Experimental Study on the Impact of Rainfall on RCC Construction

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Abstract: Water content is an important parameter for ensuring construction quality of a roller-compacted concrete (RCC) dam. Due to large-scale and long construction duration of an RCC dam, continuous construction under rain is an inevitable option in order to complete the project on time. In general, rainfall can have a negative impact on RCC's rollability, physical, and mechanical properties. This study is based on laboratory experiments with simulated RCC construction under artificial rainfalls. The results detail the impact of rainfall on RCC's rollability, water content, vibrating compaction value, density, and bonding strength between RCC lifts. Reducing water content is studied as a countermeasure to mitigate such impacts. The findings can guide site decisions on whether to continue or suspend the RCC construction based on the forecasted rainfall intensity. The results are validated with actual field data.

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Introduction

Started in the 1970s, roller-compacted concrete (RCC) is a zero-slump concrete consisting of dense-graded aggregate and sand, cementitious materials, and water (Luhr 2004). In the concrete mixture, the cement content is supplemented by fly ash and is less than in conventional concrete. The low water to cement ratio (usually ranging from 0.30 to 0.40) provides high strength in the hardened concrete. Because of the low water content, it cannot be placed with the same methods for pouring conventional (slump) concrete. Instead, RCC is usually placed and compacted with earth-moving and paving equipment, such as dump trucks, bulldozers, vibratory rollers, etc. It has been widely used for building pavements and dams (Jackson 1985).

As compared to conventional concrete or earth and rock-filled dams, an RCC dam has the following major advantages: less volume, high strength, high antiseepage ability, simple construction procedure, leverage of large machinery for earth dams, faster construction, and lower cost.

The first RCC dam, Shimajigawa Dam, was built in Japan in 1980. The first RCC gravity dam, Willow Creek Dam, was built in the United States in 1982 (Tatro 1984). RCC dams became very popular in South America, Europe, Asia, and Australia since 1986. In the 1990s, the research and the application of RCC dams reached the highest level. Four special conferences on RCC dams were held. The papers published in the proceedings cover many aspects including planning and design, construction methods, construction equipment and techniques, quality control procedures, performance of completed dams, rehabilitation of existing dams and completed pavements, materials, mixture proportioning, laboratory tests, and field data collection (Hansen 1985, 1988; Hansen and Mclean 1992; U.S. Army Corps of Engineers 1994).

An RCC dam is constructed layer by layer, called lifts. Each lift usually has a thickness of 1–2 ft (0.3–0.6 m). Low water content is essential for ensuring the construction quality of an RCC dam. If rainfall occurs during construction, rainwater infiltrates the cement and increases the actual water content of the concrete mixture. A heavy rainfall can even wash away cement from aggregate and cause segregation between cement and aggregate on the surface of the newly paved material. In general, rainfall can have a negative impact on RCC's rollability and physical and mechanical properties. A heavy rainfall may force the construction to stop, and therefore cause delays to the project (Dolen et al. 1988). Due to its large-scale and long construction duration, construction under rain is inevitable for a high RCC dam.

A few studies were reported on the impact of rainfall on RCC dam construction. Inconsistent guidelines were used to guide how to deal with rainfall during RCC dam construction. The Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994) states: "if rainfall intensity exceeds 3 mm per hour (mm/h), the construction of an RCC dam should stop." The Tamagawa Dam in Japan adopted the 2-mm/h rainfall intensity as a criterion for stopping its RCC construction based on an experimental study with artificial rainfall (Yang 1992). The RCC construction continued if the thickness of a lift was 300 mm or less and rainfall intensity did not exceed 7 mm/h in the Pangue Dam in Chile (Forbes et al. 1992).

Since the first RCC dam built in Fujian province in 1986, China has made significant progress and breakthroughs in dam style, raw material, design, and construction methods (Wang 1994; Mei and Zheng 2005). The world's tallest dam with a maximum height of 216.5 m, Longtan Dam, is currently under con-

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Table 1. Theoretical Mix Proportion of RCC (kg/m^3)

				Aggregate (mm)		
Water	Cement	Fly ash	Sand	5–20	20–40	40–80
95	90	110	730	442	591	442

struction (Special Council of Construction Technology of RCC Dam in China 2004).

This research aims at evaluating the impact of rainfall on RCC construction in the Longtan RCC dam. The project is located in a semitropical climatic zone in Guangxi Province, China. It is the world's tallest RCC dam with a maximum height of 216.5 m. The project broke ground on July 1, 2001 with an estimated duration of 9 years. Its first turbine unit started generating electricity on July 1, 2007. The project is expected to be completed in December 2009. In this geographical region, the average number of days with a rainfall amount of 0.6–10 mm/day is 84 days in a year, and the number of days with a rainfall amount exceeding 10.1 mm/day is 41 days in a year. Moreover, most of the rainy days are concentrated during the May–August period, which accounts for 69% of the total raining days in a year. Rainfall can have a significant impact on the construction of the project.

This study has four objectives: (1) to determine the impact of rainfall on RCC's rollability; (2) to determine the impact of rainfall on RCC's density; (3) to determine the impact of rainfall on bonding strength between RCC lifts; and (4) to evaluate alternative measures for achieving continuous construction in the Longtan RCC dam under different rainfall intensities.

Experimental Setup

The study was based on laboratory experiments with simulated RCC construction under artificial rainfalls. It was conducted in a trough with a dimension of $6 \times 2.8 \times 0.6$ m (length $\times$ width $\times$ depth) in a controlled environment. The trough could hold two lifts with each lift at a compacted thickness of 0.3 m, which was identical to the actual thickness of a lift in the Longtan dam. The experiments were conducted in the summer under relatively high temperature (29–31°C) and relative humidity of 75%, which are similar to actual construction conditions on the site.

Raw Materials and Mixture

The RCC raw materials and mixture proportion were based on the design specifications for the Longtan RCC dam provided by the Midsouth Design and Research Institute of China. The RCC mix proportion is shown in Table 1. In addition, 0.6% of the cement content of ZB-1-RCC15 superplasticizer and water reducing agent was added as admixture.

Compaction Machine and Capability

An NZSIA hand vibratory roller was used for compaction in the experiments. The capability is shown in Table 2. In order to reach the same density on the site, 14 compaction passes were used in the experiments.

Table 2. Capability of the Compaction Machine

Weight (kg)	Vibration force (kg)	Frequency (Hz)	Amplitude (mm)	Roller length (m)	Speed (m/s)
1,000	2,500	50	0.6	0.7	0.417

Test Device and Apparatus

An MC-3C nuclear density and moisture gauge manufactured by CPN International Corporation in the United States was used for measuring density and water content of the RCC specimen at various depths in the lift. The vibrating compacted value (VC value) is used to measure the consistency of RCC in China (Ministry of Water Resources of People's Republic of China 1994). In this study, an HGC-1 vibration consistency device was used for measuring the VC value.

Rainfall Simulation

According to the provision of meteorology in China (Zhou 1997), rainfall can be classified in different ways. If rain is classified with rainfall intensity (defined as q_i in whole paper), it should be that

1. Light rain: rainfall within 1-h precipitation less or equal to 2.5 mm, or within 24-h precipitation less or equal to 10 mm;
2. Moderate rain: rainfall within 1-h precipitation between 2.6–8.0 mm, or within 24-h precipitation between 10.1–24.9 mm;
3. Heavy rain: rainfall within 1-h precipitation between 8.1–15.9 mm, or within 24-h precipitation between 25.0–49.9 mm;
4. Rainstorm: rainfall within 1-h precipitation more than 16.0 mm;
5. Heavy rainstorm: rainfall within 24-h precipitation between 100–200 mm; and
6. Super-rainstorm: rainfall within 24-h precipitation more than 200 mm.

It was found in the laboratory tests that, if rainfall intensity exceeds 8 mm/h with raindrops at a diameter of 3 mm or larger, the falling rain can wash away cement and separate the mortar around the coarse aggregate. The vibratory roller sank and its moving speed decreased rapidly. In other words, it could not compact properly. Therefore, any rainfall intensity exceeding 8 mm/h was considered not suitable for construction and was not considered in the study.

A device was created for simulating artificial rainfalls at the intensity of 0, 2.6, 5, and 8 mm/h, respectively. For each lift, the experiment conducts the following tasks:

- Dumping and paving the concrete mixture with a loose thickness of 34 cm;
- Generating artificial rainfall at a desired intensity;
- Compacting with a vibratory roller at the designed speed and passes;
- Measuring VC value; and
- Measuring the water content and wet density.

The above procedure is adopted to simulate the actual construction conditions on the project. In the experiments, one lift was used for measuring rollability and density while two lifts were used for measuring bonding quality. At the job site, if heavy rain starts or is predicted to fall soon before a new lift of materials is dumped, dumping materials is postponed after the rain stops. A key concern is what to do when rain starts after a new lift has started: either to continue and finish the lift or to stop and disregard the materials that have been placed. The worst scenario, therefore, is that rain starts immediately after dumping starts. To simulate the worst scenario, artificial rain starts falling right after the materials are dumped and continues until compaction is com-

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Table 3. Water Contents and VC Values under Different Rainfall Intensities q_i

Depths from surface (cm)	Water contents per unit volume (kg/m^3)			
	q_i=0.0 mm/h	q_i=2.6 mm/h	q_i=5.0 mm/h	q_i=8.0 mm/h
0.0	95.13	101.02	104.26	106.57
5.0	97.91	101.34	103.45	106.49
7.5	97.66	101.26	104.56	106.59
10.0	96.96	101.10	104.72	106.70
12.5	96.93	99.16	103.24	107.93
15.0	97.96	98.06	101.23	108.96
17.5	97.32	97.63	99.52	105.18
20.0	97.00	97.73	98.04	98.70
30.0	97.34	97.73	98.63	98.07
Average water content in the impacted depth (kg/m^3)		101.18	103.58	106.92
Average water content for the entire lift (kg/m^3)	97.12	99.48	101.96	105.02
Average VC value in the impacted depth (seconds)	8.00	6.00	5.30	4.30
Average VC value for the entire lift (seconds)	8.00	7.00	6.00	4.80

plete in the experiments. Under the given equipment and designed compaction requirements, it takes about 10 min to complete a normal lift. Therefore, the rainfall lasts for about 10 min corresponding to the construction time of a lift. The rainfall intensity does not change during the same experiment.

Rain often comes with wind. Wind can accelerate water evaporation rate, and affect air temperature and humidity. In the laboratory experiments, wind conditions were not simulated separately; instead they were considered in conjunction with air temperature and relative humidity near the surface. The conclusions from this study are applicable to normal wind conditions (wind velocity is 20–28 km/h). Strong wind may have more significant impact on the time interval between adjacent lifts, relative humidity, and construction safety. This study did not address strong wind condition.

Experiment Results and Analyses

The quality of a RCC construction is widely evaluated from three aspects: (1) rollability; (2) density; and (3) bonding strength between RCC lifts. The impact of rainfall on the three parameters is discussed as follows.

Impacts on Rollability and Water Content

For a given RCC mixture under the specified mix proportions, the common parameter for measuring its consistency is water content per unit volume or VC value in China (Ministry of Water Resources of People's Republic of China 1994). Either one of the two parameters can determine the rollability of the concrete mix. During construction, water content must be controlled in an allowable range to meet the design specifications. If the change in the water content caused by rainfall is within the allowable range, it is believed that the rainfall should not cause a significant negative impact on rollability; otherwise, the quality is believed not to meet the designed standards and the constructed layer must be disregarded and reconstructed.

In the Longtan RCC dam, the relative degree of compaction is set at 97%; the allowable range of water content is $94–101\ kg/m^3$; and the allowable range of VC value is 10–5.s. Because it is hard to directly control the water content of the RCC on the field, it is more common to control the VC value. The Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994) require that the VC value at any points in the lift not be less than 5 s.

The experiments were conducted at different levels of rainfall intensities. The measured water contents and VC values from the experiments are shown in Table 3. In the experiments, the optimal water content of $95\ kg/m^3$ was used in preparing the concrete mixture and the actual measured water content was $97\ kg/m^3$ as measured from the samples.

The results in Table 3 indicate that the actual water content has increased due to rainfall; and the increase is more significant for more intense rainfalls. If the water content below the surface exceeds $101\ kg/m^3$, the point is impacted by the rainfall. At the rainfall intensities of 2.6, 5.0, and 8.0 mm/h, the impacted depths from the surface are 10, 15.0, and 17.5 cm, respectively. The impacted depth clearly increases with the rainfall intensity.

The relationship between rainfall intensity q_i (mm/h) and average VC value (seconds) for the impacted depth is as follows:

$$\mathrm{VC} = 7.76 e_i^{-0.0731q}, \quad \text{correlation coefficient } r = 0.9962 \quad (1)$$

The relationship between rainfall intensity q_i (mm/h) and average VC value (seconds) for the entire lift is as follows:

$$\mathrm{VC} = 8.34 e_i^{-0.0732q}, \quad \text{correlation coefficient } r = 0.9849 \quad (2)$$

According to Eqs. (1) and (2), if rainfall intensity q_i is 6 mm/h, the average VC values are 5 and 5.8 s for the impacted depth and the entire lift, respectively. This indicates: if rainfall intensity q_i is less than 6 mm/h, the average VC value of the impacted depth and entire lift is not less than 5 s and meets the requirements of the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994). However, if rainfall intensity q_i exceeds 6 mm/h, the average VC value of the impacted depth is less than 5 s, and cannot meet the requirements of the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994), a significant impact should be expected on the construction quality.

One countermeasure to mitigate the impact of rainfall is to reduce water content in the mixture. However, reducing water content in the mixing stage will reduce the water cement ratio globally while rain typically falls on the surface. The construction

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Table 4. Adjustment of Water Contents on Jiangya RCC Dam

	Rainfall intensity q_i (mm/h)				
	<2	2–3	3–6	6–9	10–13
Adjustment of water content (kg/m^3)	0	−(2–3)	−(6–7)	−(9–15)	−(20–40)

process of a RCC lift includes transportation, dumping the concrete mix on the grand, spreading the material, and compacting. During the process, the exposure surface changes several times. Before the lift is compacted, the rainwater can quickly infiltrate through the loose surface into the dry concrete mix. After the lift is compacted, the rainwater is typically captured on the hardened surface and the construction crew can take measures to remove it before it can cause local water saturation. Although reducing water content in cement mix to accommodate certain rainfall condition may cause uneven distribution of water content in RCC, a proper construction method and management strategy shall minimize the negative impact.

The amount of water to be reduced in the mixture should correspond to the amount of rain water expected to be added to the mixture. The Longtan RCC dam is similar to the Jiangya RCC dam (Lin 1999), which has the same weather condition and construction methods. Therefore, the amount of water to be reduced in the study adopted the actual adjustment values as in the Jiangya RCC dam as shown in Table 4 (Xiao and Xu 2001).

After reducing the water contents in the concrete mixtures at the different rainfall intensities, a set of experiments was conducted with the actual water contents and VC value as shown in Table 5. The results in Table 5 indicate that the actual water content below the surface does not exceed 101 kg/m^3, and the VC value also meets the requirements of the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994). Table 5 shows that if rainfall intensity does not exceed 8 mm/h, reducing the water content in the concrete mixture properly is a feasible measurement for mitigating the impact of rainfall.

Impact on Density

The relative degree of compaction is a common parameter for evaluating the quality of RCC construction. It is expressed as a percentage of the ratio between the actual density of the RCC lift and the theoretical density ($2{,}500\ kg/m^3$) derived from a theoretical mix proportion of the RCC. The compaction quality is good when relative degree of compaction is close to 100%.

Clause 5.4.9 of the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994) requires that the relative degree of compaction should not be less than 98% for exterior concrete and not be less than 97% for interior concrete. Similar criteria are found in many countries, such as in the United States (Yang 1992). As in conventional concrete, water content can have a significant impact on the density of an RCC. Under the given rainfall intensities, the density and the relative degree of compaction of the RCC samples are shown in Table 6.

The results in Table 6 clearly indicate that rainfall has a negative impact on density. Interpolating from the results in Table 6, it can be concluded that the relative degree of compaction cannot meet the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994) when rainfall reaches 5.69 mm/h.

A reduction in water content may also help improve compaction quality. Using the same strategy to reduce water content in the mixture as in the previous section, the density of the RCC and the relative degree of compaction under different rainfall intensities are shown in Table 7. Table 7 shows that if the water content in the concrete mixture is reduced corresponding to the rainfall intensity, even when the rainfall intensity q_i reaches 8 mm/h, the relative degree of compaction can still meet the Construction Specifications for Hydraulic RCC of China (Ministry of Water Resources of People's Republic of China 1994).

This study shows that both rollability and density can meet the design requirements without additional measures if rainfall intensity does not exceed 5.69 mm/h. If rainfall intensity is greater than 5.69 but less than 8 mm/h, properly reducing water content in the concrete mixture is a viable strategy to improve rollability and density. The RCC construction should be suspended if rainfall intensity exceeds 8 mm/h.

The above findings are different from the ones recommended

Table 5. Actual Water Contents and VC Values after Reducing Water Contents in Mixtures

	Water contents (kg/m^3)		
Depth from surface (cm)	q_i=2.6 mm/h	q_i=5.0 mm/h	q_i=8.0 mm/h
0.0	94.46	95.72	96.05
5.0	94.12	95.58	95.64
7.5	93.36	94.40	96.42
10.0	93.17	94.27	97.68
12.5	91.07	94.78	96.51
15.0	91.75	92.65	96.78
17.5	93.72	92.65	96.78
20.0	93.64	93.71	95.33
30.0	92.16	89.93	94.46
Average water content in the lift (kg/m^3)	92.49	93.52	96.07
Amount of water reduced in mixture (kg/m^3)	3.00	6.00	9.00
Average VC value (seconds)	10.00	9.80	8.50

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Table 6. Compacted Densities at Observation Points in RCC Lift under Different Rainfall Intensities q_i

	Rainfall intensity q_i (mm/h)			
Depth from surface (cm)	0.0	2.6	5.0	8.0
0.0	2,400	2,403	2,415	2,324
5.0	2,474	2,430	2,411	2,347
7.5	2,488	2,438	2,451	2,404
10.0	2,481	2,443	2,461	2,406
12.5	2,471	2,440	2,447	2,430
15.0	2,476	2,445	2,406	2,430
17.5	2,469	2,463	2,433	2,432
20.0	2,471	2,458	2,433	2,414
30.0	2,483	2,460	2,430	2,406
Maximum density γ_{max} (kg/m^3)	2,488	2,463	2,461	2,432
Minimum density γ_{min} (kg/m^3)	2,400	2,403	2,406	2,324
Average density γ_{ave} (kg/m^3)	2,468	2,442	2,433	2,399
Relative degree of compaction (%)	98.7	97.7	97.3	96.0

by the Construction Specifications for Hydraulic RCC of China and the guidance used in the Tamagawa Dam in Japan. The Construction Specifications for Hydraulic RCC of China do not consider the rainfall duration and rainfall classifications as this study did. In the Tamagawa Dam in Japan, the thickness of a lift was 0.75–1 m, in comparison to 0.3 m in this project. According to field testing, the RCC strength did not reduce if rainfall intensity did not exceed 4 mm/h (Liu and Wang 1984).

Impact on Bonding Quality of the Interface between Lifts

Another parameter of measuring the quality of RCC construction is the bonding strength at the horizontal interface between two adjacent lifts. In order to ensure bonding between concrete lifts, RCC construction requires that two adjacent lifts must be completed within an allowable time interval (about an hour) to avoid cold joints. Rainfall may also have a negative impact on bonding quality. During construction, rainfall may occur at two different time periods: (1) during the interval between two adjacent lifts (addressed as Scenario 1) and (2) during the continuous construction of the two lifts (addressed as Scenario 2). Reducing the water content may be also a good strategy to mitigate the impact on bonding. For Scenario 1, however, reducing water content is not an option because the rain water does not directly infiltrate into the concrete mixture of the underlying lift, it just stays on interface. For Scenario 2, reducing water content may be a viable solution, and therefore Scenario 3 is used to represent the water content reduction strategy corresponding to Scenario 2.

Experiments were conducted corresponding to the three scenarios. For each scenario, six samples were taken with four as

Table 7. Compacted Densities at Observation Points in RCC Layer after Reducing Water Content

Rainfall intensity q_i (mm/h)	2.6	5.0	8.0
Amount of water reduced per unit volume (kg/m^3)	3.0	6.0	9.0
Depth from surface (cm)			
0.0	2,458	2,445	2,422
5.0	2,455	2,457	2,457
7.5	2,448	2,458	2,481
10.0	2,424	2,450	2,411
12.5	2,436	2,460	2,488
15.0	2,414	2,418	2,461
17.5	2,432	2,416	2,479
20.0	2,418	2,419	2,453
30.0	2,417	2,405	2,411
Maximum density γ_{max} (kg/m^3)	2,458	2,460	2,488
Minimum density γ_{min} (kg/m^3)	2,417	2,405	2,411
Average density γ_{ave} (kg/m^3)	2,434	2,438	2,451
Relative degree of compaction (%)	97.3	97.5	98.0

Table 8. Measured σ and τ Values and Derived Shear Strengths at RCC Interface

Mode	Rainfall intensity q_i (mm/h)	σ_1/τ_1	σ_2/τ_2	σ_3/τ_3	σ_4/τ_4	C' (MPa)	f'
Scenario 1	0	0.82/5.14	1.28/5.90	2.40/7.54	3.00/8.90	3.73	1.67
	2.6	0.81/4.73	1.34/5.59	2.31/7.07	2.98/8.33	3.38	1.64
	5.0	0.79/4.56	1.28/5.27	2.34/6.95	2.97/8.00	3.28	1.58
	8.0	0.77/4.41	1.26/5.22	2.26/6.87	3.01/7.90	3.24	1.57
Scenario 2	2.6	0.78/4.53	1.31/5.42	2.34/7.00	2.97/8.07	3.29	1.60
	5.0	0.76/4.13	1.27/5.16	2.41/6.45	3.01/7.48	3.17	1.42
	8.0	0.77/4.01	1.26/4.65	2.36/6.22	2.98/7.01	2.95	1.37
Scenario 3	2.6	0.75/4.47	1.29/5.33	2.37/7.04	3.03/8.04	3.30	1.57
	5.0	0.74/4.43	1.26/5.15	2.42/7.08	2.99/7.87	3.25	1.56
	8.0	0.76/4.12	1.25/5.15	2.39/6.45	3.00/7.54	3.14	1.45

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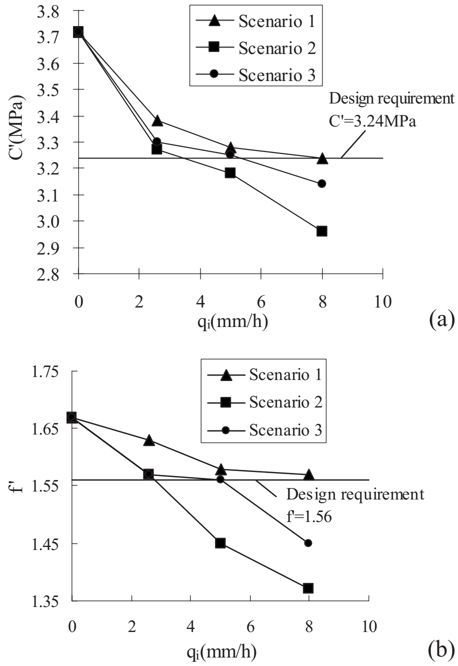

Fig. 1. Shear strength C' and f' versus rainfall intensity q_i

specimens and two as standbys from the compacted lifts. All specimens were tested at a nominal age of 90 days. Based on the design requirement, each specimen was imposed with horizontal stresses of 0.75, 1.50, 2.25, and 3.00 MPa, respectively. The obtained normal stress σ (MPa) and shear stress at the interface τ (MPa) from the experiments are showed in Table 8.

Based on the Coulomb formula (Yang 1992), shear stress τ(MPa) can be expressed as

$$\tau = C' + f'\sigma \tag{3}$$

where τ=shear stress; σ= normal stress; C'=cohesion; and f' =internal friction coefficient at the interface.

If the measured σ_i and τ_i (i=1–4) data are plotted in a scatter chart, C' and f' values can be derived by linearly fitting the Coulomb formula with the least-squares method. Their values are listed in the last two columns in Table 8.

Shear strength C' and f' versus rainfall intensities q_i are plotted in Fig. 1. The design required C' and f' values are also indicated in Fig. 1.

For Scenario 1, the results show that if rain falls directly on a completed lift before the next lift is placed on top of it, rainfall does not have a significant impact on shear strength C' and f'. Fig. 1 shows that when rainfall intensity q_i reaches 8 mm/h, shear strength C' and f' at the RCC lift interface can still comply with design requirement.

In Scenario 2, shear strength C' and f' at the interface reduces rapidly with rain intensity because rain water can increase the water content of the RCC mixture in the unrolled lift. As rainfall intensity increases, more mortar floats on the interface, and bleeds water. As a result, the interface becomes the weakest part in the concrete. Fig. 1 shows that if rainfall intensity q_i exceeds 2.6 mm/h, shear strength cannot meet the design requirement. In this scenario, nearly all specimens failed at the interface.

In Scenario 3, reduced water content was shown to alleviate the deterioration of the shear strength C' and f' at the interface. Fig. 1 indicates that if rainfall intensity q_i does not exceed 5 mm/h, the design requirements can still be met.

Conclusions

Based upon the laboratory experiments of the Longtan RCC dam, the following conclusions can be drawn:

1. If rainfall intensity is less than 2.6 mm/h, it will not impact RCC construction quality in terms of rollability, density, and bonding strength. The RCC construction should be suspended if rainfall intensity exceeds 8 mm/h;
2. If rain falls during the interval between the two lifts and rainfall intensity q_i does not exceed 8 mm/h, the next lift should be constructed after the standing water on the lift surface is removed and before the underlying lift reaches its initial setting. If rain continues at an intensity greater than 2.6 but less than 5 mm/h, reducing water content can be a viable countermeasure to ensure RCC construction quality. The study also finds that reducing water content can improve rollability and density, but cannot ensure bonding strength if the rainfall intensity is in the range between 5 and 8 mm/h; and
3. Although reducing water content in the concrete mixture is a feasible measure to mitigate the negative impact of rainfall, water content must be properly adjusted based on the rainfall intensity, rainfall duration, and construction method to assure overall construction quality.

Notation

The following symbols are used in this paper:

C' = cohesion of RCC lift;
f' = internal friction coefficient of RCC lift;
q_i = rainfall intensity;
γ_{ave} = average of compacted density;
$\gamma_{\max}$ = maximum value of compacted density;
$\gamma_{\min}$ = minimum of compacted density;
σ = normal stress of interface lift; and
τ = shear stress of interface lift.

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