FOR ECONOMICAL ROADWAYS OF CONTINUOUS CEMENT-CONCRETE REINFORCED WITH STEEL FIBER

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ABSTRACT

FRCC™ (Fiber reinforced Roller Compacted Concrete) is an innovated roller-compacted concrete process in which high performance steel fiber is added to control the cracking of the concrete and establish bending reinforcement. This process is a manner of obtaining joint-free continuous concrete roadways. The investigations into roadways in service demonstrate that the FRCC™ crack opening is less than 1 mm and that the load transfer is 100% between crack edges.

To achieve this result, the contribution of steel fibers is optimized by the use of concrete manufactured with low water content (according to Proctor testing) and a cement dosage of generally 12% or 280 kg per m^3. This concrete has high density related to high compacting energy: strength is comparable to pre-vibrated traditional concretes mixed at a rate of 350 kg cement per m^3.

A principle of functional separation is applied between the various courses of the roadway:

- an FRCC™ concrete base course, controlling the cracking, anti-rutting with high mechanical strength, guaranteeing the long life of the pavement under heavy traffic and avoiding deformations;
- a surface course of asphalt mix, designed to make the most of the quality of this material in terms of evenness, texture, running noise reduction.

The FRCC™ process applies to the construction or strengthening of roadways; it makes for significant gains in roadway thickness and therefore saves on aggregates.

An economic investigation in Europe and China shows that the FRCC™ process is more than competitive for traffic exceeding 500 heavy goods vehicles per day and per direction,

compared to traditional rigid, semi-rigid and flexible techniques (including high modulus asphalt).

The innovation process put underway with the FRCC™ technology in China can be applied to other emerging countries which, like China:

- have a high demand for new roadways for heavy goods vehicles,
- are short of aggregates in some regions,
- have to import bitumen to carry through their motorway program,
- but in parallel, have good quality cement available.

KEY WORDS

ROADWAY / CONCRETE / CEMENT / COMPACTED / FIBER / STEEL

1. DESCRIPTION OF THE FRCC™ PROCESS

The FRCC™ (Fiber reinforced Roller Compacted Concrete) process is a way of using high strength compacted concrete to which steel fibers with particularly high performance anchorage are added, producing operation of the reinforced concrete type. The result is:

- the construction of a continuous roadway without any joints,
- a crack opening comparable to that of continuous reinforced concrete (CRC), i.e. less than 1 mm,
- a 100% load transfer between crack edges, with total absence of slab movement,
- the possibility of reducing the thickness of the roadway structures with respect to a non-reinforced solution.

Depending on the forecasted use and the type of constraints encountered, the FRCC™ can be covered with either one of the following surface coats:

- for roadways: an asphalt running course consisting of a thin, very thin or porous asphalt;
- for industrial areas exposed to shear failure, or aircraft or truck parking areas: surface treatment by a cement micro-concrete forming a wearing course that is insensitive to hydrocarbons.

The FRCC™ concept at sites are more particularly monitored by the Laboratoire Régional de l’Ouest Parisien (LROP) team which has issued opinions concerning designs and investigations into the use of the process, as from the very first experiments in the urban environment and in the open country.

1.1. Characteristics of the compacted concrete used for the FRCC™ process

The composition of the compacted concrete is defined with reference to French standard NF P 98-128. The mechanical strengths obtained allow this material to be classified in the highest specifications of class G 5 of the standard. The crushed aggregates used have a 0/10 mm particle size to limit segregation. The cement dosage is generally 280 kg per m^3 of concrete. A retarding plasticizer is added to the manufacturing of the concrete. The water content is determined according to the results of the Modified Proctor test.

With a composition like this, at 280 kg for cement, the FRCC™ concrete offers strength at 28 days exceeding 35 MPa for compression and 3.8 MPa for traction by splitting, i.e.

performance at least equivalent to that of the basic pre-vibrated concretes proportioned at 330 kg or even 350 kg of cement per m^3.

With respect to sensitivity to cracking, roller-compacted concrete offers limited hydraulic shrinkage because it contains less water and less cement. The fiber therefore works under favorable conditions and allows controlled cracking in a well-formulated compacted concrete.

1.2. Steel fibers used for application of the FRCC™ process

The steel fibers selected for the FRCC™ process derive from developments on large-scale industrial slabs without joints or with minimized joints: these are Bekaert Dramix 80/60 type hook-ended and bundled fibers of drawn steel with high slenderness ratio, making the concrete particularly ductile. Bonding with a water soluble glue prevents the forming of fiber balls and releases the fibers at the desired time, i.e. during plant mixing.

The fiber dosage is more often 30 kg/m^3 of concrete; the dosage can increase to 40 kg when there are specific needs, for instance on roundabouts and junctions between rings and branches of roundabouts which, like basic roadway sections, are also constructed without joints.

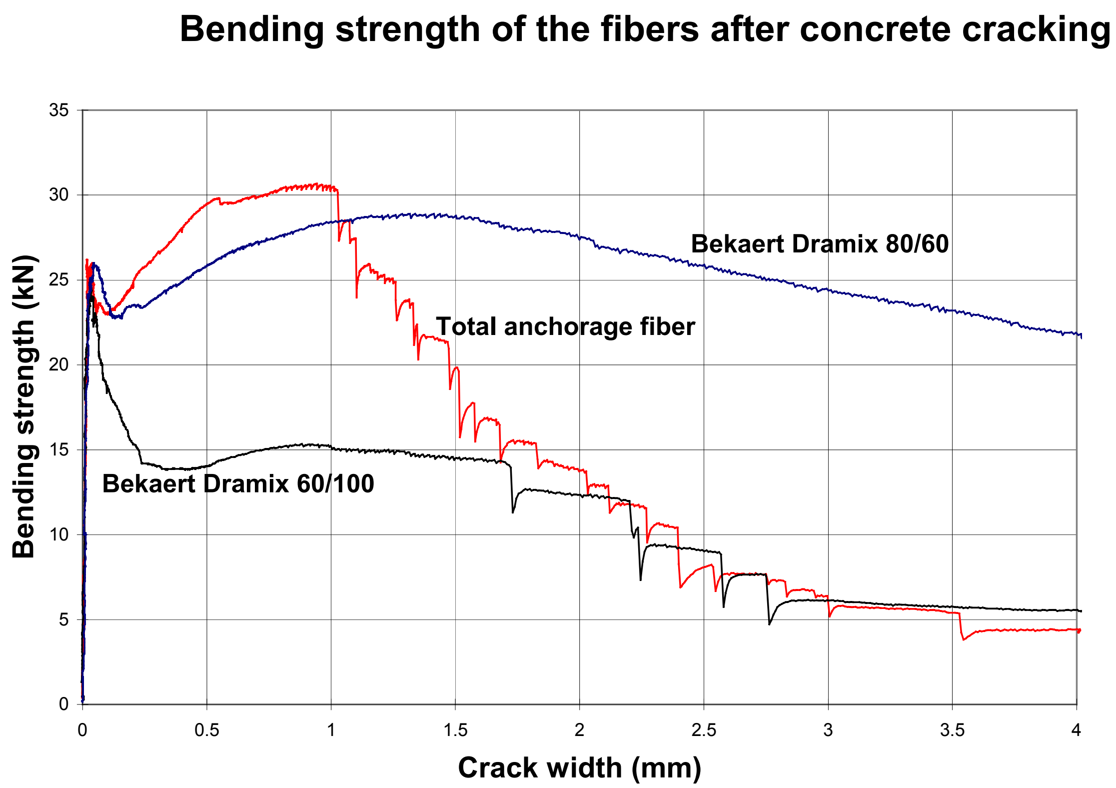

Figure 1 - Comparison between different types of fibers in concrete bending tests

The 80/60 fiber consists of a 0.75 mm diameter wire, 60 mm long (80 represents the length/diameter ratio). Note that the number of fibers per unit of fiber weight, for equal fiber length, is in proportion to the square of the wire diameter. For the same weight of fiber, a wire having diameter 0.75 mm can therefore double the number of fibers compared to a 1 mm diameter wire. Therefore, 30 kg of 80/60 in 1m^3 of concrete represent a network of more than 8,000 linear meters of fibers. The wire has an elasticity limit of 1.050 N/mm^2, compared to the customary value of 900 N/mm^2 for a 1 mm diameter wire. These two factors explain the performance increase permitted by the 80/60 fiber compared to 60/100.

At an equal dosage for the various investigated fibers, the graph of Figure 1 highlights the very high ductility level obtained with 80/60. Up to a crack opening of 3 mm, the resistance to bending of the concrete + fiber composite is equivalent to that of concrete before cracking: this behavior of the composite is outstanding, representing a safety backup for a roadway in service where cracking can be controlled with crack openings of less than 1 mm.

1.3. Manufacturing and implementation of FRCC™

The manufacturing mode of the FRCC™ depends on the available equipment. In China, new cement concrete roadway sites on the national roads and motorways are generally large, lasting several months, justifying the transfer of high capacity discontinuous plants. The quantity of fibers added therefore corresponds to the capacity of the mixer (e.g. 2.5 m^3) by successive mixes. The integration of fibers for FRCC™ is then either manual using 20 kg bags or by an automatic dosing unit supplying the desired quantity of fibers (i.e. 75 kg in the previous example) on the aggregate supply belt, or directly to the mixer.

In Europe and more particularly in France, the road construction companies have continuous plants having a capacity sometimes exceeding 300 m^3/hour for the more powerful among them. Compared to discontinuous plant units, continuous plants offer the advantage of a larger production capacity (for equal size) and better mobility. This means that the mixer is supplied continuously and not in batches by mixes, using a precise system of dosing by weight of the aggregates and the cement. FRCC™ manufacturing is therefore also possible in the “hypermobile” plants having a capacity of 100 m^3/hour that can be moved very easily from one site to another by means of two tractor trucks only. For continuous operation, fiber integration is by means of a new type of weight dosing system. This machine guarantees fiber dosing accuracy of + or – 5% for the production duration.

The FRCC™ is transported in conventional dump trucks rather than in truck mixers.

The production of an FRCC™ structure is carried out as per the French standard NF P 98-115. The material is implemented with a heavy screed finisher, preferably a HPC high compacting capacity screed, making it easier to obtain high quality evenness. The compacting workshop includes a vibrating roller and a rubber tire compactor weighted at 3 or 5 tons per wheel. Generally, the thickness varies between 8 and 20 cm, allowing correct densification at the bottom of the compacting layer. The FRCC™ concrete is cured by a bituminous emulsion (unless a concrete surface is required in which case a conventional curing product is used).

1.4. Asphalt wearing course on FRCC™

The surface course used over FRCC™ generally consists of:

- either a 4 cm thick asphalt layer using 35/50 bitumen, more particularly for shearing mechanical solicitations related to use in roundabouts or areas near traffic lights,
- or a 2.5 cm thick asphalt layer.

Investigations on the site and laboratory tests by LROP indicate that bonding between the asphalt wearing course and the FRCC™ is of the same level of strength as a well-formed bond between two asphalt layers.

Figure 2 – Fiber dosing system using Bekaert Dramix 80/60 in continuous plant

2. FRCC™ PROCESS: A COST REDUCTION INNOVATION

2.1. Dimensioning of FRCC™ roadway structures

For a period of more than 10 years, the application of fiber concrete to large-size joint-free industrial slabs has resulted in many designing studies and experiments to evaluate the contribution of fibers to concrete bending. The method used is based on the energy dissipated by the fibers in the concrete + fiber composition after the bending breakage of the concrete matrix. According to the energy method, and compared to a non-reinforced concrete, the Dramix 80/60 fiber at a rate of 30 kg per m^3 of concrete is a class 4 fiber which should allow the increase of the allowable bending stress by a coefficient of 1.40. Again, to preserve a sufficient safety margin for the dimensioning of FRCC™, we have opted for a 1.26 increase factor, corresponding to a class 3 fiber.

The FRCC™ fibers comprise both a bending reinforcement and a means of controlling cracking. On this point, for information, and although the calculation is only an equivalence, based on the respective elastic limits of the steels is approximate, the steel ratio for FRCC™ is 30 kg of fibers / m^3 for a steel elasticity limit of 1050 N/mm^2: this ratio can be compared to 0.67% of steels in CRC corresponding to 52 kg / m^3 for a steel elasticity limit of 500 N/mm^2 .

In the same way as all innovative techniques, the FRCC™ designing parameters are first defined on the basis of the laboratory test results and investigations of methods used on site. Subsequent "alignment" can be used, if needed, in the course of time to adjust the initial values. To date, after more than 6 years of operation under intense and heavy traffic, the satisfactory evaluations of the FRCC™ sites in service are leading us toward confirmation of the pertinence of the initial retained dimensioning parameters.

2.2. Economic evaluation of the FRCC™ technique in Europe

Figure 3 is an extrapolation of the French new roadway dimensioning catalogue of 1998 to which FRCC™ structures have been added.

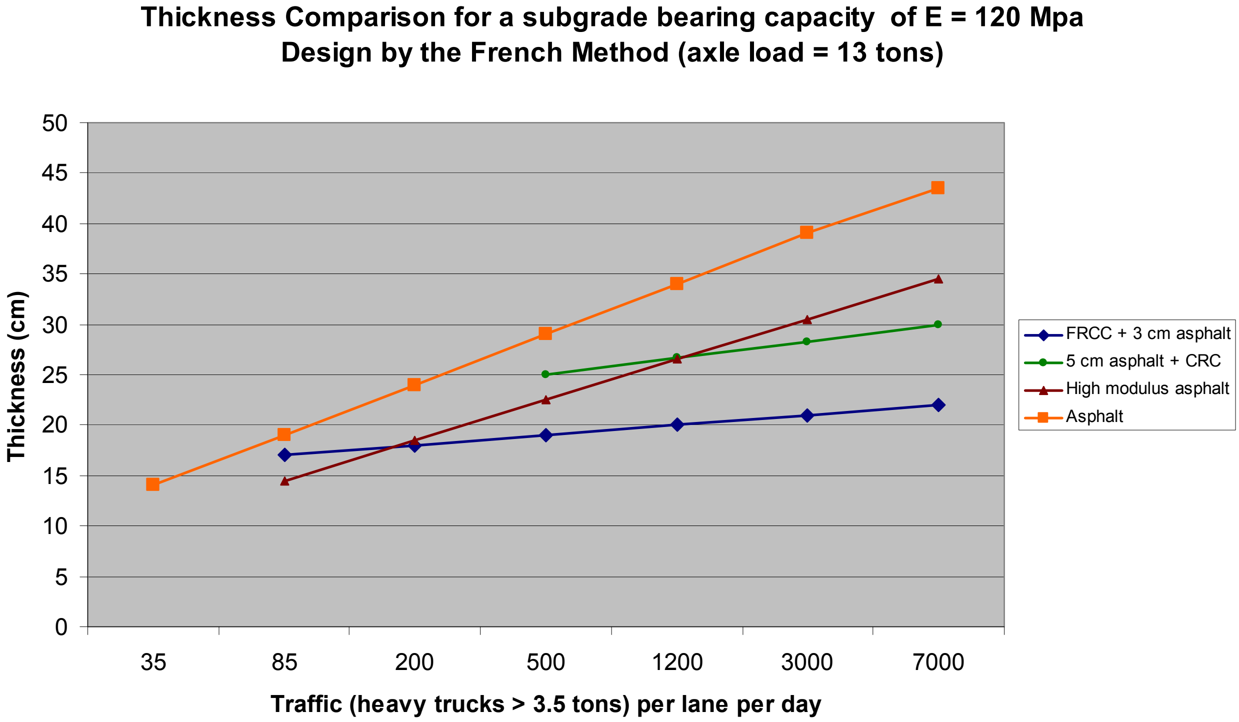

Figure 3 – Thicknesses of roadway structures on road platform at 120 MPa bearing capacity (according to French Catalogue of 1998 extrapolated by addition of FRCC^{TM})

The graph of figure 3 indicates the slopes of the respective material fatigue lines i.e. 1/5 for asphalt and 1/16 for cement-concrete. It shows that the respective thicknesses of high-modulus asphalt and FRCC^{TM} are equivalent to traffic of 200 heavy goods vehicles per day and per direction, then that the increase in the thickness of FRCC^{TM} is not as fast as for that of the bituminous materials for higher traffic factors.

Figure 4 (next page) gives, as a function of trafic, a general comparison of the costs per m^2 of roadway pavement for various techniques, on the basis of the individual average pretax sales price in each of the materials concerned.

To conclude, the FRCC™ prices are not competitive for low traffic conditions but becomes so as soon as the traffic totals 500 heavy goods vehicles per day and per direction. Then the difference to the benefit of FRCC™ is on the order of 8 to 10% when compared to the highest performing asphalt solutions. The difference then increases in parallel to the traffic increase.

Similarly, in terms of sustainable development, for a road pavement liable to bear traffic amounting to 500 heavy goods vehicles per day, the FRCC™ solution makes for a saving in noble aggregates varying between 15% with respect to EME2 and 35% compared to GB3 road base asphalt + asphalt wearing course.

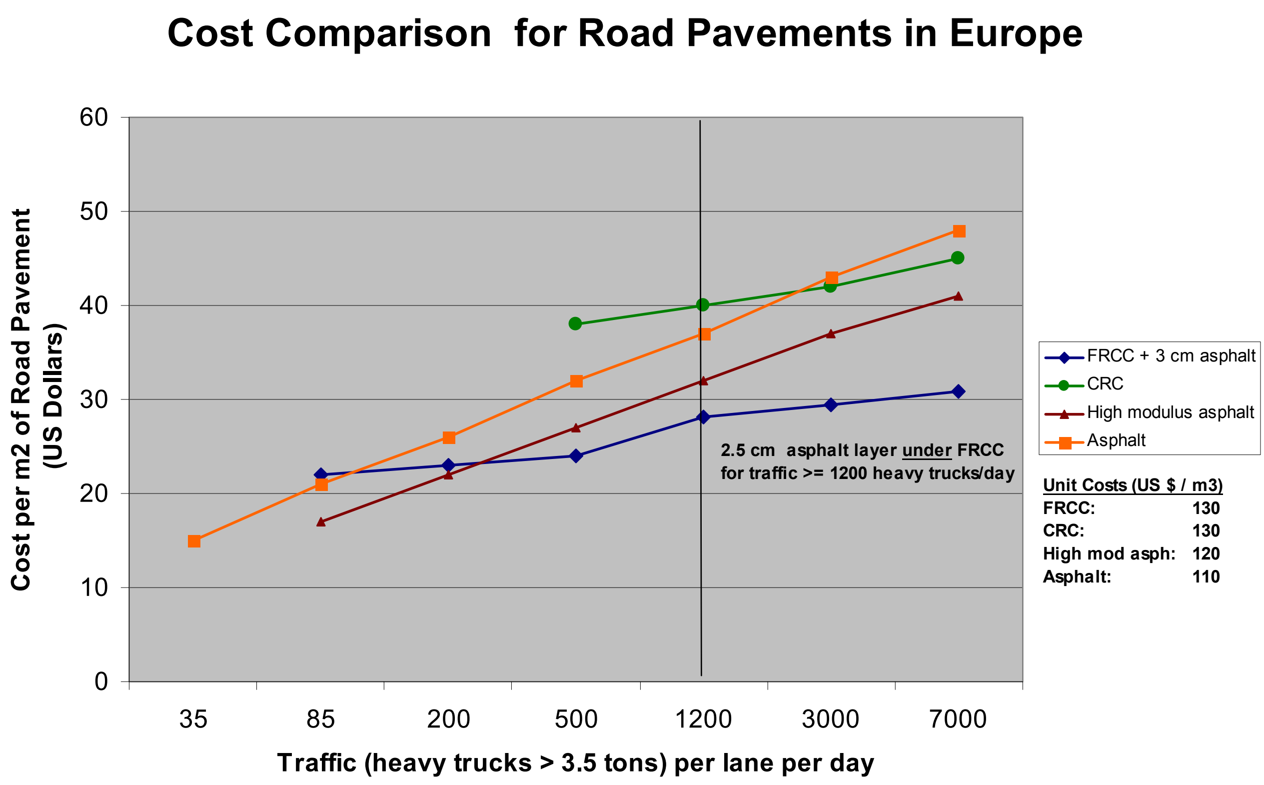

Figure 4 – Comparison of costs per m^2 of roadway in Western Europe (average prices)

In Central and Eastern Europe, the countries in the former Soviet bloc used an 8.5 ton standard axle. The change to the 11.5 European ton for standard axle therefore led to generalized degradation, systematic rutting to a depth of around 10 cm and excess fatigue damage in the national road network structures through all the countries concerned. In Poland in particular, and in Romania, including new motorway programs for which there may have loans from international banks or concession setups, the potential market for the FRCC™ process involves the upgrading of the national road networks for which considerable efforts yet have to be made.

In Poland, the habitual technique of reinforcing rutted national highways, after the milling of any materials that have crept, involves the application of 15 cm of road base asphalt + 5 cm of asphalt on the wearing course. Figure 5 (next page) shows that for equivalent structural capability, the solution of 10 cm of FRCC™ + 4 cm of thickness asphalt mix at 35/50 bitumen offers a radical remedy to the problem of rutting as well as a saving of around 10 to 12% per square meter of roadway reinforcement.

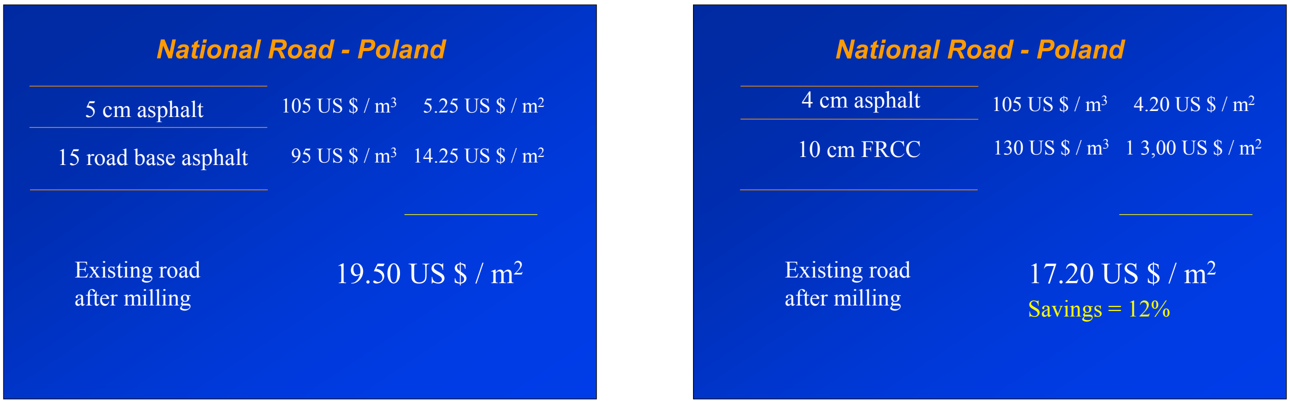

Figure 5 –FRCC™ Alternative for the reinforcement of national roads in Poland

2.3. Economic evaluation of the FRCC™ technique in China

Figure 6 shows the economic positioning of FRCC™ compared to conventional mix layers, high modulus asphalt and continuous reinforced cement concrete(CRC).

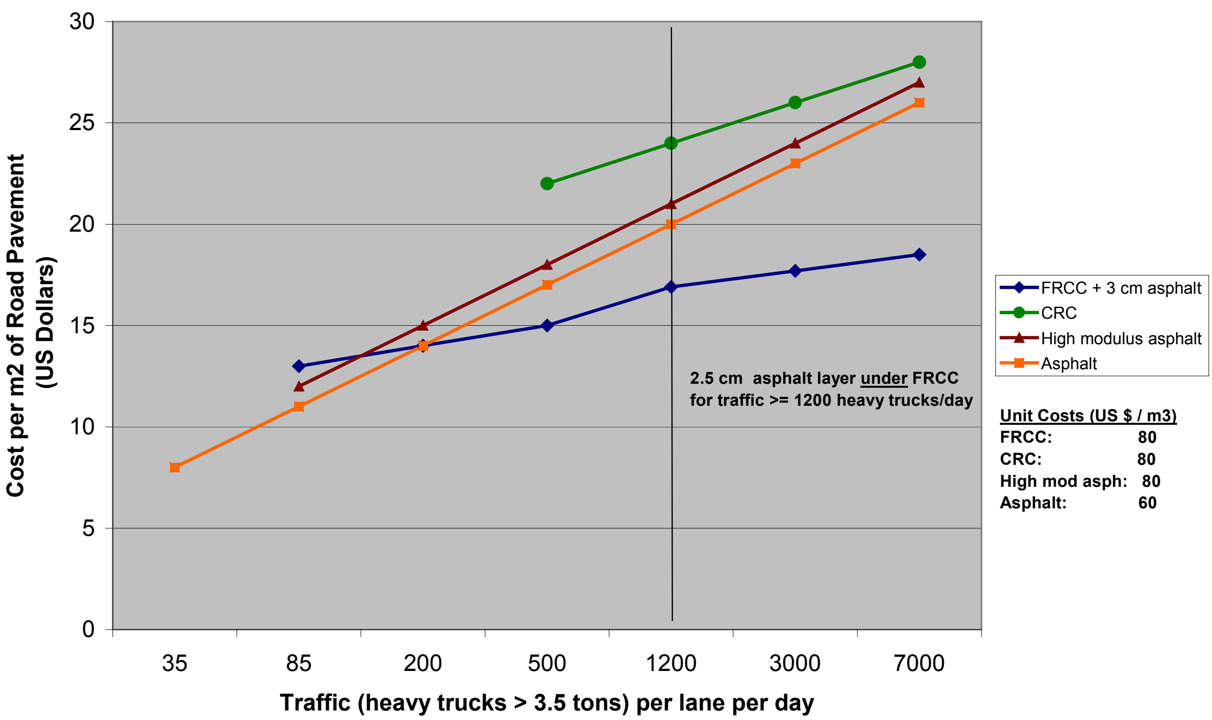

Figure 6 – Comparison of costs per m^2 of roadway in China (average prices)

An experimental FRCC™ site is being planned in China in the Shanxi Province for the autumn of 2003, as part of a technology transfer between CTI and the *Communications Planning, Surveying and Designing Institute of Shanxi Province*. This operation represents 120.000 m^2, i.e. 12 km of new dual carriageway roadway on a class 1 national highway. This roadway will support traffic amounting to 2,500 heavy goods vehicles per day and per direction, including a high number of overloaded vehicles with axles loads often more than 19 tons (the legal axle load China is 10 tons) in coalmining and transport region.

Other FRCC™ operations are currently being negotiated with the municipality of Shanghai.

With respect to the comparative results observed in Western Europe in the various investigated techniques, but related to a price level that is generally approximately 20 to 30% lower in China, the conclusions of the economic evaluation are nevertheless in the same direction. Indeed, there is an economic advantage of around 10 to 15% to the benefit of FRCC™ for traffic of 500 HGV's per day and direction, and the difference to the benefit of FRCC™ increases in parallel to the traffic increase.

More specifically, Figure 7 is a comparison of structurally equivalent motorway courses. This is an example taken from the Hubei Province for a structure that is often used, corresponding to the national standards of the *MOC* (*Ministry of Communications*), i.e. a semi-rigid thick pavement comprising 18 cm of asphalt materials. The saving offered by the FRCC™ solution (whose individual price is US$ 75 / m^3 in Hubei against approximately US$ 80 / m^3 in Shanghai) is around 8 to 10% and the difference in terms of aggregate consumption is of 30% to the benefit of the FRCC™ solution.

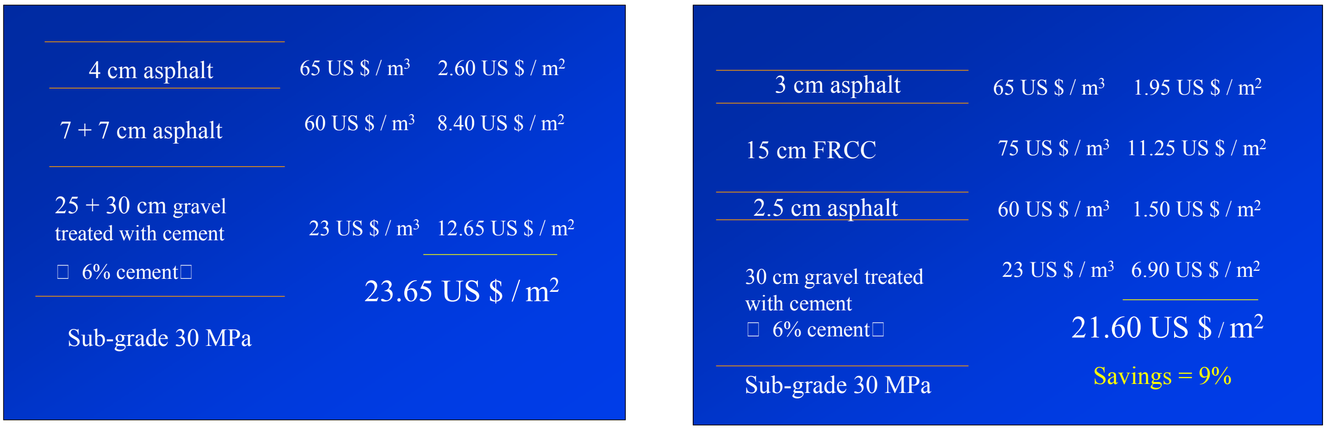

Figure 7 –FRCC™ alternative for new motorway course in Hubei (China)

Note the good quality and the relatively low price of Chinese cement, and therefore the choice of semi-rigid structures for economic reasons designed to reduce asphalt imports. According to the *MOC* directives for the recycling of by-products derived from the production of electricity by thermal power plants, cement in foundation layers is often replaced by fly ash, which is particularly abundant in the mining provinces, especially in Shanxi. Also note that Dramix 80/60 fibers for FRCC™ are manufactured in Shanghai by a Bekaert subsidiary.

To conclude, for China, the national efforts to use local products and decrease asphalt imports should be underscored, although this is at the disadvantage of road pavement cracking, especially when fly ash is used. In this context, it is noteworthy just how much the FRCC™ technique can contribute to a response to economic criteria aligning with *MOC* prescriptions and also technical criteria aimed at improving the quality of roadway courses by controlled cracking. That is why the perspectives for the development of the FRCC™ process in China are considerable, but as long as the economic advantages counted upon are confirmed on site and each step is successful, including the most modest, in this process development.

3. SPECIFICATIONS BASED ON PERFORMANCE

Compared to asphalt technique, the FRCC™ process has the same advantages as traditional pre-vibrated concrete techniques as a means of:

- correcting any problems of rutting,
- and as long as the construction is correctly designed, ensuring that the roadway lasts a very long time while limiting maintenance costs to the simple periodic renewal of an asphalt wearing course.

However, by nature, cement concretes are exposed to the shrinkage of the binder and have the drawback of cracking generated by the corresponding mechanical stresses. The concrete used in FRCC™ is not exception to the rule, in spite of the high mechanical performance obtained with a relatively low cement and water content, to minimize hydraulic shrinkage. Steel fibers are added specifically to control this cracking of the FRCC™: we have to define acceptable limits for this cracking.

The core drilling and the surveys carried out by the LROP team show that the opening of the cracks in FRCC™ is between 0.8 and 1 mm through the entire thickness of the slab and that the load transfer is 100% between the crack edges. Prism samples of FRCC™ also reveal the presence of many micro-cracks having an opening of between 0.2 to 0.3 mm, invisible at the surface of the asphalt running course. A proportion of 30 kg of fibers per m3 of FRCC™ corresponds to a cracking distance of around 30 to 60 m.

It is important to underscore the difference between:

- the cracking of both continuous reinforced concrete and FRCC™ roadways which is not damaging; and
- the cracking of gravel treated with hydraulic binders the opening of which is several mm, especially in China with the use of gravel treated with fly ash whose economic advantage is undeniable, but to the detriment of the quality of load transfer between crack edges.

Then there is the question of the corrosion of the fibers in FRCC™ cracks. On this point, note that the observations of the CRC in use for the last 20 years, revealing for cracks having an opening of less than 1 mm:

- an almost total absence of steel corrosion in the cracks, especially in the roadway that are not covered with an asphalt running course;
- a load transfer between the crack edges ensured by the aggregate themselves, and not by the steels.

On the basis of these observations, and although a procedure like this does not appear to be indispensable, the cracks in FRCC™ are sealed off with a bituminous emulsion over a width of approximately 10 cm (using the example of the operation of the same type performed to seal off a hot-on-cold joint after reapplication of asphalt mixes). If this action is performed properly it is almost invisible to a motorized user. However, it has to be repeated every 2 to 3 years if waterproofing is to be preserved, pre-proposing a low cost maintenance task but which does nevertheless require partial closing of the lanes during the intervention time (short).

An experimental section using FRCC™, approximately 300 m in length, was produced with 40 kg of fibers per m^3 of concrete. After 3 winter seasons, there are only two incipient cracks in this section and it seems to be operating in optimum condition with only micro-cracks not passing through the asphalt wearing course. It is still too early to reach any final conclusions concerning this evaluation, and other experiments and investigations will be necessary. However, the trends appear to be evident in terms of the service that can be proposed with FRCC™ technical applications:

1. A “standard” service level corresponding to 30 kg of fibers and leading to a few cracks of less than 1 mm opening but with good load transfer (meaning cracks comparable to those of the CRC but spaced at intervals of 30 to 60 m instead of 1.50 to 3 m). As indicated by the price elements in chapter 2 above, the corresponding FRCC™ product is highly competitive for heavy traffic roadways and meet the needs of contractors seeking an innovative solution to cut costs;
2. A "top line" service level corresponding to a proportion of 40 kg of fibers and offering a continuous, anti-rutting cement-concrete road surface almost free of cracking, aimed at satisfying the most demanding contractors, particularly regarding the image of their roadways. The downside of the additional 10 kg of fibres is an extra cost amounting to between 6 and 8% per m^2 of road surface which, in this case, substantially decreases the competitive advantage of the FRCC™ technique compared to asphalt solutions.

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