RCC knowledge: how specific test can help to evaluate the real behavior of material and a better design of RCC dams

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ABSTRACT: Design requirements for RCC dams specify minimum values for compressive strength and tensile strength. A high compressive strength is often specified just to comply with the required tensile strength. At GERDP, the largest dam of Africa under construction by Salini-Impregilo, an extensive study has been done at site laboratory to establish the proper correlation between the compressive and tensile modulus to characterize the real stress-strain capacity of RCC. Results have been confirmed by a campaign of compressive-tensile tests in the Concrete Laboratory of Mapei. The decreasing modulus of elasticity with increasing stress may be used for more accurate stress analysis in highly stressed areas. This usually results in a reduction of stress due to "strain softening" with a subsequent savings due to lower strength requirements. The correct evaluation of stress-strain behavior allows a better evaluation of thermal cracking and more effective RCC mix design. The paper highlights the relevance of technical cooperation among designers, contractors and suppliers to share technical knowledge. Suppliers of products such as Mapei, with advanced and well-equipped laboratory, help to perform specific tests to evaluate all RCC parameters at the early stage of a project when design optimization is still possible helping contractors and designers in the correct mix design choice.

RÉSUMÉ : Les exigences des projets pour les barrages en BCR nécessitent des valeurs minimales de résistances à la compression et à la traction. La haute valeur de la résistance à la compression est justifiée par rapport à la valeur requise de résistance à la traction. Pendant la construction du barrage du GERDP (Grand Ethiopian Renaissance Dam Project), au laboratoire sur le site, nous avons étudié expérimentalement la corrélation entre le module d'élasticité à la compression et à la traction pour caractériser la capacité réelle de résistance aux contraintes et aux déformations du BCR. Cette étude a été confirmée par des essais sur les résistances à la compression et à la traction effectuées dans le laboratoire central chez Mapei SpA. La réduction du module d'élasticité en fonction de l'augmentation de la force de traction, utile pour estimer les tensions dans les domaines où les niveaux de traction sont plus concentrées. Ceci implique une réduction du niveau de la tension grâce à un relâchement des déformations, en conséquence une économie en raison de la résistance inférieur requise. L'évaluation correcte de la courbe de contrainte-déformation permet de mieux évaluer les phénomènes de craquage thermique et améliorer la composition du BCR. L'article met en évidence l'importance de la collaboration entre les concepteurs de projet, contracteurs et fournisseurs en partageant les connaissances techniques. Les fournisseurs de matériaux tel que Mapei, avec un laboratoire avancé et bien équipé, permettent d'effectuer des essais particulières pour évaluer tous les paramètres du BCR au début du projet, lorsqu'il y a la possibilité d'aider le contracteur and les ingénieurs concepteurs du projet dans le choix d'une composition correcte du béton.

1 INTRODUCTION

Very often laboratories are not equipped or adequately skilled in detailed testing of tensile and stress-strain properties of concrete. Consequently very little has been done in the past to fully understand the tensile characteristics of concrete even though everyone believes this is an important parameter. The aim of this paper is to summarize the efforts done by the authors focusing specifically on Roller Compacted Concrete (RCC), in order to establish the real behavior and correct modulus values for stress and cracking analysis. Structures constructed with unreinforced mass concrete such as dams require a much better understanding than reinforced concrete where embedded steel is the primary controller of tensile stresses and cracking performances. It must be pointed out also that results and trends from one project may not be applicable to other projects where raw materials (cement, mineral addition and aggregates) and mix design can be very different.

2 GENERAL DISCUSSION ON MODULUS OF ELASTICITY AND STRESS-STRAIN

The modulus of elasticity and stress-strain behavior of concrete has typically been assumed to be similar for both compression and tension. It also has been assumed that a single value for modulus of elasticity will describe the stress-strain relationship through the entire range of stresses from zero to the ultimate load. Typical standard test procedures for the modulus of elasticity are based on two data points, usually at 10% and 40% of the ultimate strength of the concrete. The slope line relating stress and strain between the two data points is reported as the modulus of elasticity. This value is used for all stress analysis including both compression and tension, regardless of orientation (horizontal or vertical loads) and regardless the linearity or not of the stress-strain curve. In many dam projects the modulus of elasticity is not even tested at all. Instead, a simplified calculation is done using an empirical equation from one of the applicable codes such as ACI 318 or EuroCode part 2 without knowing if the equation accurately describes the real stress-strain behavior for that particular concrete. For traditional reinforced conventional concrete structures with strength classes around 20-40 MPa and "normal" aggregates, this may be quite acceptable. In other cases, these empirical formulas simulated can underestimate the value of the modulus for special high strength concrete while on the other side of the scenario the formulas can over predict the modulus for low strength concrete and especially for Roller Compacted Concrete in dam projects and other massive structures. A high modulus results in a stiff and more brittle structure with less deformation while a low modulus results in concrete that can deform more with less cracking from thermal contraction or foundation deformations.

Figure 1 shows the significant difference that can occur in strength, strain capacity, and modulus for mixes at the same project that have the same aggregates, cement supplier, and water content (with equivalent workability) but different strengths due to the different cement contents. In this case, if the actual stress is low and the extra strength is not really necessary, as often happens in some dams, it is better from a cracking, cooling, and cost standpoint to use the mix with lower strength and much more strain capacity. In figure 1 two different samples of the same mix are plotted for each cement content. The almost identical non-linear stress-strain curves for the companion samples demonstrates excellent reliability and credibility of the test results and non-linear shape of the stress-strain curves.

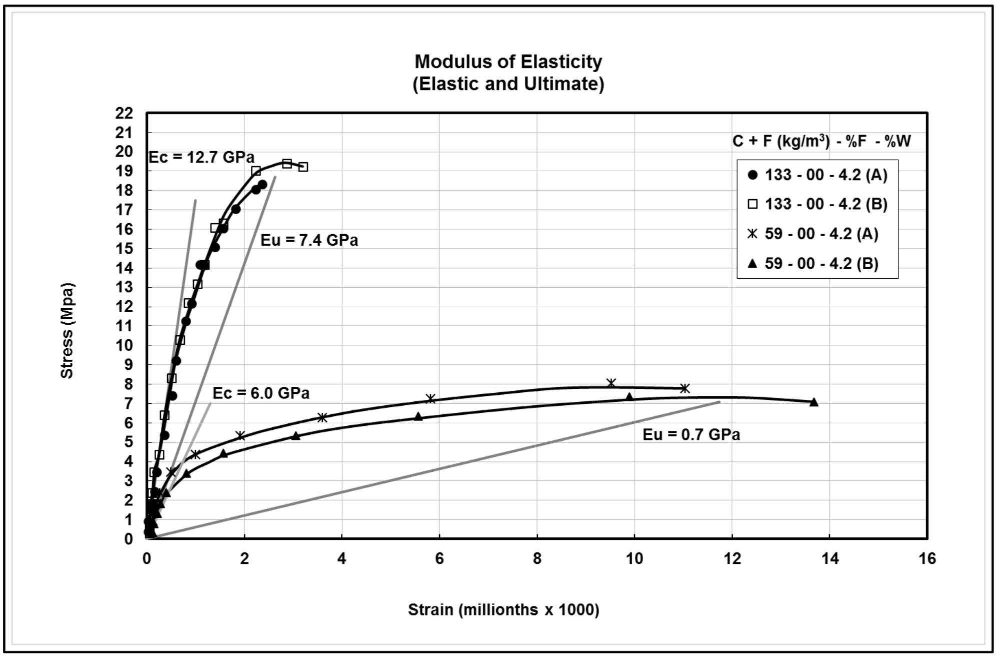


Fig. 1: Compressive modulus (RCC) at different strengths

The challenge is how to relate non-linearity to the designer so that it can be effectively used. A procedure for mass projects has evolved. The secant modulus is simply reported at 25%, 50%, 75%, and 100% of the ultimate load. The designer starts with an estimated value for modulus. He runs the analysis and then compares the modulus value he used to the actual modulus for stresses determined by the first run. The modulus is then re-set for the different parts of the structure, and the analysis is re-run. This usually requires about four iterations, unless the program being used has the capability of accommodating a non-linear equation for the stress-strain curve, in which case only the first run is needed. An example with the iteration method was first presented by Schrader & Rashed in 1995[5], demonstrating that the otherwise high tensile stresses that resulted when the analysis was done using a single modulus and assumed linear stress-strain curve, actually did not exist[1]. Essentially, the otherwise high stresses are re-distributed to areas of lower stress in the structure as the concrete "stretches" without significant real additional stress for the areas of otherwise high stress. It has been a common assumption that the shape of the stress-strain curve for tension and for compression are the same and, therefore, the modulus of elasticity is the same for tension and compression. Very little actual testing has been done, and less has been reported, to substantiate this assumption. Because the tensile strength is much less than the compressive strength, the stress-strain curves using actual stress values cannot be directly compared by plotting them on the same chart with the same stress and strain scales. However, they can be compared on the same chart by plotting the stress as a percent of ultimate load and plotting the strain as a percent of ultimate strain. Figure 2 shows results for mixes tested for the Balambano RCC dam. In this case the compressive and tensile stress-strain curves, and consequently the modulus values at 25%, 50%, 75%, and 100% of ultimate load, are similar.

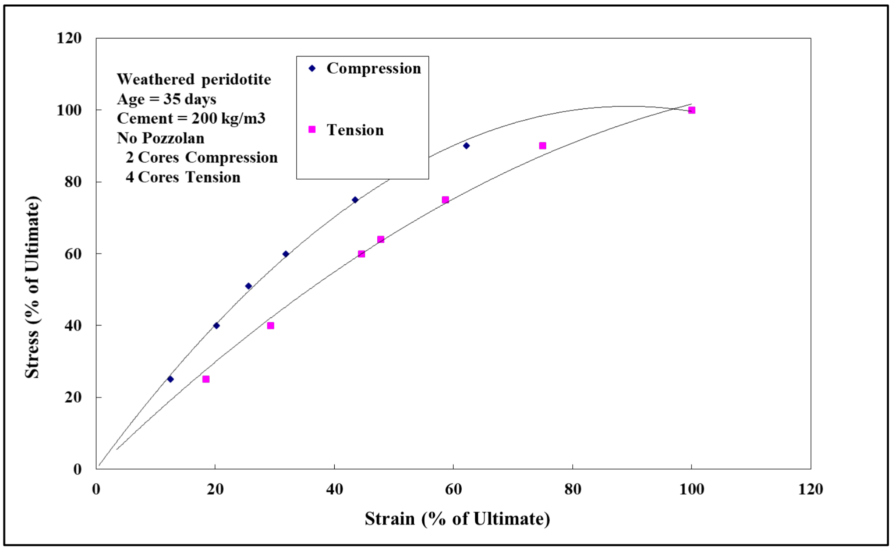


Fig. 2: Compressive vs tension, vertical core Balambano dam.

At other projects, compressive and tensile properties have also been generally similar, but this testing is seldom done, number of credible samples is limited, or the results are not published. However some projects have shown that, for their site specific materials and mixes, the tensile and compressive modulus values can be very different.

3 DESCRIPTION OF GERD PROJECT AND TESTING CAMPAIGN

The testing campaign of tensile and stress-strain analysis described in this paper has been performed at the Grand Ethiopian Renaissance Dam (GERD) Project, currently under construction by Salini-Impregilo with the support of the highly qualified Concrete Laboratory of Mapei in Milan (Italy), to confirm the results from the site. Mapei also supplied the admixtures for the project. The dam where the RCC samples were taken will be the largest dam in Africa with a roller compacted concrete volume of 10,2 million cubic meters. The project also has a 15,000 m^3/sec capacity concrete spillway and a concrete faced saddle dam 5 km long by 50 m high with 17 million cubic meters of rockfill. The testing campaign for RCC and some conventional concrete included about 500 cores from different zones of the dam body, comparing compressive and tensile strength with accompanying stress-strain curves and modulus values for both horizontal and vertical samples. In addition to testing on site, some cores were also sent to the Mapei laboratory in Milano, Italy, for further verification and comparison.

Results of the comparison are summarized in Table 1. Results for strength were very similar for both labs. Both labs showed the tensile modulus to be significantly lower than the compressive modulus.

Table 1: Comp. and tensile modulus at GERDP and Mapei (avg values)

	Compressive Modulus					Tensile Modulus				
	Ultimate strength	Modul 25%	Modul 50%	Modul 75%	Modul 100%	Ultimate strength	Modul 25%	Modul 50%	Modul 75%	Modul 100%
	MPa	GPa	GPa	GPa	GPa	MPa	GPa	GPa	GPa	GPa
Gerdp	16.5	28	22	16	7	1.1	10.5	9.5	8.5	6.5
				Ratio tensile / Compressive			38%	43%	53%	93%
Mapei	16.5	22.5	21	16	9	1.1	16	15	13.5	9
				Ratio tensile / Compressive			71%	71%	84%	100%

Typical compressive and tensile stress-strain curves, plotted as a percent of ultimate strength and ultimate strain for the GERD project are shown in Figures 3 and 4. Tests have been carried out in both laboratories to compare results.

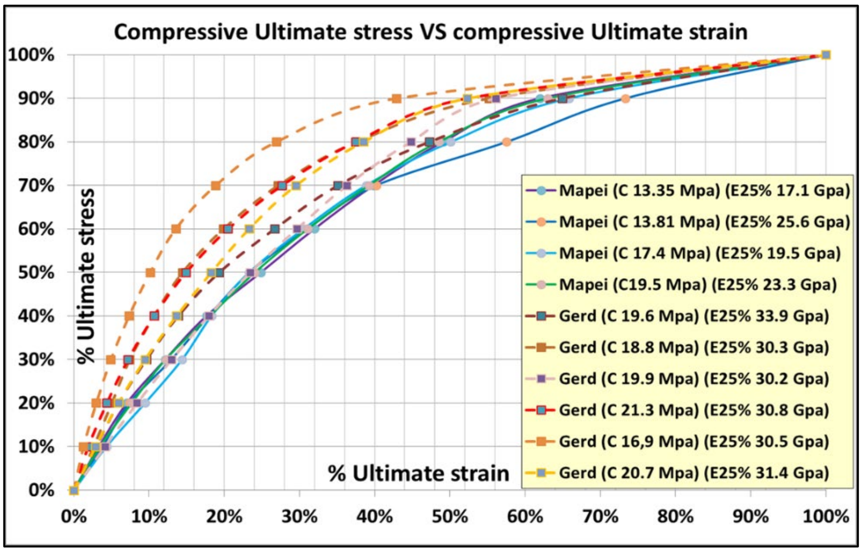


Figure 3: RCC, Typical stress-strain curves for compression at GERD

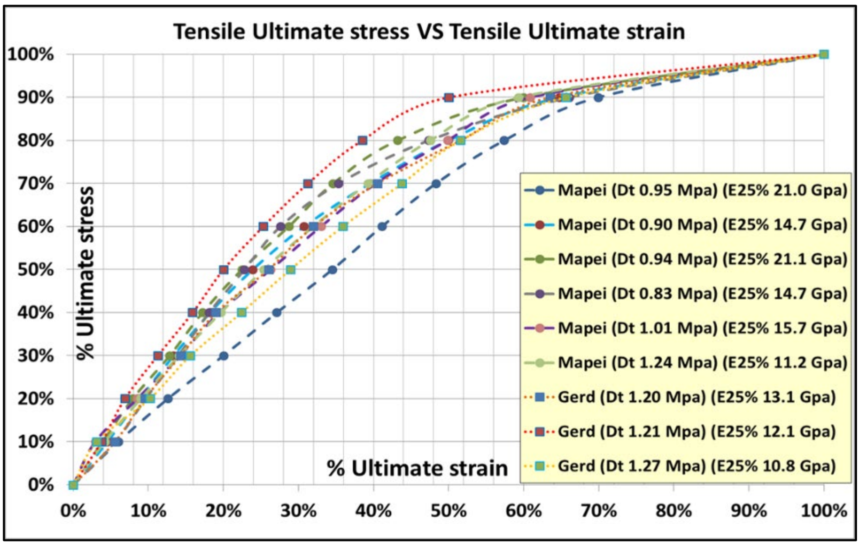


Figure 4: RCC, Typical stress-strain curves for tension at GERD.

The properties of concrete for a horizontal core are typically thought to have the same properties as for a vertical core. However, this is not always the case, especially for tensile strength and tensile modulus of elasticity, and especially with RCC. ASTM C 42, "*Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*" cautions that concrete strength is affected by core orientation relative to the horizontal plane of the concrete as placed, with strength tending to be lower when measured parallel to the horizontal plane. The authors have found that the opposite can also be true. That is, the strength from a horizontal core can be greater than the strength from a vertical core. This again points out the need to do site specific testing.

At the GERD project, a very substantial investigation was made to establish the difference between properties in the horizontal and vertical directions. This included about 100 adjacent companion cores, with and without horizontal joints between successive layers of RCC, that were obtained by first sawing blocks about 250 x 250 mm in area and approximately 800 mm deep from the floor of the internal gallery or tunnel through the dam. Horizontal and vertical cores were taken from the same material, of the same lift, at the same place after the blocks were removed, as shown in Figure 5.

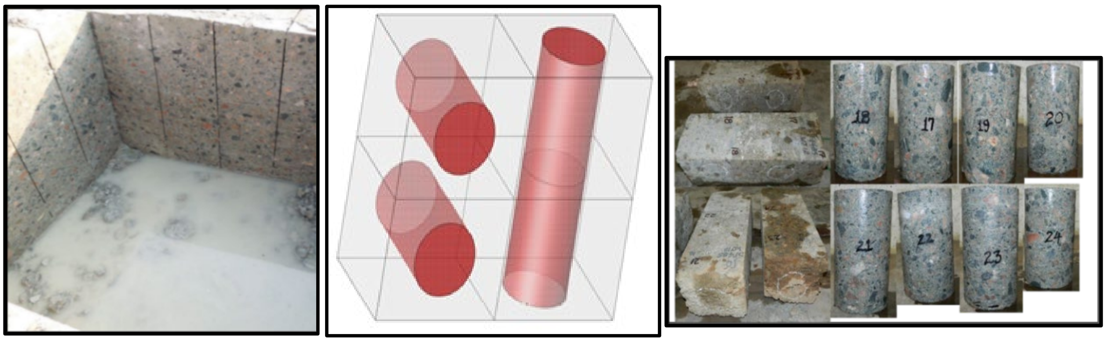


Fig. 5: Sampling of prisms and coring for Vertical vs Horizontal direct tensile strength

Each of the three main zones in the dam with cement contents of 130 to 142 kg/m^3 (A), 80 to 85 kg/m^3 (B), and 110 to 119 kg/m^3(C) were tested. RCC had much greater tensile strength and strain capacity in the horizontal direction compared to the vertical direction. This was critical to avoiding thermal cracking which applies loads horizontally and would otherwise cause serious vertical cracks through the dam. Table 2 summarizes results obtained.

Table 2. Correlation between vertical and horizontal properties for different zones (mixes) at GERD

DT cores results in MPa		Zone A			Zone C			Zone B		
DT_{VP}	Direct tensile vertical parent	1.29	1.25	Ratio V/H	1.01	0.97	Ratio V/H	0.96	0.84	Ratio V/H
DT_{VJ}	Direct tensile vertical joint	1.27		65%	0.95		52%	0.76		57%
DT_{HP}	Direct tensile horizzontal parent	1.91	1.93		1.93	1.85		1.43	1.48	
DT_{SP}	Direct tensile by splitting parent	1.96			1.83			1.5		

The overall average horizontal tensile strength was a significant 172% of the vertical tensile strength. A close examination of the concrete, including microscopy and petrography did not identify any issue such as trapped air or microscopic horizontal separations under coarse aggregate particles. The overall air voids of the RCC was on the order of 2%. The above assessment is for the RCC. A separate study was made to see if the difference in properties between Direct Tensile Vertical (DTV) cores and Direct Tensile Horizontal (DTH) cores exist also in the conventional concrete. Adjacent cores were taken in both directions from a block of the same conventional concrete made with the same aggregate (same source and crusher but different gradation), admixture, water, and cement as the RCC, Table 3.

Table 3. Comparison of horizontal and vertical properties for conventional concrete at 33-196 days, GERD.

	33 days results						196 days results					
			Modulus of Elasticty (GPa)						Modulus of Elasticity (GPa)			
Core Orientation	Compressive Strength (MPa)	Direct Tensile Strength (MPa)	25%	50%	75%	100%	Compressive Strength (MPa)	Direct Tensile Strength (MPa)	25%	50%	75%	100%
Vertical	18.1	1.13	15.2	12.8	11.2	8.2	25.3	1.86	20.1	19.9	16.2	11.3
Horizontal	\	1.19	12.2	11.4	10	6.9	\	2	18.1	16.5	14.1	12.3
Ratio DTV/DTH	\	95%	125%	112%	112%	119%	\	93%	111%	121%	115%	87%

The conventional concrete modulus of elasticity for vertical cores was consistently slightly higher than for horizontal cores (113%) while the direct tensile strength was slightly lower at an overall average of 94%. For practical purposes, unlike RCC, the vertical and horizontal properties of the conventional concrete were generally similar.

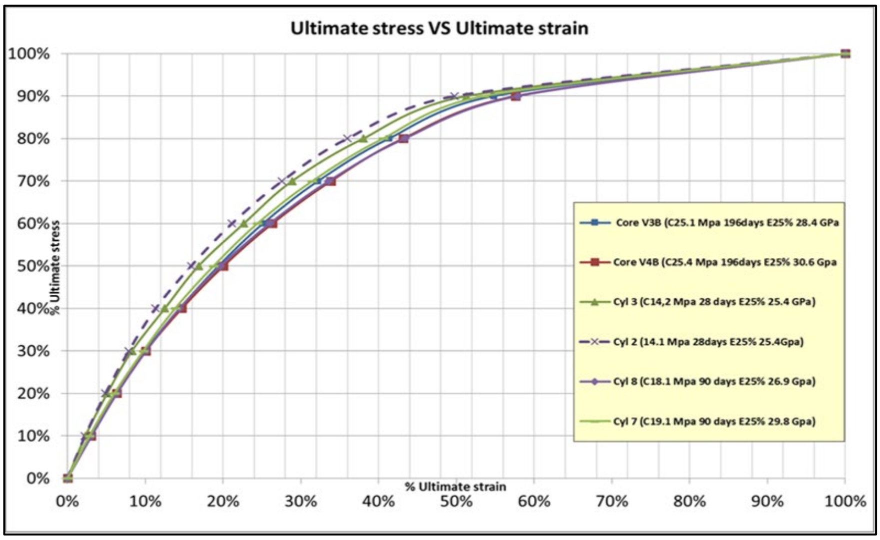
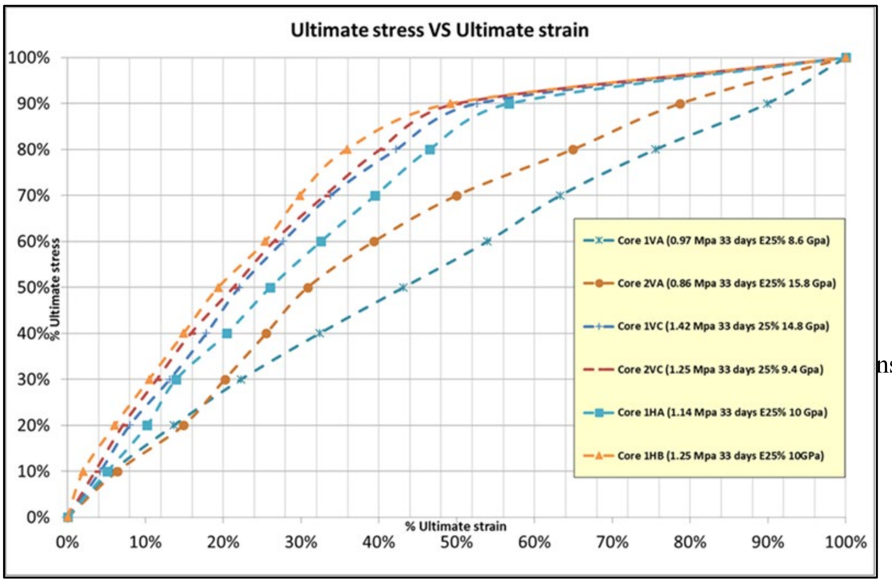


Figure 6: Non-linear stress-strain curves for conventional concrete, compression, GERD



nsions, GERD
Figure 7: Non-linear stress-strain curves for conventional concrete, tensions, GERD

The decreasing modulus with increasing level of stress for the conventional concrete is apparent in Table 3, thereby demonstrating that, like the RCC, it has a non-linear stress-strain curve. This is shown in figures 6 and 7.

4 EFFECT OF TEMPERATURE CYCLES SIMULATING REAL FIELD CONDITION

The Mapei laboratories in Italy conducted further investigations in order to check the effect of curing conditions of RCC samples on the stress-strain curve and elastic modulus both under tensile and compressive load. The scope of this new testing campaign was to simulate the weather conditions at GERD site (11°13’,0N, 35°05′,5E, Ethiopia) where the temperature difference between night and day is very high (40°C during the day to +10°C at night in some periods of the year). These weather conditions can have a strong influence on strength development and modulus of elasticity of RCC when samples from coring need to be stores out from the laboratory for many weeks. This condition happened for a huge project such as GERD because borehole campaigns of investigation can produce even more than 200 meters of cores which need many weeks to be evaluated, cut and definitely stored in special big water tanks.

In this regard, 16 samples (150mmx300mm cylinders) were made with the following mix design:

Tab.4 Mix design details

Cement type	32,5 IV/A Pozzolanic type
Cement dosage, kg/m^3	100
Dmax aggregate,mm	50
Water content, l/ m^3	93
Set retarding admixture	Mapetard Plus
Admixture dosage, kg/m^3	0,8
Water/cement ratio	0,95
Concrete density, kg/m^3	2448

After a common curing of 56 days at 20°C and 95% R.H., 8 samples were moved to the thermal room for another 14 days with a cycle of temperature between +40°C and +10°C. The duration of each cycle was 6 hours at +40°C and 6 hours at +10°C (4 cycles per day). Total number of cycles after 14 days was 56 cycles. The remaining 8 samples were kept in the normal curing room for another 14 days. After 70 days all cylinders were tested both under compression and tensile load for comparing the stress-strain curve between normal curing (20°C, 95%R.H.) and thermal cycle curing. Figures 8 and 9 show the thermal cycle room and the trend of the thermal cycles used in the lab programme.

Fig.8 Mapei laboratory: Angelantoni thermal cycle room used

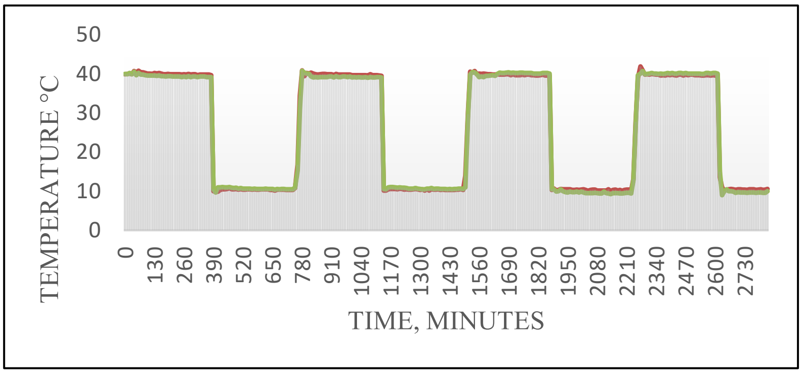


Fig.9 Thermal cycles

The results of the tests show that the effect of the cycles simulating the real weather conditions at the dam have a higher influence on the tensile elastic modulus than on other mechanical properties (see figures 10 and 11 below).

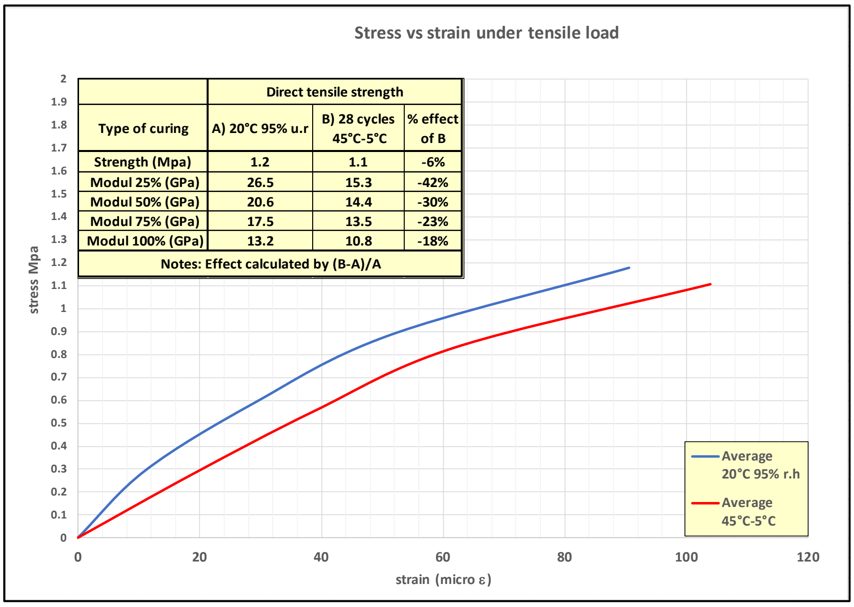


Fig.10 Direct tensile tests

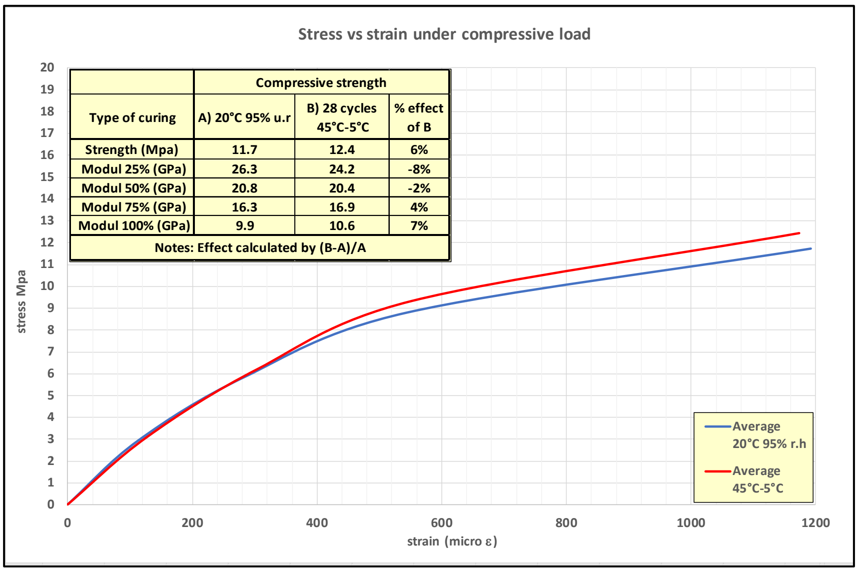


Fig.11 Compression tests

This result may be related to microcracks generating from the thermal cycle curing condition allowing a greater deformation of the samples in the lower part of the curve before final cracking. In the middle part of the curve at 50% of the maximum tensile stress the reduction of the modulus of elasticity with thermal cycle curing is 30% lower than the one gained with normal curing (20°C and 95% r.h.). The results also confirmed values of elastic modulus for tensile load lower than compressive loads after the thermal cycles.

5 LABORATORY COMPARISON MAPEI VS SALINI-IMPREGILO GERD SITE

Compressive tests are not particularly difficult whereas tensile tests with meaningful strain measurements require significant care, expertise and equipment. That was the reason why some tests were repeated again in the Mapei laboratory in Italy, where greater skills of technicians and more sophisticated equipment allowed comparison and subsequent the confirmation of the results. Both laboratories have confirmed the trend of lower values of tensile modulus in comparison with compressive modulus, but Mapei laboratory found some values greater than indicated by tests at the Gerd, as reported in Tab.1 above. The reason for this difference is not entirely clear. For sure the type of the equipment plays an important role. The jobsite lab used mechanically attached 100mm long strain gauges (LVDT) while the Mapei lab used 150mm long electric resistance strain gauges that were carefully adhered to the surface of the cores with a very thin glue line. A further point could be the rate of loading which is different for the two testing machines used at lab site and Mapei as well as the frame capacity and stiffness. Other factors to be considered are shipping conditions and the handling of the core samples. In fact, transportation took quite a long time from the job site in Ethiopia to Milan and on top of that even the long custom procedure in the two countries gave an additional issue. Under these conditions, without guaranteeing a proper continuous moist curing and temperature of the samples, there may have been some surface drying of the Mapei cores that influenced the final results. Furtherly, the number of identical samples tested at each lab was limited, whereas a proper comparison between labs requires a large number of tests of companion samples. However, it is important to say that the confirmation of the results was a fundamental step to highlight the issue of lower tensile modulus of RCC compared to the compressive one at this project. A short technical description of the testing machines used at the two different laboratories follows.

Fig. 12: Direct tensile test at Gerdp laboratory

Galdabini quasar 100,
Frame Capacity 100 kN
Load reading resolution 1/200000 f.s.
Stroke resolution 0,1 micron
Speed at maximum load 0,0005-200 mm/min
Extensimeter 100 mm base, resolution 0.6 micron

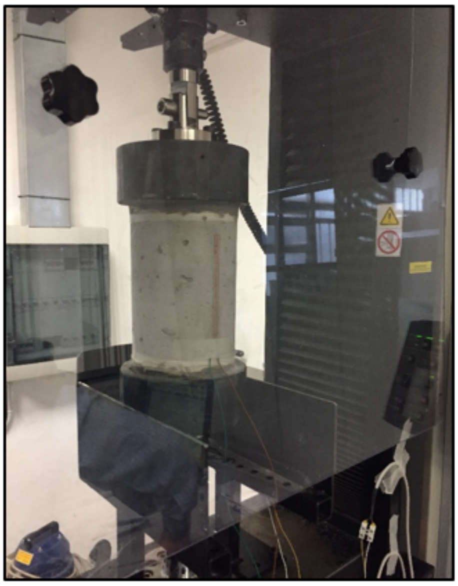


Fig. 13: Direct tensile test at Mapei laboratory

Instron 4507
Frame Capacity 200 kN
Load reading resolution 1/200000 f.s.
Stroke resolution 2% (20000x10^{-6} strain)
Speed at maximum load 0,001-500 mm/min
Strain gauges, 120 mm base, resolution 0.1%

- Especially with RCC, the modulus of elasticity can range considerably from project to project. It can be well outside the range considered normal for concrete;
- The stress-strain behavior of both RCC and conventional concrete can be very non-linear and also elastic. A single value for modulus of elasticity can result in erroneous calculated stresses in the structure that are higher than actually occur;

- During the evaluation of the results coming from the test campaign special attention should be given to the real difference of performances between the test samples and the structure. Obviously, every project can lead to different values;
- Established formulas for calculating the direct tensile strength of concrete based only on its compressive strength can be erroneous and misleading;
- Site specific testing is required in order to confidently establish the following properties of RCC and, at times, conventional concrete;
  - Stress-strain behavior and modulus of elasticity
  - Horizontal properties compared to vertical properties
  - Direct tensile strength.
- As said above, not many laboratories in the world are well equipped, trained and organized for running proper direct tensile tests on concrete. That's why designers, contractors and client consultants need a technical cooperation with reliable and very skilled laboratories for helping them to understand the real response of a dam structure under different stress and strain situations. This is important not only at the initial stage of one project but even more during the construction phase, for a continuous improvement of the structure and safety conditions.

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Schrader Ernest, is a consulting engineer specializing in both RCC and conventional concrete. He has been involved in the development of RCC since its early inception. His experience includes involvement with RCC in over 100 dams in more than 35 countries. His work has been as a principle designer, Engineering consultant, construction manager, or advisor for owner, designer or contractor. Dr Schrader has authored over 100 papers concerning design and construction aspects of concrete including RCC.

Mastrofini Paolo, Construction Material Specialist in Salini-Impregilo, graduated in Geological Sciences at university of Rome. He has acquired 25 years of experience in material testing for concrete, RCC, bituminous mixture, rock and others various material and instrumentations for monitoring, in numerous projects in the world. In the GERD Project, he coordinates laboratory and site investigations including the evaluation of test results.

Saccone Roberto, Master Degree Civil Engineer, graduated at the State University of Rome in 1982. He started working with UNICEM Group, Italian cement producer, as specialist for concrete applications and new product development. He has more than 30 years of experience in concrete technology and admixtures; he also worked in many projects including Gibe 3 in Ethiopia. From 2008 he's working in Mapei as Senior Project Manager, responsible for new projects focusing particularly on the hydropower market, supporting the Mapei subsidiaries and countries all over the world.

Surico Francesco graduated in industrial organic chemistry at the State University of Milan. He started his professional career at Mapei's central Research Laboratory in Milan, Italy in 1997 as a synthesis specialist for new concrete admixtures. Now he is leading Mapei's development of new concrete admixtures globally, in cooperation with the group's technological laboratories in Europe, America and Asia. He has authored many papers on concrete technology and admixtures for concrete presented at the most prestigious international conferences for concrete and admixtures technologies. He also holds three international patents in the field of concrete admixtures.

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