

Mechanical Properties of a High Volume Natural Pozzolan Roller Compacted Concrete for Dams – Laboratory and Field Trials

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Abstract— This article reports the experimental findings of critical thermo-mechanical properties of Roller Compacted Concrete (RCC) containing a high proportion of natural pozzolan as a Supplementary Cementitious Material (SCM) for RCC dam construction, and was accomplished through laboratory and field trials. Natural pozzolan such as volcanic ash is a promising alternative to the industrial SCM such as flyash, especially where the industrial SCM are economically unavailable as well as due to their expected shortage in the near future following greener energy sources and the need to reduce carbon emissions of concrete. The trials involved an initial laboratory phase for selection of optimum cementitious materials proportions for the RCC, followed by field trials through construction and testing of a Fullscale Trial Embankment. Based on this research, the RCC with a cement replacement of up to 68% with natural pozzolan has produced satisfactory mechanical properties for dam construction and with nearly ideal thermal properties. The results are comparable to other international RCC dams and the RCC mix is considered appropriate for construction of a high quality and durable dam structure whilst contributing to sustainable construction.

Keywords: Roller Compacted Concrete (RCC), Trial Mix Programme, Ordinary Portland Cement (OPC), Natural Pozzolan, Accelerated curing, Full-scale Trial Embankment (FSTE)

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1. Introduction

RCC is a zero-slump concrete which is compacted by vibratory rollers to layers of typically 300mm thickness and in its fresh state, will support a vibratory roller and other earthmoving equipment without sinking [1]. The technique utilizes high production capacity equipment to produce and rapidly place the RCC in successive layers and is mostly suited for dams and roads construction where there are large open areas available for concrete placing [2]. As a result, RCC has three key properties that make it uniquely suited for dams that is, economy, performance and high-speed construction [3]. RCC in dams has a history of about four decades and as of 2022, there were about 1000 RCC dams constructed globally [4].

Modern RCC is highly workable with a VeBe time of 8 to 12 seconds or less, and is super-retarded with an extended initial setting time of about 20 hours through incorporation of set retarding admixtures for effective layers bonding. The aggregate specification is more restrictive in terms of better particle shapes and with continuous grading to produce lower void content especially for the fine aggregates fraction [5]. The mixes utilize significant amounts of SCM for cost reduction, reducing rate of evolution of heat of hydration and to improve RCC properties such as workability, mix cohesiveness, impermeability, etc. [6].

To mitigate against thermal cracking, the RCC mix should be designed with as low cement contents and with replacement with as much pozzolanic material such as low-lime flyash, ground granulated blast-furnace slag, natural pozzolan etc. as practicable [7]. Approximately 68% of the RCC dams in the world have been constructed while utilizing low-lime flyash as SCM [8]. However, there has been an increasing trend towards use of natural pozzolan in RCC especially where the industrial SCM are economically unavailable and probably due to the expected shortage of pulverized flyash in

the future due to transition from coal fired thermal plants to greener energy sources, and the need to reduce carbon emissions of concrete [8] [9].

While use of high proportions of SCM is technically desirable for improving the mechanical properties of the concrete, replacing cement with SCM has the additional benefits of reducing the greenhouse gases emissions and global warming associated with cement, leading to sustainable construction [10]. Cement production accounts for about 8% of global CO₂ emissions whereby for each ton of clinker produced, about 850kg of CO₂ is released into the environment [11]. Partial replacement of cement can therefore significantly reduce the industry's carbon footprint and is highly endorsed [7].

Natural pozzolan is a pyroclastic material that is abundantly availability in many regions of the world. To date, approximately 110 RCC dams have been constructed globally utilizing ASTM Class N natural pozzolan as a supplementary cementitious material. However, in majority of these dams, the proportion of the natural pozzolan used has been relatively low [8]. Compared to industrial SCMs such as low-lime fly ash which have been extensively researched, natural pozzolan RCC remains relatively underreported in literature [12]. Nonetheless, Malkawi et al [13] demonstrated that the performance of RCC incorporating natural pozzolan is comparable to that of flyash and other pozzolanic material. Their findings support the effective use of natural pozzolan in RCC dam construction, especially in regions where industrial SCMs are unavailable or uneconomical.

In this study, Kenya's huge deposits of volcanic ash natural pozzolan in Ngelani area near Nairobi was investigated as a potential SCM for the RCC in order to avoid overreliance on imported flyash [14]. The research was motivated by the specific design requirements of Mwache Multi-Purpose RCC dam, which is the first RCC dam in Kenya and is also the first major concrete structure to utilize the Ngelani natural pozzolan in the proportions envisaged. The key objectives of the study were: i) to determine the optimum proportions of ordinary Portland cement and natural pozzolan for RCC and ii) to conduct a detailed study of the mechanical and thermal properties of the RCC for dam construction.

Critical thermo-mechanical properties of the RCC were evaluated through laboratory and field trials. The fresh properties of the RCC investigated included the RCC workability by the VeBe time, initial and final setting times. The hardened properties investigated included the compressive strength, split tensile strength, direct tensile strength of the parent/unjointed RCC and across layer joints. In addition, some RCC specimens were cured at elevated temperatures of 90°C for a period of between 4 and 14 days, and the results correlated with those of the normally-cured specimens, enabling determination of the long-term mechanical properties within a relatively short duration of time.

The field trials were accomplished by construction of a full-scale trial embankment which was comprehensively cored and tested. The thermal properties of the RCC investigated included the heat of hydration in accordance to ASTM C1702-17 and adiabatic temperature rise properties of the RCC by studying thermocouple data installed in the core of the full-scale trial embankment. Detailed thermal analysis and modelling of the dam were conducted under a separate study.

The RCC mechanical properties were checked against the structural design requirements of Mwache Multi-purpose dam which are summarized in Table 1.

Table 1. RCC Mechanical Properties requirements

Parameter	Factor	Property
RCC Workability	8-12 seconds	Optimum workability for the highly workable RCC for better in-situ properties
RCC Density	2,300 kg/m ³	Required unit weight for stability of the gravity dam
Compressive strength at 365 days	18.5 MPa	Characteristic cube compressive strength at design age of one year. (Target strength = 20.9MPa)
RCC Direct Tensile Strength	0.75 MPa	Interlayer bonding strength for the dam static and dynamic stability.
RCC Split Tensile	1.80 MPa	To limit potential for cracking of the dam due to

Parameter	Factor	Property
Strength		long term thermal-mechanical stresses

Source: Detailed Design Report of Mwache Multi-Purpose Dam [14]

2. Materials

The materials utilized in the manufacture of RCC comprised of CEM I 42.5 cement conforming to BS EN 197-1, a natural pozzolan conforming to ASTM C618-Class N, Set-retarding admixtures meeting the requirements of Type B and/or Type D in accordance to ASTM C494 and Aggregates. The aggregates were in four bands of 50-25mm, 25-12.5mm, 12.5-4.75mm and 4.75-0mm. The aggregates were required to be of an ideal shape with the sum of Flakiness index and Elongation index of less than 20% when tested in accordance with BS812-105:1 and 105:2. The void ratio of the fine aggregates when using the compacted bulk density in accordance to ASTM C29 should be less than 30%.

3. Methods

The RCC mix proportions were developed by firstly conducting an extensive laboratory trial mix programme for selection of the optimum cementitious materials for the RCC. Four mixes with a total cementitious materials contents of 220 kg/m³ in varying proportions of cement + natural pozzolan of 60+160 kg/m³, 70+150, 80+140 and 90+130 kg/m³ were manufactured for selection of the optimum proportions meeting the mechanical properties requirements. The selected proportions were subsequently utilized in the construction of a Full Scale Trial Embankment where evaluation of the in-situ properties of the RCC was made through extraction and testing of cores.

3.1 Laboratory Trial Mix Programme

The laboratory trial mix programme was carried out in the following steps;

3.1.1 Stage 1 - Optimization of the aggregate gradation

The optimum gradation of the aggregates was achieved by combining the various sizes of aggregates in varying proportions and by obtaining the maximum bulk density and thus minimum voids while using procedures of ASTM C29. The selected optimum aggregate proportions which gave the minimum voids was selected as 20:20:26:34 for the 25-50:12.5-25:4.75-12.5:0-4.75 mm aggregates respectively. The gradation curve of the combined aggregates using these proportion is shown in Figure 1. A continuous grading curve was achieved which is in line with the requirements of RCC mixes [9].

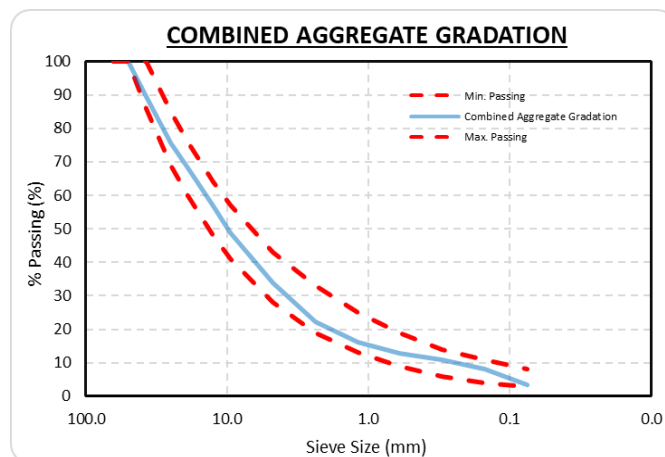


Figure 1. Overall Aggregate Gradation curve

3.1.2 Stage 2 - Optimization of the Water contents of the RCC

A VeBe time of 8-12 seconds in accordance to ASTM C1170 procedures was defined as the optimum range for the RCC workability. RCC was trialed by varying the water content to obtain the optimum workability and the water content producing the optimum VeBe time was determined whilst assessing the mix cohesiveness visually. A typical optimization of the RCC water contents is shown in Figure 2. A free water content range of 111 – 115 kg/m³ was established as the optimum for the required VeBe time of 8 to 12 seconds, representing a water to cement ratio of 0.5.

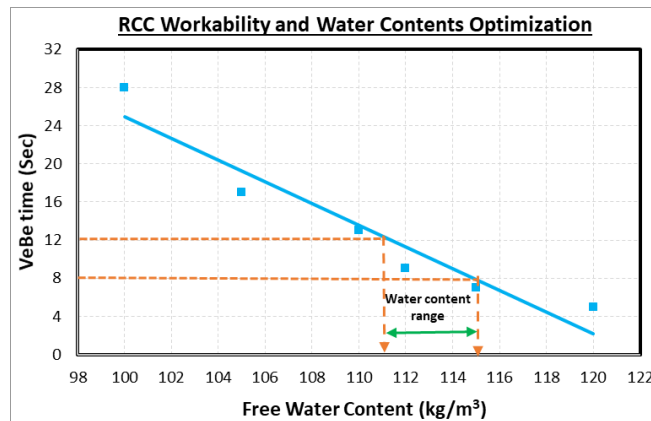


Figure 2. Optimization of the RCC Workability & Water contents

3.1.3 Stage 3 - Optimization of the Retarder Dosage

It was intended to delay the Initial Setting Time of the RCC to 21± 3 hours in order to allow placement of successive RCC layers within a day. The Final Setting Time was required to be less than 60 hours for formwork design. The RCC mix was trialed with different retarders and the setting times at different dosages was assessed on a 5mm screened mortar in accordance to ASTM C403. A typical RCC setting time results at different retarder dosages is shown in Figure 3. A retarder dosage of 1.35% was found optimum and gave an initial setting time of 22 hours and a final setting time of 42 hours.

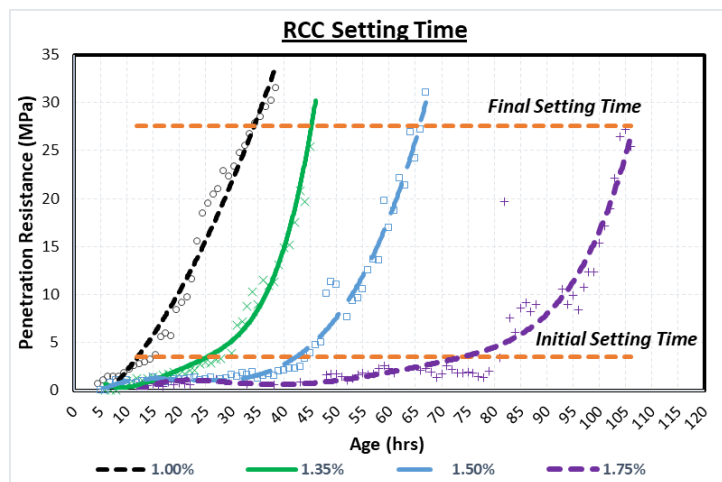


Figure 3. Optimization of the Retarder Dosage

3.1.4 Stage 4 – Optimization of the Cementitious Materials Proportions

Optimization of the cementitious materials contents was conducted by designing mixes with a total cementitious materials contents of 220 kg/m³ at four levels of cement + natural pozzolan contents of 60+160 kg/m³, 70+150, 80+140 and 90+130 kg/m³. At least two 150mm cubical and 150mm dia. x 300mm high cylindrical RCC specimen were prepared for each mix for periodic testing of the mechanical properties up to the design age of one year. The samples were cured at temperature of 23±2°C as per ASTM C192 whilst some additional samples were accelerated cured at elevated temperature of 90°C for 4, 7 and 14 days in accordance to ASTM C684. Selection of the optimum

cementitious materials proportions was done based on the one-year compressive strength of the normal cured samples. Detailed analysis of the test results is included in Section 4 of this paper.

3.2 Full-scale Trial Embankment (FSTE)

As part of the RCC mix qualification in terms of its in-situ application and properties, a Full Scale Trial Embankment (FSTE) placement of the RCC was carried out. The FSTE was constructed on a 60m long section, 10m wide and was 2.7m high. Nine RCC layers each 300mm high were constructed, resulting in eight horizontal joints. The horizontal joints were planned in accordance to the initial and final setting time of the RCC and were categorized as hot, warm or cold joint. For hot joints with exposure time of less than 18 hours, no treatment was applied to the RCC receiving layer. For a warm joint with exposure time of between 18 to 42 hours, a cement grout was applied to a RCC layer surface. For cold joints with exposure time of more than 42 hours, they were treated by removing the laitance by green-cutting to expose the coarse aggregates and with addition of a cement grout prior to RCC placement. Figure 4 shows a transverse section of the FSTE while Figure 5 shows construction of the FSTE in progress.

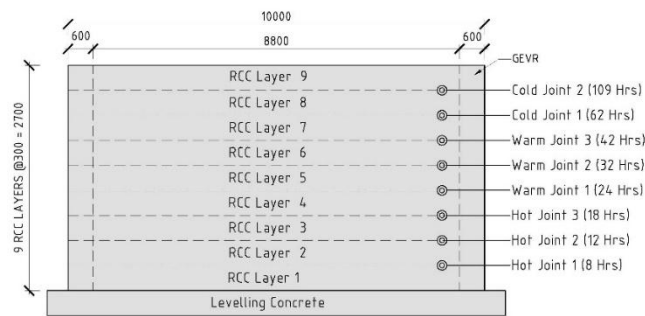


Figure 4. Transverse section of the FSTE



Figure 5. Construction of the FSTE

A comprehensive coring programme for the FSTE was developed and a total of 28 cores, 150mm in diameter were extracted and tested in accordance to ASTM C42. Figure 6 is a photograph of one of the cores with a length of 2.7m. Test samples were obtained by trimming the cores into 300 mm high cylindrical samples which were tested at the age of 90 days for the direct tensile strength of both the parent/unjointed RCC and across horizontal joints of various exposure times, indirect/split tensile strength of the parent RCC, compressive strength, modulus of elasticity and in-situ density of the RCC.



Figure 6. Photograph of one of the extracted core from the FSTE

4. Results and Discussion

4.1 Compressive strength

The development of cube compressive strength with age up to the design age of one year of the

RCCs containing various proportions of the ordinary Portland cement ranging from 60 to 90 kg/m³ and with the Ngelani Natural Pozzolans ranging from 130 to 160 kg/m³ is shown in Figure 7.

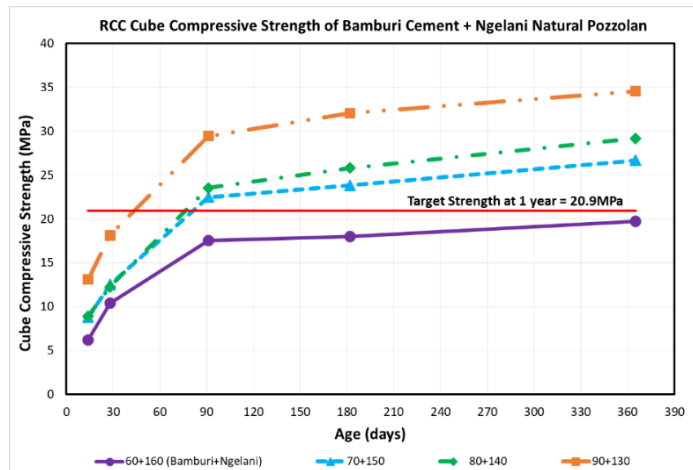


Figure 7. Development of cube compressive strength with age

As expected for concrete, the compressive strength increased with age and there is a proportionate increase in the compressive strength of the RCC with reduced supplementation of cement by the natural pozzolan in the RCC. It is also noted of the continued gain in compressive strength of the RCC far beyond the customarily design age of conventional concrete of 28 days due to the activation of the pozzolan by the calcium hydroxide produced from the hydration of cement, and the one-year compressive strength is about twice that of 28 days. Consequently, considering the fact that a significant portion of a large dam do not generally experience significant loading immediately upon construction and the maximum loading do not usually develop until the concrete is at least one-year-old, it is thus practical to specify the RCC design age based on the long term strength and the cementitious materials content can be optimized accordingly.

It can be noted that the 60+160 kg/m³ (OPC + Ngelani natural pozzolan) mix did not attain the target compressive strength at the design age of one year. This suggests that the higher levels of natural pozzolan reduces the amount of available cement leading to fewer cement hydration products, which reduces the compressive strength. Therefore, a slightly higher cement content is required to satisfactorily attain the design strength requirements. The 70+150 mixes met the target compressive strength requirement of 20.9MPa at the age of about 90 days and continued to gain strength to attain a cube compressive strength of 27MPa at the age of one year. The 80+140 and 90+130 kg/m³ mixes far exceeded the design strength requirement with considerable margins of between 39% and 63% respectively, and while such high levels of compressive strengths and cement contents would be unnecessary for a gravity dam, such mixes would be far less desirable from thermal considerations due to considerable generation of heat of hydration and the consequent potential of cracking due to thermal stresses.

Therefore, based on the one-year compressive test results, the optimum cementitious materials proportions to achieve the design compressive strength was concluded as an ordinary Portland cement content of 70 kg/m³ with a Ngelani Natural Pozzolan content of 150 kg/m³. This cementitious materials content was selected for detailed investigations including for the thermal properties and in-situ mechanical properties through construction and testing a full scale trial embankment. For similar cementitious materials contents, these research results are comparable to those obtained by Dunstan et. al, while utilizing a natural pozzolan sourced from Holili from near Mt. Kilimanjaro in Tanzania where the RCC attained a compressive strength of 24MPa at the age of one year [15].

4.2 Comparison of the compressive strength of the normal and accelerated cured samples

A logarithmic extrapolation of cylinder compressive strength of the normally cured samples and of the samples which were cured at elevated temperature of 90°C for 4, 7 and 14 days is shown in Figure 8. The figure also includes the average compressive strength of at least 20 cylindrical samples

cut from the cores extracted from the FSTE which were tested at the age of 90 days. All the mixes in this figure contained 70+150 kg/m³ of OPC + Ngelani natural pozzolan respectively. The figure also includes typical compressive strength from several RCC dams globally, which shows the compressive strength of the RCC mix with the Ngelani natural pozzolan was in line with the reported figures [9].

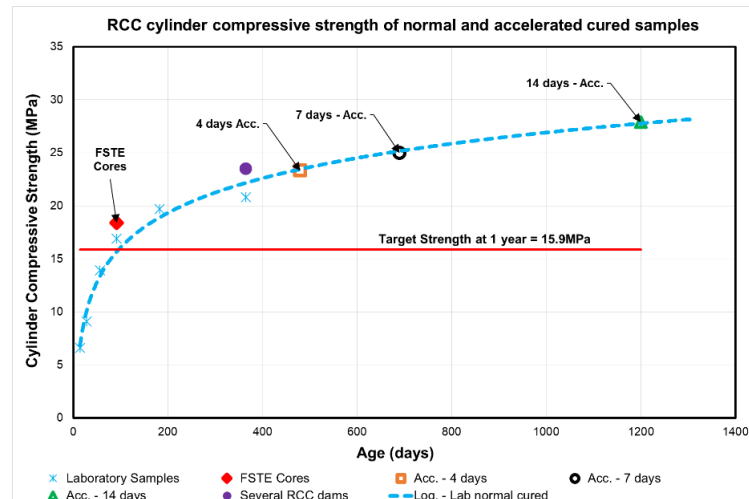


Figure 8. Comparison of the normal cured and accelerated cured samples

It can be noted that the compressive strength of the cores extracted from the FSTE at the age of 90 days were similar, although marginally higher than the laboratory manufactured samples. The accelerated cured samples at 4, 7 and 14 days produced cylinder compressive strengths of 23.3, 25.0 and 27.9MPa respectively. These results exceed the cylinder compressive strength of 20.8MPa at the age one-year of the normally-cured samples and they possibly represent the ultimate compressive strengths of the RCC. By assuming the same rate of pozzolanic reaction and compressive strength development, the RCC will accordingly attain a cylinder compressive strength of 28MPa at the age of about three years. These results are comparable to those obtained by Pauletto et al. [16] where the 14 days accelerated cured tests were indicative of 240 day strength of the normally-cured specimen.

4.3 Tensile Strength of the RCC

The tensile strength is one of the most critical design parameter for RCC dams for dam stability from both the static and dynamic conditions and is particularly a design criterion for seismic loading where the dam may be subjected to significant vertical tensile stresses [17]. While the direct tensile test is not an easy test to conduct, it is however the most reliable measure of the actual in-situ static tensile strength across the horizontal joints of an RCC dam. The indirect or the split tensile test is much easier test to undertake than the direct tensile test but the test is not a reliable indicator of the true tensile strength due to the complex stress state of the test and size effects common when testing specimen with large aggregates [2], [18]. The split tensile test therefore may overestimate the true tensile strength of an RCC with implications on both the static and dynamic performance of RCC dams [17]. The tensile strength of the RCC was evaluated on various samples as outlined below.

4.3.1 Direct tensile strength of the unjointed / parent RCC

Results of the direct tensile strength development with age of the parent / unjointed RCC for the various samples is shown in Figure 9. It can be observed that the RCC cores extracted from the FSTE had a direct tensile strength of 1.1MPa at the age of 90 days while the laboratory samples attained a direct tensile strength of 1.2MPa at the age of one year. These results are comparable with cores taken from several RCC dams in the USA where the average tensile strength was 1.7MPa [9]. Results of the accelerated cured samples shows that the RCC will attain an ultimate direct tensile strength of approximately 1.4MPa. While the RCC met the design requirement for direct tensile strength, it can however be noted of the ‘flattening’ of the tensile strength development curve after the age of about 90 days and the insignificant gain in direct tensile strength with age and/or compressive strength.

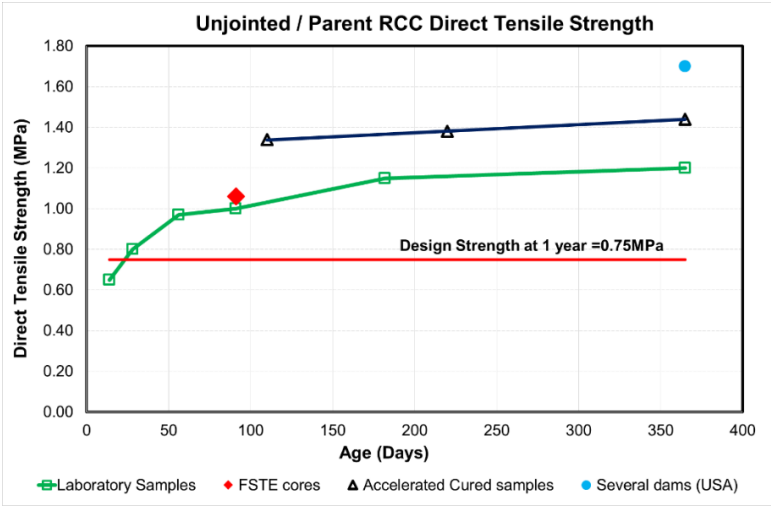
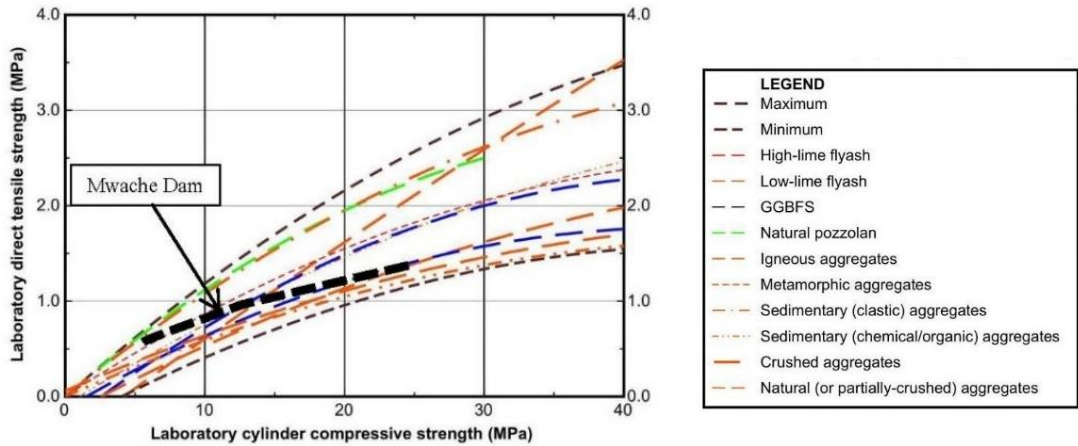


Figure 9. Direct Tensile Strength development of the unjointed/parent RCC

The direct tensile strength results have been plotted against a relationship as developed by Dolen & Dunstan [17], which relates the direct tensile strength to the cylinder compressive strength for several RCC dams as shown Figure 10. The figure shows that the direct tensile strength as a percentage of the compressive strength can vary significantly from 4% to 10% depending upon the type of aggregate and even the type of pozzolan that is being used. The figure obtained at Mwache dam was about 5% and as shown, it was unusually on the lower limit, which can be attributed to the quality of the sandstone aggregate in this case.



Source: Dolen & Dunstan (2012)

Figure 10. Relationship between RCC Direct Tensile and Compressive Strength

Figure 11 shows fractured aggregates, which suggests the primary failure mode associated with the RCC direct tensile test was the aggregates which initiated failure during direct tensile test. In view of this, further tests on the long-term durability of the concrete have been recommended and are ongoing.

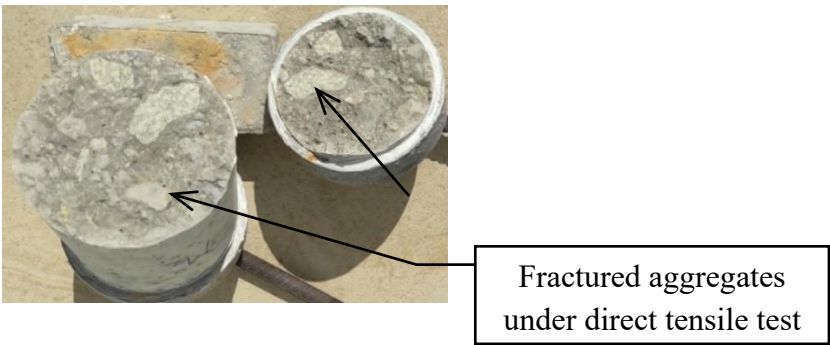


Figure 11. Failure surface of the RCC sample under direct tensile test

4.3.2 Direct Tensile Strength of the RCC layer joints

The direct tensile strength of joints with various exposure times and treatment were evaluated on at least four to six joints of the extracted cores from the FSTE. The joints were tested for the vertical static direct tensile strength at the age of 90 days and the results are shown in Figure 12.

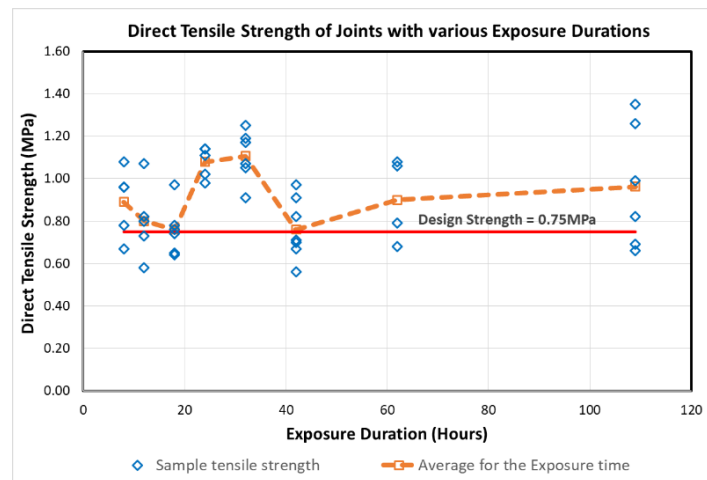
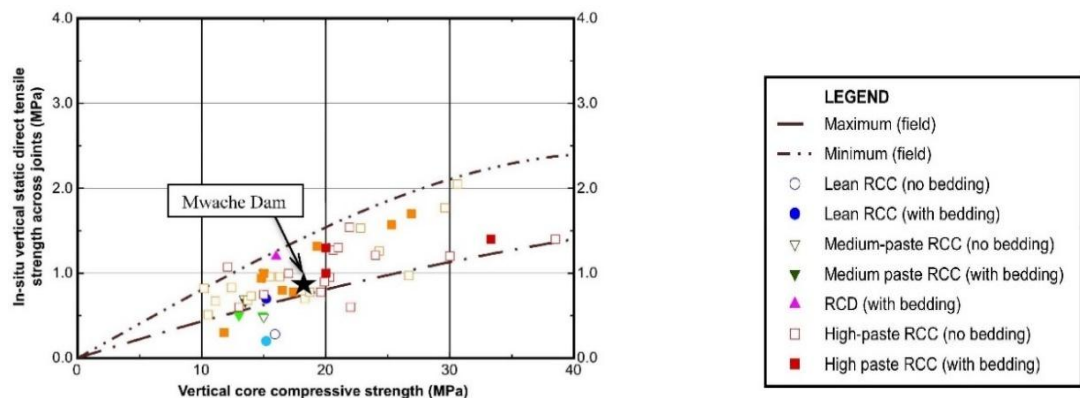


Figure 12. Direct Tensile Strength of Joints with various exposure times

The average direct tensile strength of the joints was 0.86MPa and met the design requirements at the age of 90 days. The results have been compared with a series of average in-situ vertical static tensile from over 60 RCC dams as developed by Dolen & Dunstan [17]. This relationship is shown in Figure 13. The relationship of the in-situ direct tensile strength to the core compressive strength for Mwache dam is on the lower limit at about 5%. This rather unusual relationship is comparable to the 5.2% of the Upper Stillwater RCC dam in the USA, which was completed in 1987 and was actually the first large RCC dam to be constructed in the world and has performed satisfactorily [19].



Source: Dolen & Dunstan (2012)

Figure 13. Relationship between the average in-situ vertical direct tensile strength across joints and the vertical core compressive strength

4.3.3 Split Tensile Strength of the RCC

In a large dam, it may take several years after completion for the temperature in the deeper parts of the dam to dissipate and for the external restraints due to thermal stresses to become apparent [20]. Consequently, the thermal analysis of the dam indicated that a long term split tensile strength of 1.8MPa was required to control thermal cracking as the dam cools. Results of the split tensile strength development with age of the RCC are shown in Figure 14.

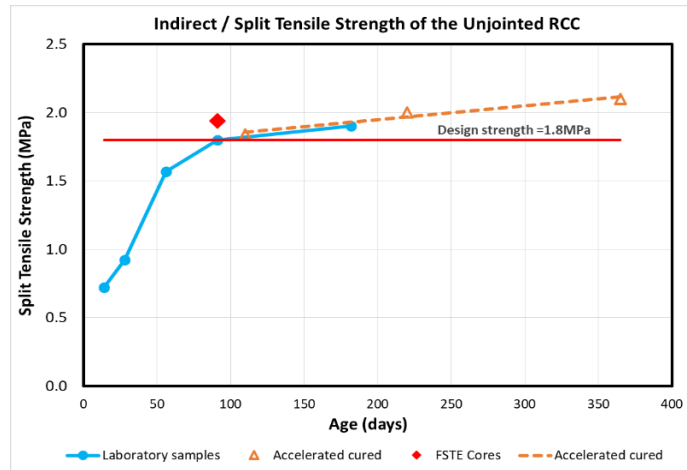


Figure 14. Split Tensile Strength of the RCC

The RCC met the split tensile strength requirements although at the age of about 90 days and the strength is expected to continue increasing with age to attain an ultimate split tensile strength of about 2.1MPa as indicated by the accelerated curing test. At the age of 90days, the split tensile strength was 1.8MPa, which is about 10% of the compressive strength and about 1.7 of the direct tensile strength. This confirms the conclusions made by Timothy & Dunstan [17] that the split tensile test may actually overestimate the true tensile strength of RCC. Nevertheless, the direct tensile has the particular advantage that it can be easily performed on both the parent and the jointed cores while the split tensile test can only be easily performed on the parent RCC and is not easily tested across RCC layer joints.

4.4 Thermal Properties of the RCC mix

Test results of the heat of hydration test of the 70+150 kg/m³ of cement + natural pozzolan are shown in Figure 15. The figure indicates that there is a reduction of about 40% to 50% in heat of hydration generation due to 68% partial replacement of cement with the Ngelani natural pozzolan.

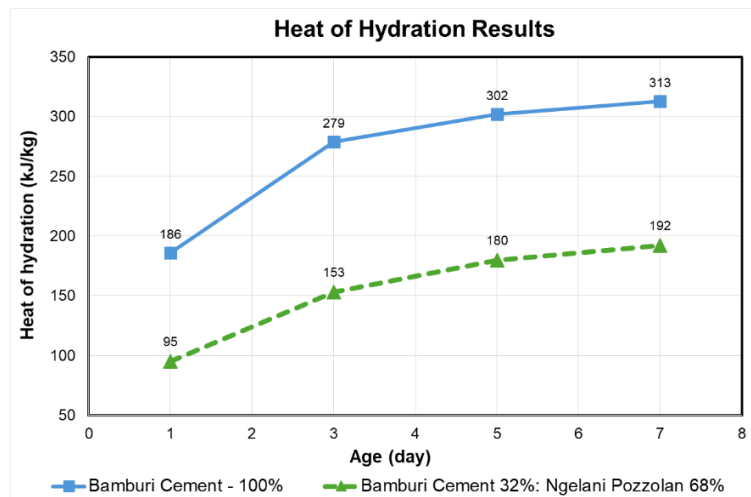


Figure 15. Test results of Heat of Hydration

Temperature rise of the RCC from thermocouple data installed at the core of the fullscale trial embankment placement is shown in Figure 16. A peak temperature rise of about 11°C was recorded after 17 days. This suggests that the 70 kg cement + 150kg natural pozzolan mix has a relatively low heat of hydration and the thermal conditions in the dam will be almost ideal in mitigating against thermal cracking risks.

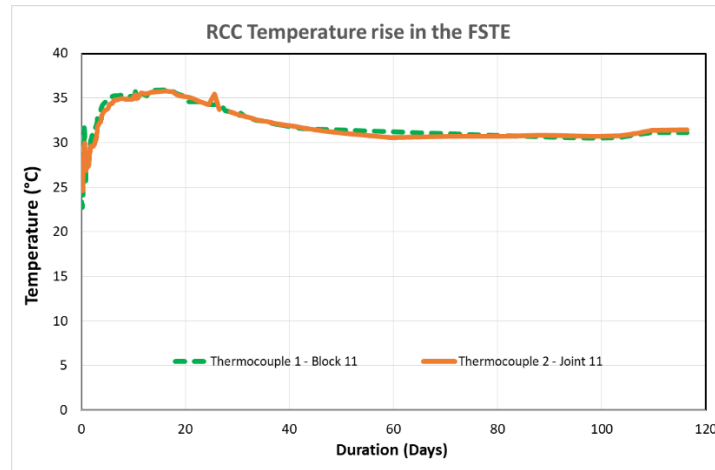


Figure 16. Temperature rise of the placed RCC from thermocouples in the FSTE

4.5 Estimating GHG Emissions associated with the proposed cementitious materials

A preliminary exercise has been carried out to estimate the Greenhouse Gases (GHG) emissions associated with the cementitious materials as shown in Table 2. It is evident that the ordinary Portland cement is a major emitting resource and extensive use of SCM to replace the Portland cement is fortified for sustainable construction.

Table 2. Estimation of the GHG emissions due to cementitious materials based on the BoQ items

BoQ item	Quantity (m ³)	Resource	Proportion (t/m ³)	EF-database (t CO ₂ e/unit)	Emission (t CO ₂ e)
RCC	600,000	Ordinary Portland Cement	0.07	0.862	36,204
		Natural Pozzolan	0.15	0.018	1,620
		Total			37,824

4.6 Summary of the results

A summary of the results of the mechanical properties of the RCC obtained is shown in Table 3, which also includes reported figures from other international RCC dams for comparison purposes [9].

Table 3. Comparison of RCC mechanical properties

Characteristic Strength at 365 days (MPa)	Mwache Dam		International RCC dams	
	Normal cured	Accelerated cured	Typical	Range
Compressive Strength	23	28	23.5	11 - 40
Parent Direct Tensile Strength	1.2	1.4	1.5	0.7 - 2.9
Joint Direct Tensile Strength	0.9	-	1.1	0.6 – 1.9
Split Tensile Strength	1.9	2.1	-	-

5. Conclusions

The RCC mix development exercise was successfully conducted and the RCC mechanical properties were confirmed to be satisfactory for construction of a high quality concrete dam. While the results are specific to the material properties and local context constraints, a number of important conclusions can nonetheless be drawn from this study. The RCC containing 70+150 kg/m³ of OPC + Ngelani Natural Pozzolan was concluded as the optimum cementitious materials proportions to attain a compressive strength of 20.9MPa at the design age of one year. The one-year compressive strength was about twice that of the 28 days, proving a long term pozzolanic reaction between the cement and natural pozzolan. The accelerated curing test was confirmed as an effective tool to give indications of

the RCC quality and enabled determination of the ultimate mechanical properties of the RCC within a relatively short period of time. The unusual relationship between the direct tensile strength of the RCC to the cylinder/cores compressive strength of about 5% was noted to be on lower bound of the several RCC dams globally, and this was attributed to the inferior quality of the sandstone aggregates in this case. The aggregate quality therefore impacts greatly on the concrete quality and the choice of rock quality should be carefully considered alongside the cementitious materials. The split tensile strength of the unjointed RCC was found to be about 1.7 times of the direct tensile strength and confirms the conclusions that the split tensile test may overestimate the actual tensile strength of RCC and the direct tensile strength is the true measure of the actual RCC tensile strength. Substitution of ordinary Portland cement with 68% of natural pozzolan in the RCC resulted in a peak temperature rise of about 11°C, indicating a relatively low heat of hydration and suggesting the thermal conditions in the dam will be nearly ideal against thermal cracking. An estimation of the greenhouse gases associated with the proposed mix demonstrates that the ordinary Portland cement is a major emitting resource and extensive use of SCM to replace the Portland cement is fortified.

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