FIBER-REINFORCED ROLLER-COMPACTED CONCRETE – APPLICATIONS TO PAVEMENT WORKS FOR HEAVY DUTY PORTS

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ABSTRACT

Roller-Compacted Concrete (RCC) technology has been used successfully for more than 25 years in port pavement structures, notably in container terminals and intermodal areas. RCC is a "dry" zero-slump concrete usually placed with an asphalt paver and densified by compacting with a heavy vibrating roller. Since cracks develop in RCC concrete pavements as a natural result of the shrinkage process, joints are generally sawn every 8-. Nevertheless, random shrinkage cracking and joint spalling remain significant drawbacks in RCC pavement structures for ports. This is why RCC pavements are often covered with concrete blocks which provide a better level of service.

Steel fibers are currently used in conventional vibrated concretes for industrial floors and container terminals in ports. However, the mix design for such concrete is based on relatively high cement and water contents that require saw cut joints, generally spaced at around 7.5 to 8 m.

Where behavior under cracking mechanism is concerned, RCC is more worthwhile than vibrated concrete because it contains less cement and less water for equal strength. Conditions are therefore more favorable for fiber efficiency.

The purpose of this communication is:

1. To present an overview of the integration of high performance steel fibers in RCC mixes to improve the RCC's mechanical characteristics. This process is used to obtain joint-free pavement structures, concrete reinforcement and cracking control by steel fibers to reduce RCC thickness, particularly for port terminals.

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2. To introduce an analytical pavement design method based on rational-mechanical multi-layer models that aims at widening and improving the design capabilities of alternative pavement structures when compared to the semi-empirical methods including particularly Interpave / British Ports Association.

3. To describe the main results of the French Recyroute research program on fiber-reinforced RCC structures submitted to accelerated pavement testing.

BACKGROUND

Roller-Compacted Concrete for ports pavement structures

According to David R. Luhr's contribution for the Portland Cement Association, entitled *Design and Construction of Roller-Compacted Concrete Pavements for Container Terminals* (2004) [1], Roller-Compacted Concrete (RCC) for pavements (see fig. 1) can be described as a zero-slump concrete consisting of dense-graded crushed aggregate, sand, cement and water. Because it contains a relatively small amount of water, it cannot be placed by the same methods used for conventional (slump) pervibrated concrete. For pavement applications, RCC concrete is usually laid with an asphalt paver and densified by compacting with a vibratory roller.

The low water-cement ratio (usually ranging from 0.30 to 0.40) provides for high strengths with design compressive resistance commonly in the range of 35–55 MPa in 28 days.

The principal advantages of RCC result from the construction process. When compared to conventional concretes, construction costs are lower because there is less labor involved in placing the concrete (no formwork or finishing is required) and no reinforcing steel wire mesh or dowels are used. The frost durability of RCC material was confirmed by the study by the Portland Cement Association and the Quebec Service d'Expertise en Matériaux Inc. *Frost Durability of Roller-Compacted Concrete Pavements* (2004) [2]. RCC main properties can be extended to fiber-reinforced RCC material described below.

In RCC mix design, common values of cement content range from 10% to 16%, depending on the minimum dosage that will satisfy the required design flexural strength. The common method of proportioning aggregate, water and cement in RCC mix is based on evaluation of compacted laboratory specimens. The design optimum water content refers to the Modified Proctor procedure (ASTM D1557).

RCC is transported in dump trucks (not in truck mixers) covered by a tarpaulin to reduce moisture loss during haul from mixing plant to site. The material is usually placed with an asphalt-type paver. After paving, compaction by smooth-wheel vibrating rollers is necessary to meet density requirements, sometimes followed by pneumatic-tire rollers for finish rolling. More information about RCC can be found in the report *Roller-Compacted Pavements*, by ACI Committee 325 – 1995 reapproved 2001 [3].

With the low water-cement ratio in RCC, there is less paste in the concrete matrix and no bleed water. Therefore less shrinkage cracking occurs when compared to conven-

Figure 1. RCC in a container terminal - Source D. Luhr for PCA

Figure 2. Typical condition of RCC surface - Source R. Piggot for PCA.

tional concrete. Cracks will develop in RCC pavement slabs as a natural result of the shrinkage process. These cracks will normally occur on a random basis of every 9 to 20 meters. D. Luhr concludes that usual crack width generally remains less than 3 mm under USA and Canada climates. R. W. Piggott's contribution to the Portland Cement Association, entitled *Roller-Compacted Concrete Pavements - A Study of Long Term Performance* (1999) [4], mentions crack widths varying from "hair line" to 6 mm. To improve the appearance of the RCC final product, joints can be sawn every 8 to 12 meters to eliminate most of the random shrinkage cracking (see fig. 2).

In conclusion, the main drawback of RCC technology lies in the fact that crack width is frequently higher than the maximum limit of 2.5 mm required for obtaining a minimum acceptable load transfer between the crack edges - see the report F. Marleau for Canadian Cement Association : *Rapport de l'étude des caractéristiques du béton compacté au rouleau routier* (2003) [5]. It should be noticed that the 100% load transfer level refers to crack width that remains less than 0.5 mm in either continuous reinforced concrete (reinforced by longitudinal steel bars) or FRCC® (reinforced by steel fibers - see chapter 2 here under).

The result of insufficient load transfer is slab faulting at crack edges and joint spalling. This is why RCC pavements are often covered with concrete blocks which provide a better level of service. An alternative is to use optimized steel fibers in RCC mix to improve the material's cracking performance, as illustrated by experience from port terminals where such fibers have been used in conventional (slump) concretes, described below.

Steel fibers used in conventional (slump) pervibrated concretes for ports terminals

Steel fiber reinforced concrete was first used for pavements in 1971, in the USA. Since the 1970's a considerable amount of research has been carried out on the material properties and structural behavior of steel fiber reinforced cement composites.

For utilization in ports terminals, M. Meletiou and J. Knapton in UNCTAD Supplement to Monograph N° 5 *Container terminal pavement management* (1990) [6] consider that the most efficient type of steel fibers employed in concrete reinforcement are those produced from drawn steel wire with hooked ends, available under the brand name Dramix® (manufactured by Bekaert company - see website in reference [9]). These fibers offer strong mechanical anchorage in the concrete, originally with a diameter of 0.60 mm, length 80 mm and tensile strength 1,200 N/mm², now replaced by diameter 0.75 mm, same length 80 mm and tensile strength of 1,050 N/mm². These hooked and glued fibers are added, as an extra aggregate, in bundles of approximately 40 fibers, thereby avoiding the "balling effect" and causing no serious difficulty in mixing, as can occur with separate/individual fibers. Gluing the loose steel fibers together creates a compact bundle making it possible to mix steel fibers of greater length and consequently greater reinforcing capacity. During the mixing process, the bundles spread throughout the entire mass and, since the glue is water soluble, separate again into individual fibers giving a homogeneous mixture (see fig. 3).

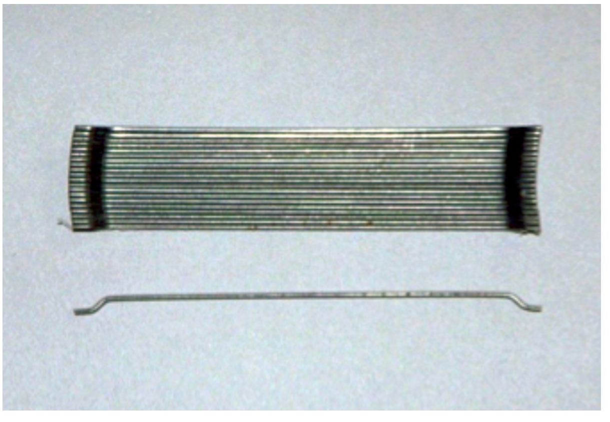


Figure 3. Dramix® 80/60 steel fiber - Bundle and individual fiber

Fiber dosage is generally in the range of 30-35 kg per cubic meter of concrete. The inclusion of steel fibers in the concrete matrix alters the properties of the resulting concrete material. The ductile, high tensile strength fibers compensate for the low tensile strength and ductility of the concrete, and enhance the mechanical and physical properties of the composite. Properties such as fatigue endurance, impact resistance and toughness are significantly improved. Another property of steel fiber reinforced concrete is the resistance to spalling and punch-out effects under shocks or at proximity to the joints. As the fibers absorb and distribute the shrinkage stresses, it is possible to increase the joint spacing to 7.5 to 8 meters, compared to the usual 5 meters in conventional (slump) non-reinforced concrete.

The feed-back from ports terminals that use this kind of steel fiber reinforced concrete underlines satisfactory mechanical performances of the corresponding pavement structures, as evidenced, notably, by the Algesiras terminal (Spain), over a an area of 350,000 m² (see M. Meletiou's contribution in reference [7]). However, the cost of fibers and saw-cut joints penalizes the cost-effectiveness of this technology when compared to conventional concrete paving blocks.

This is why further intensive research was carried out to associate "dry" low shrinkage RCC concrete with steel fiber reinforcement, with the aim of compensating for RCC excessive crack width and also of allowing construction of joint-free pavements. The result of this research program is an innovative technology introduced below.

ROLLER-COMPACTED CONCRETE (RCC) REINFORCED BY STEEL FIBERS

Overview of fiber-reinforced RCC technology

In all types of cement concrete, the effect of hydraulic shrinkage combined with thermal gradients creates high tensile stresses, which in turn causes cracking. The advantage of sawing into the slab and creating joints is to get rid of spontaneous random cracking by making weak points at which cracking will occur naturally. But joints are potential water inlets and run the risk of eventual degradation. They therefore require the use of thick concrete layers over a non-erodable foundation, and possibly dowelling.

Considering behavior under shrinkage and cracking, "dry" RCC concrete is more worthwhile than conventional (slump) concrete because RCC contains less cement and less water for equal strength. Conditions are therefore more favorable for fiber efficiency. This is precisely the basis of the fiber reinforced concrete RCC concept known under the brand name FRCC® (Fiber-reinforced Roller-Compacted Concrete - see reference [10])

For fiber-reinforced RCC composition, the grading curve of crushed aggregates is generally 0 to 14 or 20 mm so as to limit the effect of segregation. The proportion of cement is about 280 kg per m³ of concrete, with a water content of 4 to 5% which gives a moisture density of around 2,400 kg/m³ when measured by Proctor Test. A plasticizing retarding admixture is added at the manufacturing stage. With this composition, RCC or FRCC® compressive strength is in the range of 35-40 MPa after 28 days at a cement dosage of only 280 kg per cubic meter. To obtain the same resistance, con-

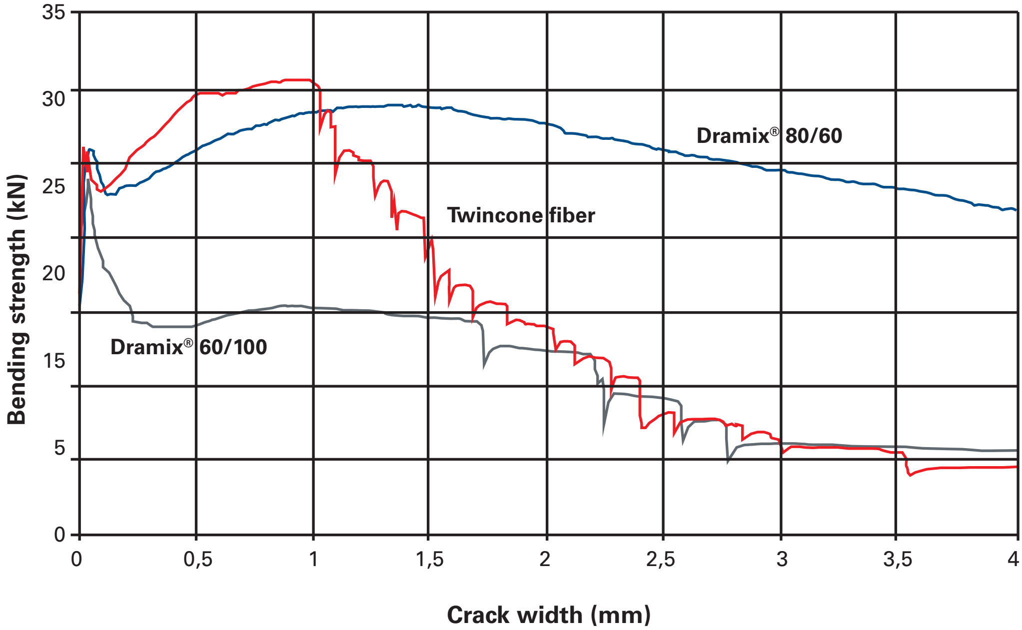


Figure 4. Comparison between different types of fibers in concrete bending tests.

ventional pervibrated (slump) concrete would request a cement dosage of at least 350 kg (or additives like silica fume) because of their higher water content and lower density, compared to RCC or FRCC®.

The steel fibers used for FRCC® mixes are the same Dramix® as the ones selected for Algeciras port terminal, and described in the here above Meletiou and Knapton contribution. The number of fibers per unit of fiber weight, for equal fiber length, is proportional to the square of the wire diameter. Thus, for the same weight of fiber, a wire with a diameter of 0.75 mm with Dramix® 80/60 can double the number of fibers compared to a 1 mm diameter wire with Dramix® 60/100. Therefore 30 kg of Dramix® 80/60 fiber with a diameter of 0.75 mm in 1m^3 of concrete represent a network of more than 8,000 linear meters of fibers.

This explains the results shown in Figure 4, highlighting the ductility level obtained with 80/60 fiber compared to 60/100. For crack openings up to 3 mm, the resistance to bending of the concrete + fiber composite remains equivalent to that before cracking.

Steel fibers are fed into continuous mixing plants with a new type of weighing-dosing machine accurate to ±5% and with a production capacity of 150 to 500 tons of concrete per hour (see figures 5 and 6).

Figure 5. FRCC® production in mixing plant.

Figure 6. Continous fiber dosing system.

So FRCC® fiber-reinforced RCC technology uses specific hook-ended fibers selected for their high ductility. When compared to RCC pavements with an average crack width of 3 mm, cracking control by steel fibers results in natural crack spacing of about 20 to 25 m, and a crack opening that remains less than 0.5 mm. This means cracking in FRCC® is quite invisible, load transfer between crack edges is excellent and there is no need for joint or crack maintenance.

FRCC® allows the construction of continuous joint free pavements, also possible in the case of ports terminals as the addition of a specific plasticizing retarding admixture provides a retarding effect of more than 80 hours in cement setting, which conducts to a “fresh” bonding when restarting the site work after night breaks or weekends.

For port terminals, the material surface texture is hardened by mechanical placing of a thin layer of cement mortar. Such surface treatment also provides a high level of service in terms of durability and adequate grip (for safety issues) for reach stacker traffic and container stacking. For truck traffic, FRCC® can be covered with a thin asphalt layer, generally 0 to 50 mm thick.

Mix design of FRCC® fiber-reinforced RCC includes the possibility of either using virgin aggregates or recycling a high rate (up to 80%) of Reclaimed Asphalt Pavements (RAP) from bituminous materials that may be available on construction or rehabilitation sites for port terminals. RAP is used in foundation layers under FRCC® surface layers mixed with virgin aggregates. In other cases, the foundation layer for FRCC® in ports pavement structures can be either cement-treated materials (RCC, lean concrete) or bituminous materials.

PAVEMENT DESIGN ISSUES

Introduction of mechanistic analytical design methods for ports pavement structures

The international reference design method for ports pavement structures is: J. Knapton for Interpave entitled *The Structural Design of Heavy Duty Pavements for Ports and Other Industries* Edition 4 (December 2008) [7], that updates the previous edition 1996 by J. Knapton and M. Meletiou for British Ports Association. This is a semi-empirical method calibrated for C8/10 lean concrete covered with concrete paving blocks. If using alternative materials, then material equivalence factors are introduced to alter the design thickness of the resulting C8/10 base layer.

For road pavements, an overview of the international mechanistic methods that are considered as references for pavement design shows that multilayer models are already in use in many Countries as Australia, South Africa and France, all Countries who developed their own models as an alternative to the mechanistic Shell one. There is also an evidence for a general trend that aims at replacing the previous empirical or semi-empirical methods for pavement design by a rational mechanistic approach based on elastic-multilayer models and mechanical performance description of the material used.

In the roads sector, the American AASHTO semi-empirical method 1993 is based on the Structural Number which is equivalent to the Material Equivalent Factor in the Interpave / British Ports Association method. The AASHTO mechanical-empirical method launched in 2004 is now progressively replacing AASHTO semi-empirical 1993 as a reference international method.

In the domain of pavements for very heavy loadings, the same evolution can be observed in the airport sector with American (FAA Federal Aviation Administration) and French STAC (Technical Civil Aviation Service). Both FAA and STAC are implementing rational mechanical methods in the purpose of replacing the previous semi-empirical methods based on material equivalence factors.

The Australian, South African and French (see reference [11]) mechanistic analytical pavement design methods can be characterized by 3 steps:

1. **Based on the mechanical performances of pavement materials**: Utilization of fatigue laws for both cemented and bituminous materials in the purpose of calculating the allowable values of stress or strain under repeated loadings, depending on the cumulated traffic during the design life span of the pavement;

2. **Mechanistic**: calculation of stress and deformation in each pavement layer with the help of a multilayer software based on Burmister model (Circly in Australia, Rubicon in South Africa, Bisar for Shell, Alize-LCPC in France);

3. **Probality based**: taking into account a reliability factor which varies depending on both requested service level and also heavy traffic volume borne by the pavement. The reliability factor is directly linked to the acceptable risk level that corresponds to the proportion of deteriorated pavement surface that the port operator will accept from construction date to the end of the design life span.

Figures 7 and 8 here under respectively show:

- A laboratory fatigue test performed by IFSTTAR on a trapezoidal cement concrete sample that measures the fatigue resistance of the material under repeated loadings;

- and the French IFSTTAR pavement testing facility that permits accelerated heavy loadings on different pavements structures as in-site fatigue tests. This device will be described with further details in the next chapter here under.

In conclusion for conventional cement-treated materials and cement concrete, the use of mechanistic analytical design methods for ports pavement structures leads to consistent calculation results when compared to the structures designed by the semi-empirical Interpave / British Ports Association method. Furthermore the analytical mechanical methods provide the possibility of rational comparisons of alternative pavement structures using different kinds of materials. The next chapter here under will describe the Recyroute research program.

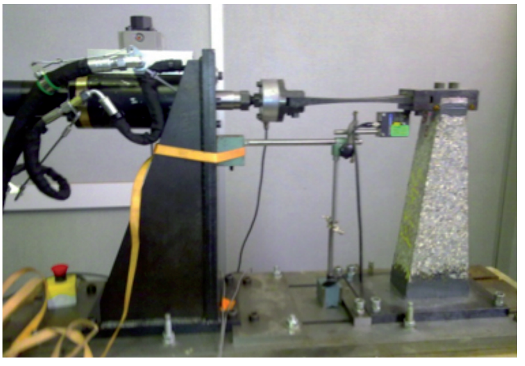


Figure 7. Laboratory fatigue test on a trapezoidal cement concrete sample.

Figure 8. IFSTTAR accelerated pavement testing facility.

Results of the Recyroute research program for FRCC® material

Within the framework of the French National Research Agency (ANR) project named "Recyroute", an accelerated pavement testing (APT) was conducted by mean of the Accelerated Load Testing (ALT) facility of the IFSTTAR (see reference [12]) in the purpose of evaluating the in-site performances of fiber-reinforced RCC material (FRCC®). This experiment which took place from 2008 to 2010 is presented in details in the paper for the next 2012 APT International conference (see reference [14]).

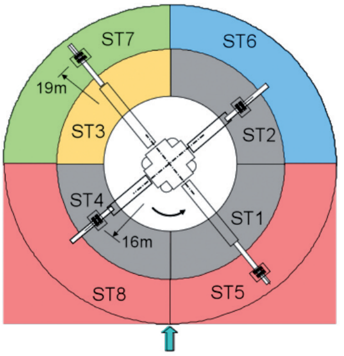
Influence of different design parameters (type of aggregate, variation of base layer thickness) has been is studied. These combinations leaded to test, in total, 8 different pavement structures shown in Figure 9. The tested structures include:

- A reference structure of standard bituminous material,
- one structure using Reclaimed Asphalt Pavement (RAP) aggregates treated with 5% hydraulic binder,
- and six other structures made of FRCC® materials treated with 12% cement: RAP (3 structures) and virgin aggregates (3 structures).

An extensive laboratory tests program including complex modulus tests and fatigue tests was also carried out to determine mechanical properties of FRCC® materials with respect to pavement design applications.

More than 2 million of 65 kN French standard dual-wheel loads were applied on the 8 tested structures within 9 months.

This experiment showed an encouraging behavior of the tested structures, despite thin thicknesses of materials used in base and surface layers and very severe loading conditions. No significant structural damage has been observed, except due to local defects in layer thickness (in a few places less than 3 or 4 cm than specified). However,



Structure	Base layer	Thickness
ST1	FRCC with RAP	13 cm
ST2	FRCC with RAP	12 cm
ST3	EME2 (**reference**)	12 cm
ST4	FRCC with RAP	15 cm
ST5	FRCC Crain on cracked pavement	13 cm
ST6	FRCC Haut-Lieu	12 cm
ST7	ERTALH	20 cm
ST8	FRCC Crain	15 cm

Figure 9. The 8 tested structures test by mean of the IFSTTAR's ALT facility.

as well known for structures made of cement treated materials, the optimum compaction of the hydraulic concrete layer, the tack coat implementation as well as the placing of the asphalt surface layer remain critical points and must be subject of special attention.

CONCLUSIONS

Roller-Compacted Concrete (RCC) technology is a "dry" zero-slump concrete that has been used successfully for more than 25 years in port pavement structures, more particularly in container terminals and intermodal areas.

With the low water-cement ratio in RCC, there is less paste in the concrete matrix and no bleed water. Therefore less shrinkage cracking occurs when compared to conventional (slump) concrete. RCC cracks will normally occur on a random basis of every 9 to 20 meters and crack width varies from "hair line" to 6 mm, so joints can be sawn every 8–12 meters to eliminate most of the random shrinkage cracking. However the main drawback of RCC technology is cracking and possible insufficient load transfer between crack edges.

In parallel, the properties of conventional (slump) concretes such as fatigue endurance, impact resistance and toughness are significantly improved by the addition of optimized hooked-ended steel fibers. The feed-back from ports terminals using this kind of steel fiber reinforced concrete underlines satisfactory mechanical performances of the corresponding pavement structures, as illustrated in Algeciras (Spain) terminal on a surface of 350,000 m^2. Nevertheless the cost of fibers and saw-cut joints penalizes the cost-effectiveness of this technology when compared to conventional concrete paving blocks.

The addition of steel fibers comes in more favorable conditions for fiber action in RCC concrete, when compared to conventional (slump) concrete. This is precisely the innovative concept of the fiber-reinforced RCC technology under the brand name FRCC®.

Reduction of crack width from about 3 mm in RCC to less than 0.5 mm in FRCC® mixes prevents the pavement structures from water ingress across the cracks and guarantees full load transfer between the cracks edges. This is why FRCC® material offers continuous joint-free pavements structures.

Compared to conventional RCC pavements, FRCC® structures are about 30% thinner when considering the same loading parameters. Costs comparisons with conventional pavement structures for ports (concrete blocks, traditional concrete slabs with or without fibers, bituminous materials) conclude to cost-efficiency of the FRCC® structures. The high production capacity of continuous mixing plants and reduced pavement thickness of RCC or FRCC® layers compared to conventional structures also allow significantly shorter duration for construction or rehabilitation of heavy duty pavements in port terminals.

The pavement design procedures for FRCC® fiber-reinforced RCC structures adhere very closely to the procedures for design of conventional concrete and RCC pavements. Both the British Ports / Interpave semi-empirical method (J. Knapton) and multilayer models can be used.

The relevance of mechanistic analytical design methods for ports pavement structures, as an alternative of the semi-empirical British Ports Association, is the possibility of rational comparisons of alternative pavement structures using different kinds of materials.

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