Environmental Impact of Steel and Fiber–Reinforced Polymer Reinforced Pavements

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Abstract: The environmental load of fiber-reinforced polymer (FRP) reinforced pavement was compared with that of steel reinforced pavement. Replacing steel rebars with FRP rebars can lead to changes in the concrete mix and pavement structure at the erection stage, to a reduced need for maintenance activities related to steel corrosion, and to different recycling opportunities at the disposal stage. The current study examined all of these variables. The environmental load of FRP reinforced pavement was found to be significantly lower than that of steel reinforced pavement. This results mainly from the fact that FRP reinforced pavement requires less maintenance, its cement content and concrete cover over reinforcement can be reduced, and the reinforcement itself generates a smaller environmental load.

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Introduction

Reinforcing bars (rebars) made from fiber-reinforced polymers (FRP) are being proposed nowadays as a substitute for steel rebars in concrete subjected to aggressive environments, which may lead to premature corrosion of the steel, such as bridge decks and structures in marine environments. The durability of FRP rebars was tested by several investigators and findings showed that, when manufactured using appropriate materials and processes, they are resistant to the aggressive environment of concrete and other external environmental conditions (Benmokrane et al. 2002; Katz et al. 2001; Bank et al. 1998; Uomoto and Ohga 1996; Nanni et al. 1998). During the past decade, many trial projects have been conducted using FRP rebars, which, so far, have been successful (ACI 2001).

After the mechanical properties of FRP reinforced concrete were established (ACI 2001; Pecce et al. 2000; Pilakoutas et al. 2002), economic considerations were applied on various FRP systems in construction in order to test their economic feasibility (Nystrom et al. 2003; Ehlen 1997, 1999, Ehlen and Marshall 1996). Increased awareness to environmental aspects requires, however, an examination of the environmental influence of these new materials and construction methods. Long-life expectancy and reduced maintenance are associated occasionally with better environmental performances, but this point needs to be examined scientifically.

The environmental analysis of long-lasting structural elements requires special considerations compared with other industrial elements. This is due to the large masses and high complexity of the materials and processes involved, as well as to their extended life, which involves maintenance considerations. Kibert et al. (1998) reviewed the environmental issues related to composite building materials, but the investigation focused only on the material itself and not its use in an entire structure. Widman (1998) and Eaton and Amato (1998) investigated the environmental impact of steel bridges and office buildings based mainly on the emission of CO_2 and energy consumption, but they did not include FRP systems in their examination. The current study compared the environmental load of steel reinforced pavement with that of FRP reinforced pavement. The parameters governing the material and structure of the two kinds of pavement throughout their entire life cycle were analyzed and compared.

Life-cycle Assessment Tool

Life-cycle assessment (LCA) is one of the tools commonly used to estimate the environmental impact of a product or a process. This tool is part of a series of international standards [ISO 14000, (ISO 1997, 1998, 2000a,b)] aimed at improving designs to enable better environmental management. According to ISO 14040 (1997), after defining the goal and scope of the environmental assessment, the assessment process itself is conducted in several stages as follows:

- Inventory analysis,
- Assessment of impacts, and
- Assessment of general influence (interpretation).

The first stage is relatively simple. All emissions resulting from the flow of materials and processes, from cradle to grave, are counted. This starts with the production of raw products from virgin materials (which are in turn counted as the depletion of raw materials), followed by the processes in which they are turned into a product (processing, assembly, shipping, etc.). This is followed by the product's entire life of service and maintenance, and ends in its disposal. In some cases, only a limited analysis is

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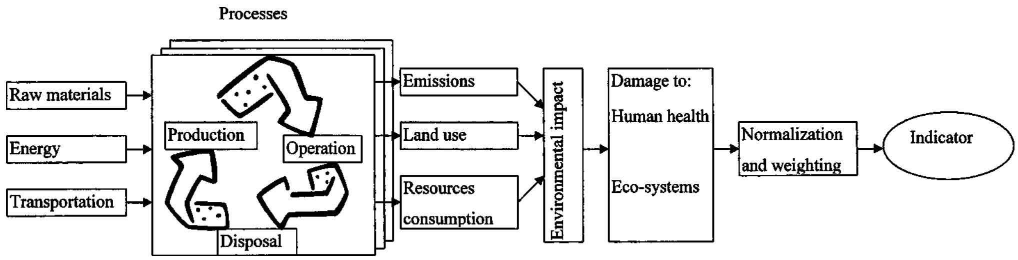

Fig. 1. Flow of environmental impact assessment of processes

performed, depending on the goal and scope of the analysis itself. Fig. 1 presents a schematic flowchart of the procedure.

Although considered simple, information on the entire process, from cradle to grave, is not always available especially when long service life of a product is expected. Thus, in these cases, only limited and partial data is collected, and it is assumed that the missing data have only a relatively minor environmental impact.

The second stage, assessment of impacts, is more complicated. It is well-known, for example, that the emission of carbon dioxide into the atmosphere increases the risk of global warming. It is not accurately known, however, to what extent and how to sum the effects of different pollutants. In addition, the exact mechanisms in which global warming directly affects human beings or ecosystems, which are in fact the final targets of the entire process, are even less known. Despite these uncertainties, a significant amount of knowledge exists today that enables a reasonable understanding of the effect of various emissions on global warming and other environmental impacts. It is still difficult, however, to compare different environmental impacts, such as the effect of global warming and resource depletion. Weighting, grouping, and normalization are important at this stage and depend, to some extent, on local priorities and on their degree of importance.

Interpretation of the information is the procedure in which all information is evaluated and examined in order to identify the important stages; test the sensitivity of the input and output to variations in the data; determine what course of action should be taken; and so on. In the current study, an LCA program (SimaPro 5) was used to gather data on the environmental impacts of the processes involved in the production of 1 km of concrete pavement, reinforced with either steel or FRP rebars. The program contains a large database on materials and processes and has the ability to add new materials or build new processes into the database. In addition, the program contains a variety of assessment tools that enable proper interpretation of the data. A procedure known as Eco-indicator 99 was used in the current study. This procedure is based on a comprehensive study in which all impacts are analyzed and divided into three groups: impacts that cause (1) damage to human health; (2) damage to ecosystems; and (3) depletion of mineral and fossil oil resources (Goedkoop and Spriensma 2000). The end result of the analysis is a single score (Fig. 1). It is also possible to compare processes on the basis of a partial score given to each category or to change the weighting procedure according to conditions that are predefined by the user. In the present study, the impact of processes was based on typical data from Europe (the Netherlands) and it affects mainly electricity production, transportation of aggregates, importance of land use, and normalization procedures. Therefore, the absolute values obtained in the analysis of this work may have a local bias, but comparing different alternatives on the same basis can prevent this problem, together with analysis of the controversial points.

Inventory Analysis

Three stages of a pavement's life cycle need to be considered when assessing its environmental impact.

- Environmental load of the erection stage,
- Environmental load of the operation stage, including periodical maintenance and renovation, and
- Environmental load of the disposal stage.

Inventory of Erection Stage

It is hard to find an equal basis for a comparison between steel reinforced and FRP reinforced-concrete elements, as certain pavement parameters are defined in view of the requirement to provide protection for the reinforcing steel. Such parameters include (1) maximum water/cement ratio; (2) minimum cement content; and (3) minimum concrete cover of the reinforcing steel. Less stringent requirements can be considered when steel rebars are replaced with FRP rebars and such requirements will now be discussed, in view of European and American codes.

The European code for concrete (CEN 2000) defines environment classes XS3 and XD3 as corrosive environments in which the corrosion is induced by chlorides from seawater and other sources, respectively. Such environments include structures subjected to wetting and drying cycles such as concrete pavements, car park slabs, and parts of bridges exposed to spray containing chlorides. These environments are considered the most aggressive environments to which steel in reinforced concrete can be exposed. Thus, FRP rebars are suggested as a successful substitute for steel in such environments. According to the same code (CEN 2000), environment Class X0 is designated for concrete without reinforcement (i.e., steel) or embedded metal. FRP reinforced concrete must, therefore, to comply only with limitations that apply to X0 environment since the other environment classes (apart from those exposed to freeze/thaw attack, or corrosion of the concrete itself) are defined in view of the requirement to protect the steel reinforcement.

The thickness of the concrete covering of reinforcement can have an important effect when determining the structural properties of reinforced concrete subjected to flexure. Mounting the reinforcement closer to the surface, while maintaining the thickness constant, yields improved structural properties. Alternatively, the overall thickness of the element can be reduced. Therefore, reducing the requirement for a thick concrete cover (aimed at providing better protection against corrosion to the steel) can lead to an element of smaller dimensions.

Table 1 compares the requirements for minimum cement content and maximum water/cement ratio as specified by EN 206 for

Table 1. Requirements for Concrete Properties Subjected to Different Environments, According to European Standard EN 206 and Eurocode 2, and Florida DOT

Authority	Exposure conditions	Minimum cement content (kg/m^3)	Maximum water-cement ratio	Minimum strength class	Minimum concrete cover (mm)
European code	X0	N/A	N/A	C12/15	10[a]
	XD3	320	0.45	C35/45	45
	XS3	340	0.45	C35/45	45
Florida Department of Transportation	Class IV	390	0.41	38 MPa	50[b]
	Class II (bridge deck)	365	0.44	31	—[a]
	Class II	335	0.49	23 MPa	—[a]

Note: N/A = Not applicable.

[a]Not less than one bar diameter.

[b]In some cases, an additional 12.5 mm for milling is required.

the relevant exposure classes, together with the requirements for minimum concrete cover of the reinforcing steel (CEN 1999). When the environment is less aggressive to the steel, the cement content and concrete cover are reduced and water/cement ratio increases.

Requirements in some of the United States follow along the same line. According to the Florida Department of Transportation (FDOT 2002), concrete bridge decks subject to extremely aggressive environments (exposure to high chloride concentration) require the use of Class IV concrete and a concrete cover of 50 mm (Table 1). When the risk of steel corrosion is reduced, the requirements for the concrete can be reduced to Class II concrete (or to a slightly higher class for bridge decks) and a concrete cover of no less than the diameter of one bar, the minimum required to ensure proper stress transfer between concrete and steel (ACI 440.1R-01) (Table 1).

In the current study, it was assumed that the reinforcement content was not determined from structural considerations but only as the minimum allowed. The replacement of steel rebars with FRP was done on the basis of equal quantities. The FDOT design requirements served as the basis for an investigation of the effect of replacing steel rebars with FRP rebars. Slab thickness was set to 200 mm (8 in.) and reinforcement was composed of Number 5 bars at 12 in. centers ($\varnothing 16$ at 30×30). It was assumed that the FRP reinforcement was the same. The basic unit examined in this study was a pavement segment, 1 km long and 17 m wide (two lanes in each direction).

According to the American Concrete Institute's (ACI) 440.1R-01, concrete cover over FRP rebars must be no less than $1d$ thick (d = bar diameter). Thus, the thickness of the concrete cover can be reduced from 50 to 16 mm and the overall thickness of the slab can similarly be reduced from 200 to 165 mm, i.e., a 17.5% decrease. Thus, changing the design from ordinary steel to FRP may lead to a change in the entire set of parameters relating to the concrete member; thickness on one hand and mix composition on the other. The decrease in slab thickness might be connected, however, to other structural parameters as well. Therefore, the following three types of FRP reinforced pavements were tested: Type 1—reduced thickness, Class II concrete; Type 2—reduced thickness, Class II concrete for bridge decks; and Type 3—full thickness, and Class II concrete. Table 2 lists the parameters used in the analysis of the pavements.

Another environmental parameter that may change when replacing steel rebars with FRP rebars is the transport distance of

Table 2. Summary of Pavement Data

Topics	Steel reinforced pavement	FRP reinforced pavement 1	FRP reinforced pavement 2	FRP reinforced pavement 3
Concrete class	Class V	Class II	Class II-bridge	Class II
Slab thickness[a]	200 mm	165 mm	165 mm	200 mm
Concrete composition				
Cement	390 kg/m^3	335 kg/m^3	365 kg/m^3	335 kg/m^3
Water	160 kg/m^3	165 kg/m^3	160 kg/m^3	165 kg/m^3
Gravel	1,100 kg/m^3	1,205 kg/m^3	1,145 kg/m^3	1,205 kg/m^3
Sand	750 kg/m^3	695 kg/m^3	730 kg/m^3	695 kg/m^3
Reinforcement	104 kg/m^3	32.2 kg/m^3	32.2 kg/m^3	32.2 kg/m^3
Processing				
Mixing power	9.3 MJ/m^3	9.3 MJ/m^3	9.3 MJ/m^3	9.3 MJ/m^3
Average distance of mineral transport	100 km	100 km	100 km	100 km
Average distance of reinforcement transport	500 km	1,500 km	1,500 km	1,500 km
Average distance of concrete transport	30 km	30 km	30 km	30 km

[a]In some cases, an additional 12 mm is needed for milling.

the rebars. Plants producing steel rebar are widespread, whereas FRP plants are quite rare. (At present, there are no more than three such plants on each continent, and it would be unrealistic to assume that this number is due to increase significantly in the near future.) This results in very long shipping distances for FRP rebars, that their environmental aspects must be considered.

Other parameters used in the study were cement—ordinary portland cement in which natural gas and refused fuels were used for its manufacturing; steel—made mainly from recycled ferrous waste; aggregates—from natural resources; transportation—large part of the transportation is done by barges.

Inventory of Operational Stage

Routine maintenance was the only activity considered during the operational stage. Two aspects of the environmental load generated by maintenance activities were considered, as follows: (1) materials and construction activities, and (2) disturbance to traffic during execution of maintenance.

Calculation of the environmental impact of maintenance is a difficult task, requiring many estimates, starting with the frequency and extent of maintenance works and ending with the effect of such work on the nearby traffic. Horvath and Hendrickson (1998) performed an environmental comparison between concrete and asphalt pavements but did not address the impact of maintenance due to insufficient knowledge. It is difficult to assess the environmental parameters that might be affected by maintenance; however, some assumptions can be made when accompanied by a sensitivity study. The methodology used here adopts the considerations made by Ehlen (1999) and Ehlen and Marshall (1996) when analyzing the economical impact of pavement maintenance. According to their study, maintenance work reduces the average speed on the road, and its cost is calculated based on the cost of time wasted by the delayed passengers.

In this study, the environmental effect of traffic disturbance (ETD) was calculated based on the average emission of a vehicle/kilometer, which is the standard way of presenting vehicle impact in most of the common environmental databases. Traffic in the area of maintenance was delayed due to maintenance work, leading to an increase in the time required to travel through the segment of pavement under study. In terms of emissions, this is, in fact, equal to an increase in the distance traveled. Eq. (1) presents an expression for the increased emissions

$$\mathrm{ETD} = \mathrm{VE} \times \mathrm{ADT} \times N_c \times L_{eq} \tag{1}$$

where ADT=average number of cars/day; N_c=number of days of traffic disturbance; VE=vehicle environmental impact/unit length of road; and L_{eq}=equivalent length of work zone, taking into account the actual length of road affected by the maintenance work, L, and the increased emissions due to the longer time needed to pass this area, calculated as follows:

$$L_{eq} = L\left(\frac{V_n}{V_a} - 1\right) \tag{2}$$

where V_a=average traffic speed in work zone; and V_n=average normal traffic speed.

According to Ehlen (1999) and Ehlen and Marshall (1996), maintenance activities on bridge decks begin 28 years after their erection. Starting from the 28th year, and every 3 years thereafter, 2.5% of the deck's surface is chipped away and the deck is repaired using new concrete. Corrosion of bridge decks is mainly a result of the corrosion of the reinforcing steel. It is therefore assumed that 1/2–2/3 of the previously mentioned repair activity is a result of steel corrosion that could be avoided if FRP were used instead of steel. Thus, over its entire service life (40–70 years in various states), a deck is destined to be repaired an average of eight times (5–15). Studies reviewed by Horvath and Hendrickson (1998), point to more frequent maintenance periods and extents, but their study is based on relatively old data from old pavements, whereas nowadays, new pavements are designed to last longer by using better concrete technology.

Table 3. Parameters for Calculation of One Repair Unit

Parameter	Quantity
New materials	
Concrete	29.75 m^3
Epoxy paint	20 kg
Concrete transport	60 km
Surface removal	
Diesel equipment	16 h
Waste to landfill	71.4 t
Waste transport	100 km
Daily labor transport	100 km
Duration of work	3 days
Traffic disturbance	
Daily traffic	27,000 passenger cars 13,000 trucks
Normal traffic speed	90 km/h
Disturbed traffic speed	55 km/h
Length of disturbance	0.8 km

Direct repair of the pavement involves the removal of the damaged concrete layer to a depth of 1 cm below the corroded steel (7 cm), cleaning the rebars and painting them with a protective paint, followed by casting a new concrete layer. The disturbance to traffic as a result of such activity is estimated to last approximately 3–7 days. Ehlen and Marshall (1996) estimated the duration of maintenance works to be only 3 days, but for large areas, longer times seem more realistic. Table 3 lists quantities required for the repair of one pavement unit (1 km long, 17 m wide).

Inventory of Disposal Stage

Demolition and recycling of steel reinforced concrete is nowadays a widespread practice. One of the common problems known to hinder the recycling of construction and demolition waste (CDW) is the variability of waste coming from various sources. Demolishing of concrete pavement avoids this problem since it provides uniform and homogenous rubble, which can be used successfully in the production of new concrete (Tavakoli and Soroushian, 1996).

The processing of CDW involves separating the reinforcing material from the plain concrete. In the case of steel reinforcement, separation is executed using the well-established technology of magnetic separation, which is used as a routine procedure in the crushing process (Mueller and Winkler 1998). It is assumed therefore that 100% of the steel is recycled and is used for the production of new reinforcing steel (similar to the one used for the erection of the pavement). The coarse aggregate, produced by crushing the old concrete, can be used in its entirely, but not the fine particles (RILEM 1994). According to Katz (2003), the fines content in recycled aggregate made from neat concrete is ~15%.

Table 4. Parameters for the Calculation of Pavement Disposal (1 t)

Parameter	Quantity
Demolition (diesel equipment)	5 MJ
Transport to a mobile process plant	25 km
Crushing	8.35 MJ
"In plant" transport	5 km
Water	75 kg
Waste to landfill	
FRP rebars	100%
Concrete (steel reinforced)	15%
Concrete (FRP reinforced)	100 or 50%
Recovered waste	
Reinforcing steel	100%
Concrete[a] (steel reinforcement)	85%
Concrete[a] (FRP reinforcement)	0 or 50%

[a]Conserves primary gravel

Thus, in this study, recycling rates of steel reinforced pavement were assumed to be 85 and 100% for the concrete and reinforcing steel, respectively (Table 4). It is difficult, however, to estimate the possibility of recycling FRP reinforced concrete. Separation and removal of rebars is essential for obtaining high-quality aggregate that can be reused in the production of new concrete. Therefore, recovery rates of only 50 and 0% were assumed for the concrete in FRP reinforced pavement, while the recovery rate for the FRP rebars was assumed to be 0%. All of the nonrecoverable material is directed to landfills.

Results and Discussion

Table 5 presents a comparison of the global scores of steel reinforced pavement with three types of FRP reinforced pavement, based on the performance of eight maintenance activities during the entire life cycle of the steel reinforced pavements.

Figs. 2 and 3 present flow charts for the entire life cycle of steel and FRP reinforced pavement, respectively, from erection to disposal, including the previously mentioned maintenance activities. The environmental load, expressed in Eco-indicator 99 points, is presented for each activity. The high environmental load of the steel pavement is clearly evident and results from higher erection and maintenance values. Compared with the steel pavement, a reduction of approximately 50% in the environmental load is expected when FRP rebars are used in place of steel reinforcement. The reduction stems mainly from the lack of maintenance activities related to reinforcement corrosion (36%) and a reduction in the environmental load of pavement erection (15–22%). The environmental load of each maintenance activity forms approximately 7% of the erection load, therefore, eliminating the need for maintenance related to steel corrosion can have an important effect on the overall environmental load of the pavement. In the following paragraphs, each stage of life (erection, maintenance, and disposal) is discussed separately.

Erection

Examination of the erection data (Fig. 4) reveals that cement and transportation are the main contributors to the environmental load of the erection stage. The environmental load of the steel reinforcement is also significant in the case of steel reinforced pavement; however, reinforcement contribution in the case of the FRP reinforced pavement is significantly smaller. Steel reinforcement produces approximately four times the load of FRP reinforcement of the same diameter. The actual substitution ratio of steel with FRP rebars is not 1:1, as it was taken to be in this study, since structural considerations may alter this ratio. Cement production seems to be the major contributor to the environmental load in the process of pavement production. Its manufacturing process involves high energy consumption and CO_2 emission together with the emission of minor components, which impose a significant environmental load. Therefore, reducing the cement content, either by reducing the cement content in a unit volume of concrete or by reducing the total amount of concrete by reducing the pavement thickness, will reduce the environmental load of the entire pavement. In the case examined here, both cement content and pavement thickness were reduced, leading to a reduction of over 8% in the environmental load of the pavement.

Reducing the cement and concrete content as well as reducing the total weight of FRP reinforcement to be transported (though to a larger distance) reduces also the effect of transportation in the case of FRP reinforced pavement.

Maintenance

Analysis of the maintenance load data reveals that most of the load is created by the disturbance to truck traffic (84%). Disturbance to passenger car traffic is minor (only 4%), and the construction work itself accounts for only 12% of the environmental load of maintenance. The effect due to the share of the trucks in the entire traffic and the duration of maintenance works will be addressed in the section on sensitivity analysis below.

Disposal

The environmental load of the disposal stage of steel reinforced pavement is lower than that of FRP reinforced pavement. This results from the negative load of the recycled concrete, which is used as a source of aggregate and in turn reduces the consumption of virgin aggregate. Transportation to landfill sites or processing plants constitutes the major contributor to the environmental load.

Table 5. Comparison of Environmental Load (Eco-indicator 99 Points) of Studied Pavements

Slab type	Erection	Maintenance[a]	Disposal	Total	Relative load (%)
Steel reinforced pavement	179,000	$n \times 13{,}200$	6,020	291,000	100
FRP reinforced pavement 1	114,000	N/A	7,680	122,000	44
FRP reinforced pavement 2	117,000	N/A	7,680	124,000	45
FRP reinforced pavement 3	134,000	N/A	9,310	144,000	52

[a]Only part that refers to steel corrosion; n = number of maintenance activities (n = 8)

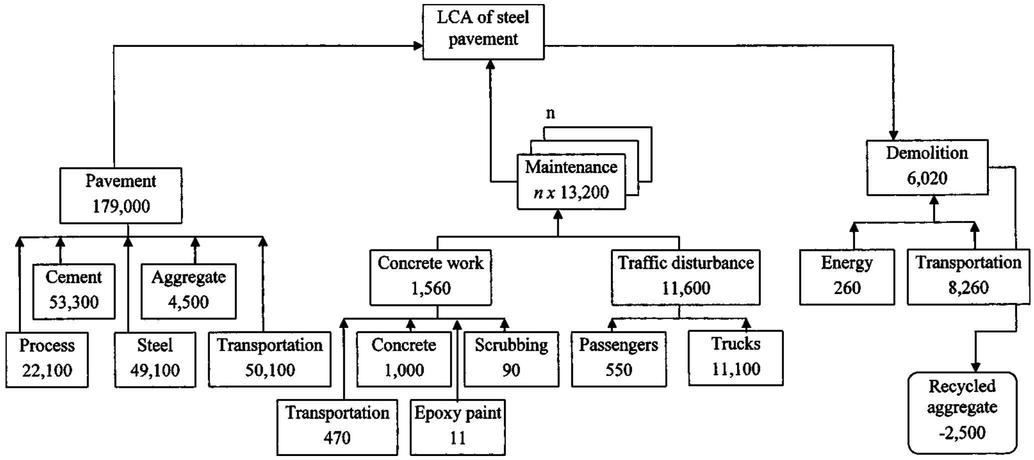

Fig. 2. Environmental load, in Eco-indicator 99 points, for entire life cycle of steel reinforced pavement

The absolute environmental load at the disposal stage is relatively small compared with that at the erection stage (less than 7%) and can be neglected.

It can be seen that truck transportation generates the major share of the environmental load due to transportation involved in all the various processes leading to the production of the pavement (~38% of the LCA in steel reinforced pavement, and ~27% in FRP reinforced pavement). The production process of each component involves several stages, from raw materials to the final product, and each stage is carried out at a different location. The concrete industry, being a mass production industry, is a large consumer of transportation. The present analysis was performed assuming conditions, as they exist in the Netherlands, in which barge transportation is quite common for the transport of raw materials. In other locations, in which trucks are used more commonly to deliver raw materials, the environmental load might be significantly higher.

Sensitivity Examination

The determination of some of the parameters just discussed involved several points of uncertainty, as follows:

Distribution of Vehicle Classes (Passenger Cars Versus Trucks) During Maintenance

In the previous analysis, trucks formed one-third of the overall traffic. In some areas, though, trucks constitute a larger fraction of the traffic. Assuming that trucks constitute two-thirds of the traffic, i.e., doubling their share and contribution, the environmental impact of maintenance will almost be doubled, since trucks have the greatest effect on the environmental load during maintenance. Environmental considerations related to major interstates highways with heavy truck traffic might be different than those for city roads, which are characterized more by heavy passenger car traffic than by truck traffic.

Duration of Maintenance

It was initially estimated that most maintenance activities are completed within only 3 days. It was found, however, that longer times are a more reasonable assumption. Thus, a duration of 6 days, for example, will double the duration of traffic disturbance, while the concrete work remains constant. Doubling the duration of maintenance work, therefore, has the same effect as doubling the volume of trucks on the road, as just discussed.

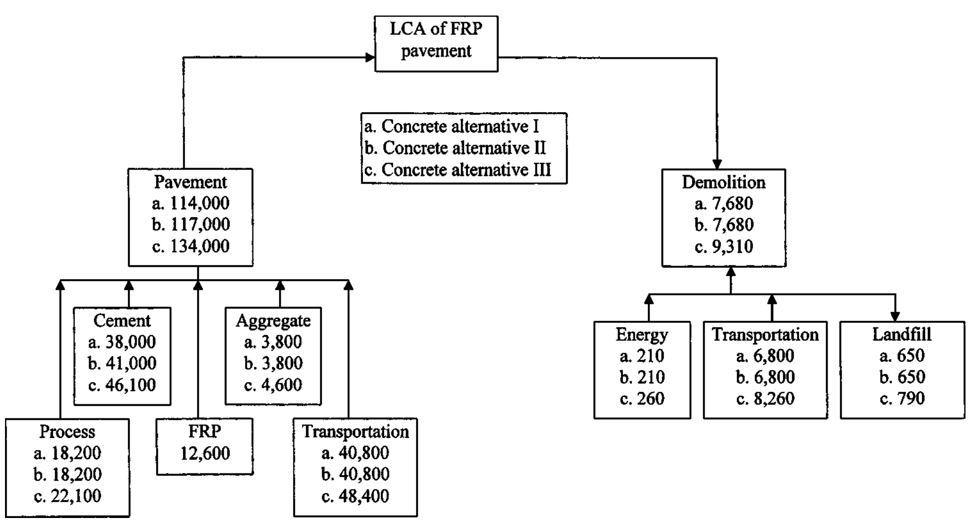

Fig. 3. Environmental load, in Eco-indicator 99 points, for the entire life cycle of FRP reinforced pavement

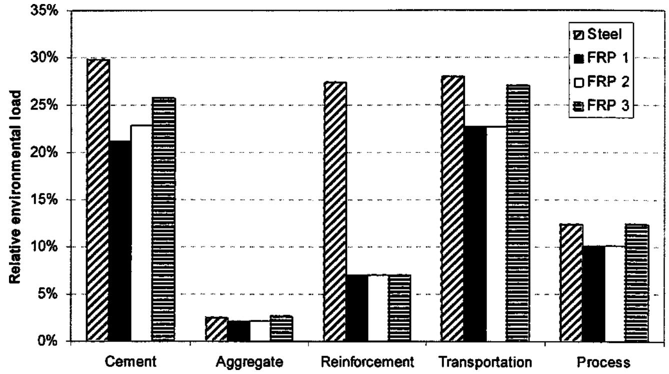

Fig. 4. Comparison of environmental load of pavement erection, using Eco-indicator 99 method, normalized to load of steel reinforced pavement

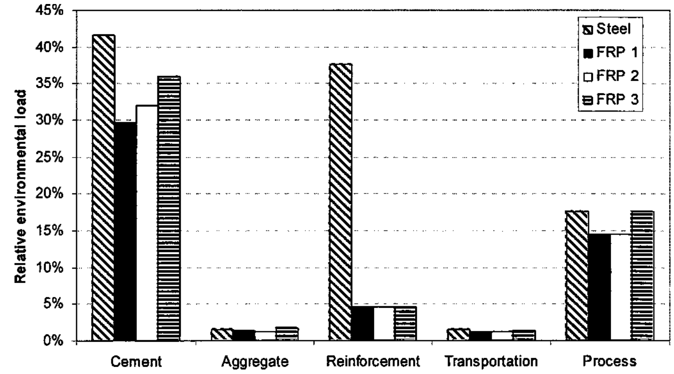

Fig. 5. Comparison of relative environmental load of pavement erection, using EPS 2,000 method, normalized to load of steel reinforced pavement

Number of Maintenance Activities

Maintenance constitutes a significant part of the LCA of steel reinforced pavement (7% of erection load). Thus, each time maintenance is required the overall environmental load is increased accordingly.

Recovery Rate of Fiber-Reinforced Polymer-Reinforced Concrete Following Demolition

The contribution of concrete recovery at the end of the pavement's life was found to be quite low (1–2% of the erection load, see Figs. 2 and 3). Any change in the recovery rate of concrete following demolition imposes an insignificant effect on the overall environmental load of the pavement, regardless of the kind of reinforcement used.

Evaluation Method

The high environmental load of truck transportation warrants special attention to this module, as well as to its environmental effect. Besides the emission of various gases into the atmosphere (NO_x, SO_x, CO_2, and others), vehicles contribute to the occupation of land, which in turn affects the local ecosystems. Occupation of land also constitutes part of the environmental load generated by concrete plants. It seems that the topic of land use is controversial, as some environmental databases do not include this effect or attribute to it only a small environmental influence compared with other effects (such as the emission of gases). The same data were reanalyzed using a different evaluation tool, the EPS 2000, in which priorities of impacts are assessed differently. Compared with the Eco-indicator 99 evaluation tool used earlier, land use, according to this tool, generates only a small environmental load.

Fig. 5 presents a comparison of the environmental effect of the erection of the tested pavements. As expected, the relative load due to the transportation component was reduced significantly in the case of the FRP reinforced pavement, whereas an increase was seen in the load due to the other parameters. In addition, the relative load generated by FRP reinforcement is reduced, as long transport distance is involved in the delivery of FRP rebars, and its effect is reduced. After subtracting the controversial effect of land use, cement and steel manufacturing are still the dominant processes; thus, reducing the use of both cement and steel may reduce the environmental load of the pavement.

The environmental load due to maintenance is reduced accordingly, since the disturbance to truck transportation has a smaller impact. Each maintenance activity adds only ~1% of environmental load to the erection load thus its importance is significantly reduced.

Summary and Conclusions

The environmental load of steel reinforced pavement was compared with that of FRP reinforced pavement using the Eco-indicator 99 method. It was assumed that changing the reinforcement type might enable a reduction in the cement content of the concrete as well as a reduction in the thickness of the concrete cover of the reinforcing bars, which may lead to a reduction in the overall thickness of the pavement.

It was found that the environmental load of FRP reinforced pavement is significantly smaller than that of the steel pavement. This results mainly from (1) the absence of maintenance activities related to steel corrosion during the entire life of the pavement (~7% for each periodic maintenance activity, with 5–15 activities expected during the entire life of the pavement); (2) substitution of steel with FRP rebars (~13%); and (3) the reduction of cement content (2.6–5.5%).

Use of a different evaluation method, which places less emphasis on the environmental load of land use, revealed a more significant effect of steel substitution (31%) and reduction of cement content (5–11%), but a lesser effect of maintenance activities (~1% for each activity, with 5–15% over the entire life expectancy of the pavement).

The significant effect of steel on the environmental load of reinforced-concrete elements emphasizes the need for an additional study for the cases in which steel reinforcement is replaced by FRP on a structural basis. In these cases, the quantities of FRP might be different (probably larger) as well as the dimensions of the concrete member itself, thus a comprehensive investigation of all design aspects and their environmental impact is needed.

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