.5%	<1%

Table 7. Admixture test results.

Item	Dosage %	Setting time (h:min.)		Rate of Water reduction %	Ratio of strength, %		
		initial	final		3d	7d	28d
Reference concrete	/	8:11	10:15	/	100	100	100
Reducer type SN-2 Test results	0.8	≥1:30	≥3:15	15.9	130	122	123
	1.0	≥5:15	≥6:30	20.4	127	145	142
ASTM C494, Type F		≥1:00	≥3:30	>12	>125	>115	>110
Retarder type SN-GH Test results	0.15	≥2:00	≥1:50		102.2	102.1	100
	0.3	≥5:15	≥6:15		98.9	106.3	100.9
	0.6	≥9:00	≥10:45		93.3	114.7	100.8
ASTM C494, type B		≥5:00	≥5:45	/	>90	>90	>90

2.2. Final RCC Mix Design and Its Performances

In order to determine the good performance in parameters of all the ingredients and aggregates of the RCC mix, the following results were considered to determine the RCC mix. Some of the parameters considered were: properties of fresh RCC mix, mechanical properties of RCC, developing rate of compressive strength, deformation properties of RCC mix and the results were recorded as shown in Tables 8-12 respectively.

Thermal Properties of RCC Mix

The thermal properties test was executed by Nanjing Hydraulic Research Institute, China. The main test results are shown in Table 13.

Table 8. Construction RCC mix.

Ratio of W/C	Fly-ash %	Reducer %	Retarder %	Quantities of materials in 1 m^3, kg/m^3							
				water	cement	Fly ash	C + F	sand	Agg. 4.75 - 19 mm	Agg 19 - 37.5 mm	Agg 37.5 - 63 mm
0.71	65	1.0	0.3	122	60	112	172	752	403	539	406

Table 9. Test result of fresh mix.

Density(kg/m^3)	Vebe time(s)	Air content %	Initial setting time(h:min)	Final Setting time (h:min)
2375	6-8	0.8	26:40	52:15

Table 10. Mechanical properties test results of RCC mix.

Compressive strength (d/MPa)						Direct tensile,(d/MPa)					Indirect tensile,(d/MPa)				
7	28	56	90	180	365	28	56	90	180	365	28	56	90	180	365
5.6	10.8	12.3	12.8	15.1	17.3	0.7	1.06	1.14	1.33	1.44	0.61	1.27	1.29	1.78	1.80

Table 11. Developing rate of compressive strength.

Age	7d	28d	56d	90d	180d	365d
Rate,%	0.59	1.00	1.19	1.24	1.43	1.60

Table 12. Test results of deformation properties of RCC mix.

Modulus of elasticity,(GPa)						Poisson ratio					Ultimate tensile strain value, (10^{-6})				
7	28	56	90	180	365	28	56	90	180	365	28	56	90	180	365
5.6	12.2	13.5	14.1	17.8	18.8	0.11	0.12	0.13	0.16	0.2	60	68	74	81	88

Table 13. Thermal performance test results of RCC mix.

Specific heat, kJ/(kg·˚C)	Thermal conductivity, kJ/(m·h·˚C)	Thermal conductivity coefficient, m^2/h	Coefficient of linear expansion $\times 10^{-6}$/˚C
0.915	9.215	0.0038	0.84

3. Study on Characteristics of Joint with Different Maturity and Treatment

3.1 Test Joint Maturity and Bonding Strength

Before the commencement of RCC Dam construction, the RCC trial section placement was executed, different exposure times of joint at 4, 10, 16, 22, 36, 48 and 60 hours were arranged. The trial section was separated into 3 zones with separately treated mortar, grout and no treatment. The test results of joint bonding strength under different treatment and maturity are shown in **Table 14**. The modified maturity factor (MMF) calculation method is MMF= (average ambient temperature + 12˚C) × joint exposure time (hours).

3.2. Criteria for Joint Treatment

According to the bonding strength shown in **Table 14**, the longer the exposure time of joint the lower the bonding strength. Beyond 22 hours of exposure time, the strength of treated joint was higher than without treatment [10]. For hot joints, the joint bonding strength is greater than 60% of parent RCC within 16 hours. Based on the bonding strength results and the modified maturity factor value, the conditions of Hot, Warm and Cold joints were initially determined as follows:

1) When the maturity is less than 757 C. H, it is defined as "Hot" joint without any treatment.

2) When the maturity is between 757 - 1200 C. H, it is defined as "Warm" joint.

3) When the maturity is more than 1200 C. H, it is defined as "Cold" joint.

In order to ensure the joint bonding strength of joints, the control criteria were defined for the RCC dam construction. The criteria for judging hot joints, warm joints and cold joints were determined as shown in **Table 15**. For hot joints

Table 14. Test results of Joint bonding strength with different treatment method.

Joint	Exposed time (Hrs)	MMF (˚C.H)	Joint bonding strength with different treatment method (MPa.)					
			By grout		By mortar		Without treatment	
			Average MPa	% by parent RCC	Average MPa	% by parent RCC	Average MPa	% by parent RCC
7/8	60	2064.9	0.9*	65.7	0.76*	55.5	0.50	36.5
6/7	48	1866.8	1.02*	74.5	0.80*	58.4	0.36	26.3
5/6	36	1330.1	1.10	60.3	0.73	53.3	0.44	40.1
4/5	22	757.1	1.02	58.6	1.25	71.8	0.64	36.8
3/4	16	589.7	1.34	77.0	1.28	72.0	1.04	59.8
2/3	10	300.1	1.47	84.5	1.33	75.0	1.28	73.6
1/2	4	178.5	1.43	82.2	1.55	88.0	1.44	82.8

*Treated by green-cut as well.

Table 15. Defined control standard of joints as to exposing time and MMF.

Month	Temperature of Ambient, ˚C	Defined control standard of joints as to exposing time and MMF					
		Hot joint		Warm joint		Cold joint	
		Exposed time, hrs	MMF, H.˚C	Exposed time, hrs	MMF, H.˚C	Exposed time, hrs	MMF, H.˚C
1	22.8	≤16	557	16 - 28	556 - 974	>28	>974
2	22.5	≤16	552	16 - 28	552 - 966	>28	>966
3	22.1	≤16	546	16 - 28	546 - 955	>28	>955
4	20.9	≤20	658	20 - 30	658 - 987	>30	>987
5	18.5	≤22	671	22 - 32	671 - 976	>32	>976
6	16.5	≤22	627	22 - 32	627 - 912	>32	>912
7	16.4	≤22	625	22 - 32	625 - 909	>32	>909
8	18.9	≤22	680	22 - 32	680 - 989	>32	>989
9	22.5	≤20	690	20 - 30	690 - 1035	>30	>1035
10	24.9	≤16	590	16 - 28	590 - 1033	>28	>1033
11	24.4	≤16	582	16 - 28	582 - 1019	>28	>1019
12	23.2	≤16	563	16 - 28	563 - 986	>28	>986

condition, no treatment was applied. In cases were the joint maturity reached warm joints condition, the joint was treated by applying grout, then the placement was continued. When the joint maturity reached extreme conditions, the joint was considered as cold joint, normally, the placement operation was halted, then joint surfaces were roughened by green-cutting machine, cleaned up and treated with grout before restarting the next placement.

4. Effect of RCC Layer Compacted Existing in the Condition of Plastic and Elasticity State

During RCC construction, if the existing RCC layer compacted was in the condition of plastic and elasticity, some RCC dams are not commissioned. This has been the motivation for the study of the effects of the joint quality. The phenomenon occurs when the Vebe time is less the 5 seconds. During the RCC trial section construction the test carried out at the KGL project was based on the core sample test results, there was no influence on the joint shear strength, impermeability and bonding strength [11]. Also the core sample compressive strength and density was as per requirement. The compacted RCC in condition of plastic and elasticity is not limited to the KGL project.

5. Quality Control System of RCC Construction

In order to ensure integrity of interlayer joints quality, the key control points were as follows:

- Temperature control measures (RCC temperature at batching plant);
- Through taking the measures of primary air cooling of coarse aggregate;
- Adding cold water and ice chips in mixer;
- RCC mixture temperature was controlled less than 20˚C at the plant and less than 25˚C at placing site;
- Sunshade used for RCC transport Truck and belt conveyor system;
- Fogy system measures was adopted to reduce the temperature at placement site and to keep the joint surface in the SSD condition;
- Height of aggregate stock pile was higher than 6 m and set up shading measures for aggregates etc.

The partial test results of temperature control were as shown in Figure 3. RCC mixture Vebe time was adjusted according to the ambient temperature, Vebe time controlled within 8 ± 2 s at placing site. For partial test records of Vebe time see Figure 4. The bedding grout mix quality control, ratio of water/cement was within

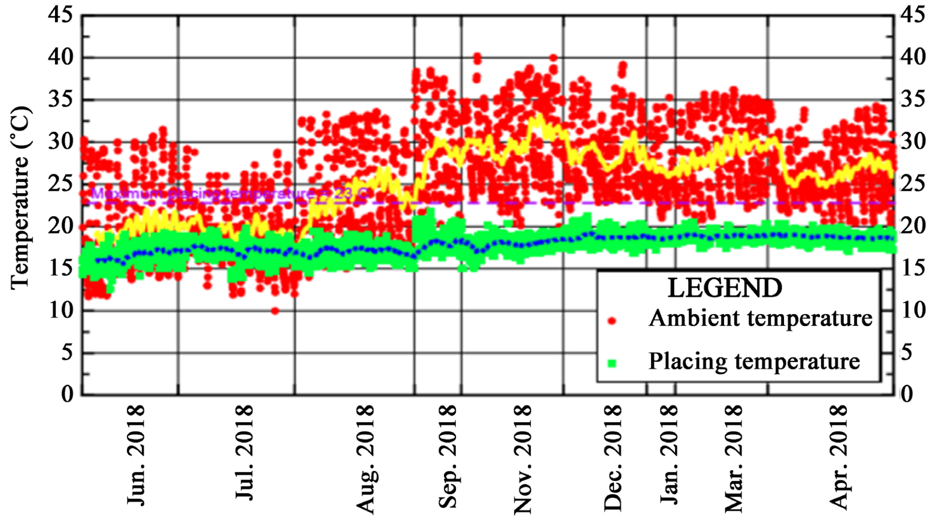

Figure 3. Temperature control at site.

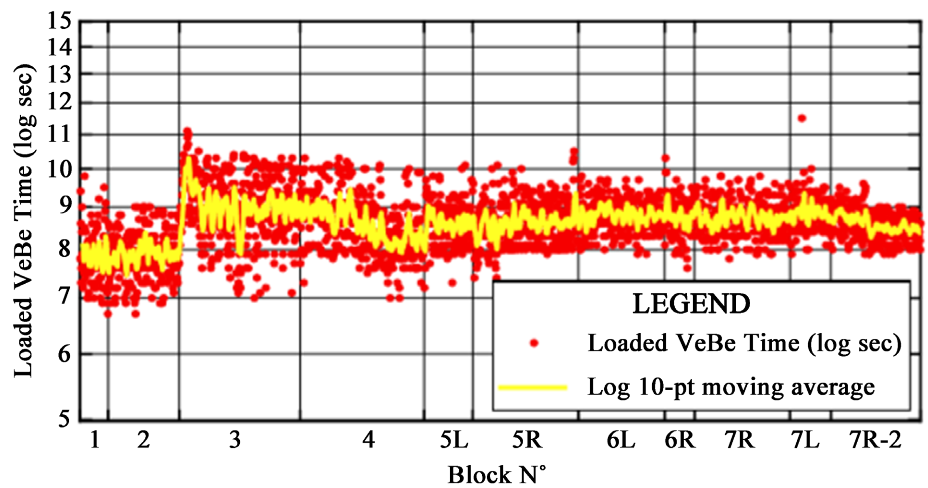

Figure 4. Vebe time control.

0.6 - 0.65 and the flow value within 40 ± 3 s.

RCC Mixture segregation control: RCC discharging on RCC surface un-compacted, so that the mixture is remixed when the spreading and leveling operation by bulldozer to reduce the segregation. Applying of grout, for the warm and cold joint was treated with grout, and the distribution had to be uniform on the joint surface [6].

6. Evaluation of Interlayer Joint Quality Control

During construction of the KGL RCC dam, for the hot joint the interlayer joint exposure time reached at a maximum of 22 hours, and the warm joint exposure time reached 30 hours. Based on the extraction of core samples, **Photo 1**, and water pressure test results, **Table 16**, the joints bonding quality and impermeability were satisfied.

7. Conclusion

Based on the conclusive evaluation of the joint quality by the core samples extraction and water pressure test, the results were satisfactory with reference to the technical requirement and the standard quality [6]. The joint exposure time has to be within 20 - 24 hours, that is, including delay time in case of all emergency events. The records presented in the study will be useful for the monitoring and evaluation of the dam structure during operation and maintenance phase, in addition to that, it provides the joint interlayer data that can be correlated to the captured information from the inserted probes which will be as basis

Photo 1. Core sample.

Table 16. Water pressure test results.

Item No.		1	2	3	4	5	6	7	8	9	10	11
Depth	From (m)	0.7	0.7	0.7	0.7	0.7	20	25	0.7	15	0.7	0.7
	to (m)	10.1	10.7	25.7	28.5	32.8	20.0	29.9	5.0	20.0	22.5	19.7
Test Length	m	9.4	9.9	25.0	27.8	32.1	5.0	4.9	4.3	5.0	21.8	18.9
Lugeon Average Value	L/Min/m	0.17	0.31	0.29	0.28	0.29	0.00	0.00	0.01	0.11	0.31	0.41

for the formulation of the dam safety monitoring index [12]. In addition, the cost of reconstructing a failed dam embankment can be a huge burden financially and worrisome socially, that is, may cause social disruption. This could be the case for seismic areas where the earthquake may tend to increase horizontal loads while decreasing the effective weight of the structure. Hence, maturity theory is appropriate and better in the strength prediction than some other methods, defined as the product of the curing time and temperature, [7] further points out that when the maturity is the same, the strength will also be appropriately the same. Therefore, the success of the KGL RCC dam construction is a special case study that may be emulated in similar RCC projects which may not be limited to the following characteristics: projects in hot and dry areas, if RCC placement intensity is high, batching plant capacity is lower than the required volume, or the combination of all three characteristics. Merging lean construction practices and using the MMF criteria applied to the quality control for RCC interlayer joint quality in the regions of dry and high temperature climate ensures continuous and improved RCC placement rate, progress and dam structure consolidation to mitigate dam failure.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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