Abstract: The rockfill dike, constructed in 1963 to form the Upper Reservoir at the Taum Sauk Pump Storage Project near Lesterville, MO, failed abruptly on December 14, 2005. The Upper Reservoir is presently being rebuilt as a 2.6 million CY RCC Dam in compliance with FERC Regulations and Missouri environmental permitting regulations. The Dam is the largest RCC project constructed in the USA and it has a symmetrical cross-section with relatively low strength RCC. Detailed mix design studies using various cement, fly ash and moisture contents have been performed to determine the RCC mix proportions and two full scale test sections have been placed. The available construction materials are challenging in nature, the source of aggregates has a high fines content and the rock has propensity to ASR. Despite these challenges, the right mix has been determined and the RCC placed in the dam so far exceeds design requirements. This paper presents the overall mix design, the testing process and test pads construction prior to dam construction, and available results from samples extracted during construction.

1 Introduction

After careful consideration of public safety concerns, regulatory agency requirements and evaluation of different remediation options, Paul C. Rizzo Associates, Inc. (RIZZO) proposed an RCC alternative for a complete rebuild of the dam. The initial proposal contemplated using a conventional gravity dam section with vertical upstream face and a steep downstream face, which contemplated a relatively high strength RCC and fairly clean aggregate. As preliminary studies [1] revealed significant presence of fines in the existing rockfill dike, it was realized that washing aggregates would demand a costly, difficult operation due to the water treatment equipment required to keep the operation self-contained and in compliance with stringent environmental regulations applicable to the project. It was concluded that a dam section consistent with the difficult foundation conditions and a RCC mix using...
available aggregate in the rockfill dike as-is, would be the most appropriate solution for the project.

In 1992, Londe and Lino proposed the adoption of symmetrical section RCC dams for weak foundation conditions, particularly in areas subject to strong earthquake motion [2]. Additionally, because of its increased mass and more uniform load distribution on the foundation, combined with water and silt loads on the upstream face, a symmetrical section is more stable and less highly stressed than the conventional gravity dam section for the same load condition. As such, a high strength RCC is not required for the symmetrical section. Londe and Lino suggested the name “hardfill” for their weak-mix RCC [1]. Based on the hardfill concept and successful RCC experiences in dams using RCC mixes with challenging materials [2], RIZZO finalized a proposal comprising a symmetrical section but using a more refined RCC mix, with a more controlled gradation than typically used in hardfill dam mixes. The RCC design strength was set at 1500 PSI.

Detailed mix design studies using various cement, fly ash and moisture contents were carried out to determine the appropriate RCC proportions. Aggregate extracted from accessible locations in the existing dike were crushed and used to produce usable aggregate for lab trial mixes. Concurrently to the lab trial batches, a comprehensive mortar bar expansion test program involving fly ashes of different sources and qualities was performed to find options to mitigate Alkali-Silice Reaction (ASR) in the potentially reactive rhyolite. Based on initial lab results, a baseline cementitious content of 200 Lbs/CY at 50% ash content was selected for full scale trials.

Two full-scale test sections of about 1500 cy each were placed prior to dam construction. The first test section was placed in December 2006 while the second was built in August 2007. The test sections pursued a variety of objectives related not only to mix design but also to RCC production and construction, such as aggregate crushing, lift joint treatments, bedding mix type and facing systems. Both test sections provided valuable lessons, which helped to refine the mix proportions, improve dam design and make the construction process more efficient. Based on acceptable results, dam construction started in October 2007 using mix 100+100 (C+FA). Available test results indicate that RCC placed in the dam complies with design requirements.

2 Aggregates
The original construction of Taum Sauk Upper Reservoir was accomplished by flattening the top of Proffit Mountain (Reynolds County, MO), using the broken rhyolite and excavated residual soil to construct the existing dike. As stated in the
Forensic Investigation Report, little or no effort was used to segregate the soil fines from the rock. The construction resulted in a dike with a gradation not typical of concrete-faced rockfill dams. Significant quantities of residual fines were mixed with the rock, and the rock itself has a wide range of particle sizes, ranging from gravel sizes to as large as four or five feet in diameter [1]. Figure 1 shows the gradation of truckload size samples extracted from accessible places in the rockfill dike scalped at 3 inches.

Figure 1. Gradation of Existing Rockfill Scalped at 3-inches

Aggregate for the initial lab work was produced at a commercial crusher, which consisted of a primary jaw crusher and a cone crusher as a secondary crushing stage. Figure 2 depicts the rockfill material before crushing. At the crushing plant, aggregate was separated in two aggregate groups (1 1/2" to 1/2" and <1/2") and additional screening was necessary at the lab in the coarse fraction to achieve an acceptable gradation. Figure 3 shows a close-up of the two products obtained at the crushing plant.

Figure 2. Rockfill Samples Before Test Crushing
Originally, the crushing scheme for dam construction used a basic, two-stage crushing plant. However, after the crushing during the construction of the Test Section I, it became evident that a tertiary crusher was required to get an acceptable gradation. On this basis, tertiary crusher was included as required equipment in the specifications.

As frequently seen in projects using mixes similar to the type used in Taum Sauk, preliminary specs considered achieving the combined RCC gradation by using a combination of only two aggregate groups (11/2” to ¾” and < ¾”). Based on the acceptable results obtained during the Test Section I, the two aggregate groups approach remained in the specifications. The typical curve produced during the first test section is depicted in Figure 4.
3 ASR & Fly Ash

In addition to the high fines content in the existing dike, the rhyolite available on site has a propensity to Alkali-Silice Reaction (ASR). To confirm ASR potential, a series of mortar bar expansion tests were conducted. Figure 5 depicts the results of ASTM C1260 mortar bar expansion tests indicating potentially deleterious behavior of the rhyolite.

Figure 5. Expansion Test (ASTM C1260) for Taum Sauk Rhyolite

The test program included tests with Class C Fly Ash and Class F Fly Ash. Figure 6 shows that Class C fly ash was not effective mitigating ASR and showed a “pessimum” effect at 30% ash; that is, this amount of ash actually increased expansion. Conversely as depicted in Figure 7, class F ash was very effective at controlling ASR. At about 25% ash, the expansion is almost completely suppressed.

Figure 6. Mortar Bar Expansion vs. Class C Fly Ash Replacement
Commercial fly ash is available in the project area, however, the Owner operates Meramec Plant, a coal fired power station located about 90 miles from the project. Some years ago Meramec plant produced class F ash, which was sluiced and stored in a pond near the power plant. RIZZO’s experience producing RCC with similar ash for use in the Saluda Dam led to a proposal for using the sluiced pond ash. Field investigations revealed that the ash quantity was enough to cover project needs and that the quality complied with ASTM C 618 requirements. Once lab testing confirmed acceptable physical and chemical properties, additional lab mixes using Meramec fly ash were prepared to evaluate ash performance in the actual RCC mix.

Extraction and handling of the Meramec pond ash was tried full-scale during construction of Test Section I. The original ash processing plan contemplated wet screening to break lumps and remove impurities and a hydraulic classifying system was used (Econosizer) to separate particle sizes by decantation to produce fine high quality ash (Figure 8). After processing, the ash was deposited in a sedimentation pond, to be later excavated and placed on the ground for further dewatering. One problem encountered was that the ash retained water longer than expected. Initially it was foreseen that in 24 hours ash water content would be at a level where ash could be easily handled; however, in reality it took several days for the ash to be ready for hauling and handling. At the jobsite, additional handling and spreading was required to bring moisture to a point where it could be accurately fed to a continuous mixing plant. It was found that “plowing” the ash with a Rototiller or agricultural disc was one effective way to bring moisture to manageable levels. The valuable lessons learned during the test pad helped to modify the overall approach to ash exploitation and helped to develop systems to feed the ash to the RCC plants accurately. Although extraction costs increased, utilizing Meramec ash still proved feasible because of the benefits to the environment and the additional ash storage capacity opened for use at the power station in the years to come.
4 Laboratory Mixes

The initial set of mixes prepared in early 2006, are presented in Table 1, this matrix included mixes with different cementitious contents, different ash types and cement only mixes. Also, different water contents were investigated and, based on test results, workability, and mix appearance, a water content of 200 lbs/cy was selected as the baseline value. In general, Vebe times for these mixes were above 30 seconds. Based on accelerated compressive and indirect tensile strength results (Figure 9) and the fact that mixes with 50% ash showed acceptable workability performance, a cementitious content of 200 lbs/cy using that ash content was selected as baseline. Thus, the preliminary mix selection resulted in the following proportions: 100+100+200 Lbs/CY (Cement+Ash+Water).

Table 1. Mix Matrix Used for the Initial Lab Mix Design

<table>
<thead>
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<th>Total C+F</th>
<th>0%</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
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<td></td>
<td></td>
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<td>300</td>
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In August 2006, three additional mixes with constant cementitious content (200 lbs/cy) but different cement/ash ratio were added. The purpose of these mixes was to evaluate performance of Meramec Class F ash available at an economical distance from the jobsite. This additional set included the following proportions: 80+120, 90+110 and 100+100 (C+FA). As shown in Figure 10 strength gain over time for all mixes with Meramec Ash complied with design requirements and, based on these results, mixes 80+120 and 100+100 were selected for full-scale trial in the Test Sections.
5 Test Sections

Two RCC test sections were built for the Taum Sauk Upper Reservoir Project. While the focus of Test Section I was mainly on materials and RCC design issues, the Test Section 2 (Production Test Section) also intended to demonstrate and test means and methods proposed by the Contractor for dam construction. A brief description follows:

Test Section I (Design Test Section)
The primary goal of Test Section I was to demonstrate that an acceptable, design-conforming mix could be produced using the challenging RCC components available for the project. Another critical objective was to demonstrate that Meramec pond ash could be extracted, processed and accurately fed to the mixing plant. Besides these relevant objectives, the test section also pursued objectives typical of RCC test sections, such as lift joint quality evaluation, bedding mix type selection (mortar vs. concrete bedding mix), and facing system evaluation. This full-scale RCC placement used crushing, mixing and RCC placing equipment typical of small to medium sized RCC projects.

Figure 11. Test Pad 1 – Aggregate Bin Feeder (left) and Placement of Base Pad (right)

In early December 2006, about 1500 CY of RCC was placed using mixes 80+120 and 100+100. Figure 11 shows RCC placement during Test Section I. Both mixes showed acceptable fresh mix properties, and mechanical properties resulted well above design requirements (Figure 12). On this basis, mix 80+120 was selected for the next phase.

Two types of bedding mix were evaluated during construction of Test Pad I: sand mortar and ¾” MSA concrete mix. Both mixes performed well and produced well-bonded RCC lift joints. Also, observations made during placement showed that mortar sand was a more user-friendly product than concrete; however, the
consensus after visual evaluation was that the concrete bedding mix produced a superior joint. Figure 13 shows close-ups of wire cuts for both types of bedding.

Figure 12. Compressive Strength vs. Age Mixes 100+100 and 80+120 Test Pad 1

![Compressive Strength vs. Age Mixes](image)

At the time Test Section I was built, the facing system for the dam was concrete curbs. For that reason, one face of the test section was built with this method; however, cracking experienced during in the curb face and schedule concerns related to long waiting times for the curb to be able to receive RCC prompted a design modification to formwork. Figure 14 shows placement of concrete curbs during the test section.

Figure 13. Mortar Bedding Mix (left) vs. Concrete Bedding Mix (right)

![Mortar Bedding Mix](image)
Test Section 2 (Production Test Section)
The primary goal of the production test section was to demonstrate mix performance with available materials produced, crushed, transported and delivered with the equipment deployed by the Contractor for Dam Construction. Another critical objective was to demonstrate the capability to produce an acceptable upstream face with concrete placed against inclined formwork achieving an intimate contact with the RCC mix. As mentioned above, the facing system of the dam was changed from concrete curbs to conventional concrete placed against forms (Figure 15). The start of the RCC placement on the dam was contingent to the quality achieved during this test section.
Placement in the test section started mid-August 2007, using mostly mix 80+120 (C+FA); however, advantage was taken of the initial lifts to try mixes with increased ash content (80+140). The work plan contemplated the placement of 12 lifts of RCC; this section height allowed to make one formwork jump, which was a required test for approval of the formwork system proposed by the Contractor.

Figure 16 depicts wire cuts of RCC with bedding mix (left) and without bedding mix (right). In general, the cuts revealed a well compacted RCC mix with a good particle distribution throughout the mass and very little segregation. On the non-bedding wire cut, segregation along high maturity lift joint lines was more pronounced, but overall quality was acceptable. Interface between RCC and conventional facing concrete at the w/bedding side, which represents the standard case on the dam, was considered good. Based on these results, clearance for placement on the dam was received early October 2007. Placement started on October, 10, 2007 using mix 100+100 and as Figures 17, 18 and 19 depict, field densities, gradation, and compressive strength of the RCC placed on the dam thus far comply with project specifications and design requirements.

Figure 16. Wire Cuts in Production Test Section – With Bedding Mix (left) and No-Bedding (right)

Figure 17. RCC Nuclear Field Densities
6 Summary

An extensive lab and field testing has been performed to define the Taum Sauk Upper Reservoir RCC mix design and related construction details. The work included not only lab mixes but also two full-scale RCC test sections. Among relevant objectives achieved during the process are the following:

- Definition of the most appropriate RCC mix for available materials;
• Determination that a tertiary crusher was necessary for the aggregate crushing plant;
• Tested and modified the means and methods to extract Meramec Pond Ash; and
• Selected and tested the appropriate facing system (Curb vs. formwork).

All these accomplishments entailed arduous efforts for the involved parties and also significant expenditure to the Owner; however, lessons learned and experiences gained in the process have been critical to correct the course and improve project design.

References
Mr. Gaekel is a Civil Engineer Specialist in Roller Compacted Concrete (RCC). His background includes experience in mix design, production and placing of both, Lean and High Paste RCC. Mr. Gaekel has produced and placed structural and mass conventional concrete. He has performed Quality Control and lab testing of RCC, concrete, soils and asphalt. He also has experience with slurry walls and jet-grouting mixes, dam and underground works instrumentation monitoring. He has participated in the construction of six large RCC dams and two conventional concrete dams in USA, Bolivia, Indonesia, Colombia and Honduras. The combined volume of concrete placed in these projects exceeds 4 millions cubic yards. Mr. Gaekel has a Master Degree in Civil Engineering / Infrastructure Planning.

Dr. Rizzo has more than 40 years of experience on a wide variety of dam projects, including embankment dams, gravity dams, Ambursen dams, arch dams, and timber crib dams. He has served as Principal-in-Charge for all of the firm’s dam projects, located in the U.S. and overseas. He has lectured on a variety of civil and geotechnical topics, and served on consulting boards dealing with various issues in dams, seismic design, and geotechnical engineering. Dr. Rizzo has extensive experience related to the civil engineering aspects of nuclear power plants, thermal plants, hydro plants, and earth and rockfill dams. He has actively participated in the industry, dealing with regulations, criteria, and professional practice in his areas of expertise. He is highly recognized for his contributions in earthquake engineering and foundation design of major structures. He has served as a Consultant to the utility, steel, petroleum, and mining industries. Dr. Rizzo’s professional and academic experience is reflected in his more than 100 publications in areas of his expertise.