APPLICATION OF GREENER ENGINEERED CEMENTITIOUS COMPOSITES FOR SUSTAINABLE PAVEMENT OVERLAY DESIGN

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Abstract

Pavement rehabilitation is a subject that has continuously worried transport authorities. Many old pavements in service nowadays are approaching the end of their design service lives and are in dire need of major repair to continue serving. Both conventional Portland cement concrete and asphalt have been used in the rehabilitation of existing deteriorated concrete and hot-mix asphalt pavements. Although these solutions may provide a reasonable performance when well designed and constructed, a critical limitation on their service life is the occurrence of reflective cracks. None of the current repair techniques can totally eliminate this problem. However, recent data suggests that some advanced fiber reinforced composites, made with polimeric microfibers, known as Engineered Cementitious Composites (ECC), may advantageously be used to create a thin, durable and cost-effective overlay. This paper focuses on the development and characterisation of an ECC mixture made with high tenacity polypropylene fibers, which are less costly than PVA fibers originally used to develop ECCs. An experimental investigation was combined with a finite element analysis, in order to assess the performance of this new material, which is marked by its strain hardening behavior. Furthermore, a Life Cycle Assessment (LCA) exercise and a Life Cycle Cost (LCC) analysis were carried out to demonstrate that this kind of rehabilitation solution leads to a more sustainable overlay design.

Keywords: Engineered cementitious composites, pavements, rehabilitation, concrete overlay, fiber reinforced composites.

1. Introduction

Pavement rehabilitation is defined as the structural or functional enhancement of a pavement that results in a substantial extension in service life, by substantially improving pavement condition and ride quality. Pavement maintenance activities, on the other hand, encompass those treatments that are used to preserve pavement condition, safety and ride quality; and therefore aid a pavement in achieving its desired design service life [1].One of the most used rehabilitation techniques, especially in pavements subjected to moderate and heavy traffic, consists in applying a structural or functional overlay over a deficient or deteriorated pavement. A structural overlay extends the remaining service life by means of an increase in the structural capacity and serviceability of the pavement. Meanwhile, a

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functional overlay extends the service life by correcting functional deficiencies, but does not increase the structural capacity of the pavement. According to Smith et al. [2] Portland cement concrete overlays are increasingly being used as a preferred rehabilitation technique for both existing Portland cement concrete and hot-mix asphalt pavements. The use of Portland cement concrete overlays offers the potential for extending the service life, increasing structural capacity, reducing maintenance requirements, and lowering life-cycle costs when compared with other overlay alternatives. As mentioned by National Center for Concrete Pavement Technology [3], concrete overlays can serve as cost-effective solutions for almost all combinations of existing pavement types and traffic conditions. However, although a well designed and constructed concrete overlay may provide an excellent performance, it is still affected by some important deterioration processes, due to concrete shrinkage, temperature changes, freeze - thaw cycles or repeated truck loading [4]. All these phenomena may result in the development of tensile stresses and, consequently, in the formation of well defined cracks. The cracks tend to establish themselves in zones of stress concentration, near existing cracks or joints already present in the original pavement. These cracks are known as reflective cracks and constitute a major limitation on the service life of overlays [5]. If the element with the reflective cracks is subjected to freeze and thaw cycles, the crack width and depth increases due to the water expansion during freezing, resulting in additional damage. This can lead to the formation of through-thickness cracks. Under repeated traffic load, the exposed crack ridges are gradually worn out, eventually leading to the loss of the capacity for load distribution in the longitudinal direction. As a result, the overlay slab ceases to behave as a plate, starting to react as a transverse beam. The presence of water accelerates the wear out process, while the passage of truck wheels on the cracked overlay may also result in severe spalling, reducing or even wiping out completely the ability to carry traffic. For both the most traditional overlay methods which involve the application of unbonded concrete or hot asphalt layers, reflective cracking acts as a serious limitation on service life. Therefore, techniques to overcome this problem have been intensively researched [6, 7].

Considering the average age of the highway infrastructure in several countries, and the consequent need for extensive rehabilitation of pavements, in association with the limited funding available for pavement repair and rehabilitation, it becomes easy to justify the need for more reliable and robust approaches to address the reflective cracking problem, in order to extend the service life and simultaneously minimize the maintenance requirements for existing pavements, resulting in more durable and sustainable roads.

A new alternative, which has shown good promise, consists in the use of highly deformable fiber reinforced composites, named Engineered Cementitious Composites (ECC), which can develop a multiple microcracking pattern that allows the relief of stresses without the definition of a major crack. This study is focused on the development of an ECC using polypropylene fibers, which are less costly than the PVA fibers traditionally used and may be an important change to make their use more viable. The proposed solution exploits the high ductility and high damage tolerance of ECC, without relying on concrete slab fracturing, creation of a stress relieving interfacial layer or adoption of any other measure to control the occurrence of reflective cracking.

Engineered cementitious composites (ECC) are a particular group of high-performance fiber-reinforced cementitious composites (HPFRCC) that present superior tensile ductility while incorporating just a moderate fiber volume fraction (typically 2%). The design of ECC is quite specific and guided by micromechanical models, which provide quantitative links between the mechanical behavior of the composite and the properties of its individual phases - fiber, matrix, and interface. The desired high tensile ductility is achieved by tailoring those components according to the micromechanics theory [8, 9]. The increase of deformability is attributed to the development of a microcracking process that helps to eliminate the problem of reflective cracking commonly observed in distressed pavements overlaid with conventional concrete. The works of Zhang e Li [4], Qian [7], Stander [10] have extensively demonstrated that when engineered cementitious composites are applied as an overlay material over a concrete substrate, both the load-carrying capacity and the deformability are increased, in comparison to those obtained using plain concrete overlays. The increase in load-carrying capacity can, on the other hand, extend the fatigue life of the structure under traffic load. For these reasons, it can be argued that Engineered Cementitious Composites (ECCs) may effectively replace hot asphalt and traditional concrete mixes for use in pavement rehabilitation, resulting in a thin, durable and cost-effective overlay [7]. Previous research [4, 7, 11] on using ECC as a repair layer over concrete substrates involved the study of the monotonic and fatigue behavior of ECC-concrete layered beams. Although the self-consolidating and sprayed versions of ECC materials used in these studies were not totally suitable for real applications, they provided valuable insights into what might be anticipated in pavement overlays if ECC were to be used. The newer versions of EEC investigated in this work, incorporating high tenacity polypropylene fibers, overcome the problem of producing mixes with appropriate characteristics for practical applications. The authors were able to produce an economic material, with excellent performance after hardening, while making sure that the characteristics of the wet mixes complied with the workability requirements established for pavement materials by the FHWA[12]. Engineered Cementitious Composites were initially developed using PVA (polyvinyl alcohol) fibers from Kuraray, Japan. Several successful field applications have demonstrated the very good capabilities of this material for pavement and repair applications, such as the creation of a steel/PVAECC deck for a cable-stayed bridge in Hokkaido, Japan; the repair of the Mitaka Dam in Hiroshima, Japan; a PVAECC patch repair placed on the deck of the Curtis Road bridge over the M-14; and a bridge deck retrofit with PVAECC link slabs, both the last in Michigan, US. However, the wider use of these materials is somehow hampered by their relatively high cost, compared to other solutions. Polypropylene fibers (PP), which cost about half the price of PVA fibers, may therefore be a good alternative for the fabrication of lower cost ECCs, making viable their application on a wider range of situations.

This paper aims to evaluate the performance of ECC reinforced with high tenacity polypropylene fibers – PPECC - under fatigue loading, via an experimental investigation combined with a finite element analysis of a rigid pavement slab overlaid with ECC. The flexural behavior under static loading is also investigated. The main purpose is to check the influence of overlay thickness on structural response and provide a comparison with PVAECC and concrete overlays, identifying the most economical alternative through life cycle cost analyses.

2. Experimental Program

2.1 Materials

Three materials were tested as overlays: PPECC, PVAECC and concrete. PVAECC and PPECC were produced with ordinary Portland cement – ASTM type I, fly ash class F provided by Boral, tap water, Grace ADVA Cast 530 super plasticizer, PVA fibers from Kuraray, polypropylene fibers, provided by the Brasilit/Saint-Gobain Group, following the mix proportion shown on Table 1. The basic properties of the PP and PVA fibers are shown in Table 2. Mechanical properties of concrete, PVAECC and PPECC are listed in Table 3.

Tab. 1: Mix proportions

Components	PPECC	PVAECC
Cement – Type I	1.00	1.00
Silica Sand	-	0.8
Fly ash	2.80	1.2
Water	0.89	0.99
Susperplasticizer	0.016	0.016
Fibers#	0.02	0.02

Proportion by volume

Tab. 2: Fiber properties

Fiber	Young´s Modulus E_f (GPa)	Tensile strength σ_f (MPa)	Diameter D_f (μm)	Length L_f (mm)
PP*	6	850	12	10
PVA**	42.8	1070	39	12

*Brasilit – Saint-Gobain **Kuralon K-II REC15 – Kuraray

Tab. 3: Material properties

Material	Compressive Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Strain Capacity (%)	Young´s Modulus (GPa)
PPECC	29.7	2.0	5.0	19.0
PVAECC	37.5	5.3	2.5	20.7
Concrete*	27.0	3.2	0.01	34.5

* Data provided by Qian [7]

2.2 Specimens, Tests and Load Conditions

Three beams measuring 355 x 75 x 50 mm were used to conduct bending tests and nine beams were to carry out fatigue tests measured 355 x 75 x 50 mm. The mixtures were cast into molds. The specimens were demolded after 24 hours and cured in air at 25 °C for 28 days. Four point bending test were conducted to determine the modulus of rupture (MOR) using a constant moment span length of 102 mm and a free span between supports of 305 mm. The monotonic tests were conducted using displacement control, with displacement rate of 0.1 mm/minute. The load pattern used in fatigue tests included a static preloading, followed by fatigue load cycles (Figure 1). The preloading was carried out using the displacement rate of 0.1 mm/minute. Fatigue loading was conducted with load control and sinusoidal waveform of 4 Hz frequency. The fatigue loading ratios (relation between maximum flexural stress, s_{max}, and ultimate flexural strength of the material) were chosen to be 0.7, 0.8 and 0.9. To prevent any impact loading during the fatigue test, the minimum flexural stress s_{min} was kept equal to 20% of the maximum flexural stress s_{max}. The maximum flexural stress and fatigue life were recorded in the form of s-N relationships.

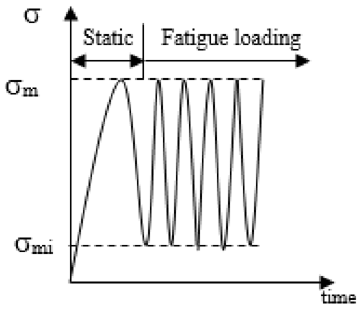

Fig.1: Loading pattern for fatigue test

3. Results

3.1 Flexural performance under monotonic loading

The monotonic test results are presented in Table 4.As can be seen, PPECC and PVAECC has achieved higher MOR values in comparison to concrete. However, the more significant difference is the improvement on bending deformability of these mixtures, which results from the ductile behavior of ECC, due to the development of multiple microcracking process under tensile stresses. While the tensile strength of PPECC and PVAECC is not significantly different from concrete, the tensile strain capacity of both ECCs is much higher, resulting in a larger deflection capacity. This effect may be explained by the fact that concrete suddenly fails when tensile strength is reached and the load carrying drops down very quickly. It means that deflection capacity is exclusively related to concrete elastic deformation. By the other hand, ECC mixtures are able to sustain the applied load or even carrying additional load without failure while multiple microcracks are formed. The flexural behavior of the PPECC can be observed in Figure 2.

Tab. 4: Flexural strength and ultimate deflection

	Concrete	PPECC	PVAECC
Flexural Strength (MPa)	4.6	6.1	10.9
Deflection (mm)	0.1	7.5	6.0

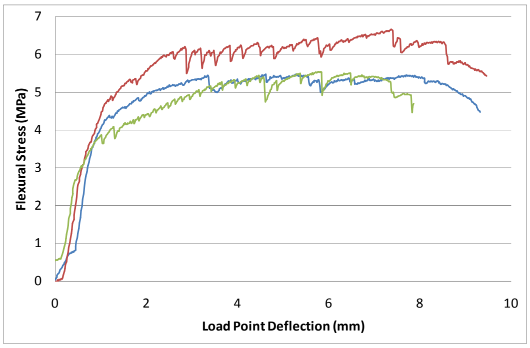

Fig. 2: Flexural behavior of PPECC

A comparison between the flexural behavior of concrete, PPECC and PVAECC and steel fiber reinforced concrete (FRC) beams is shown in Figure 3. It can be seen that, although a moderate strain capacity is necessary to suppress the brittle failure mode of normal concrete, the tensile strength governs the ultimate flexural strength. As shown in Table 3, PVAECC has a higher tensile strength when compared to PPECC, resulting in a higher flexural strength. For steel fiber reinforced concrete, fibers are able to prevent the brittle failure mode, but cannot maintain the load capacity after first crack opening. Meanwhile, high ductility of ECC increases structural safety by keeping the integrity of the structural element and maintaining load carrying capacity.

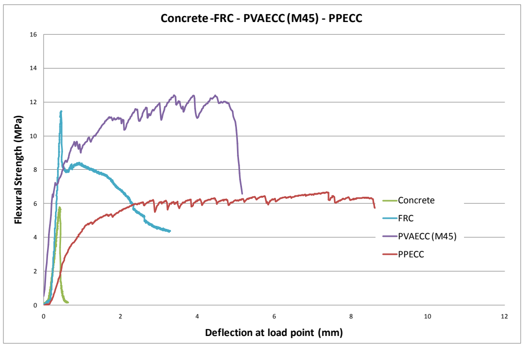

Fig. 3: Comparison of concrete, PPECC, PVAECC and FRC typical flexural behavior

3.2 Flexural performance under fatigue loading

The fatigue performance of concrete, PVAECC and PPECC are shown in Figure 4, expressed by fatigue stress versus fatigue life (s – N) diagrams, where N is the number of loading cycles. Through the s – N diagrams it is possible to compare the fatigue performance of those material.

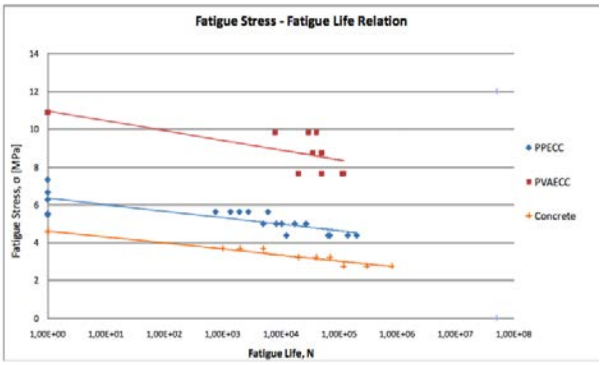

Fig. 4: Flexural stress – fatigue life relation for PVAECC, PPECC and conventional concrete

It can be seen that both ECCs show an enhancement of the fatigue stress x fatigue life relationship, when compared to concrete, as a result of the higher tensile ductility. Therefore, for a given stress level, the fatigue life of an ECCs is higher when compared to concrete. As mentioned before, PVAECC presents a better performance when compared to PPECC, in consequence of higher tensile strength. In both cases, it can be expected that ECC will greatly enhance the service life of pavement overlays, in relation to concrete and hot mix asphalt.

Figure 5 shows the crack pattern of PPECC under monotonic and fatigue loading. While plain concrete always fails by localized fracture, PPECC shows the typical multiple cracking behavior expected for ECC. As can be seen in the figure, the crack pattern of PPECC is similar for different stress levels. However, when the fatigue stress level decreases, the number of microcracks also decreases. This effect suggests that it may be more difficult to reach the microcracking saturation for lower stress level, as previously observed by Matsumoto *et al*. [15] and Qian [7]. Zhang and Li [4] have pointed out that this may be related to the fact that the fiber-matrix interface accumulates damage during the fatigue loading cycles, leading to a gradual degradation of fiber bridging stress.

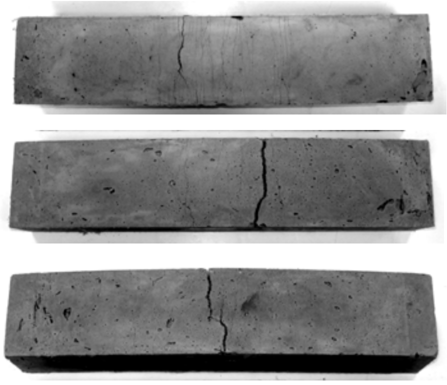

Fig. 5: Crack pattern for PPECC specimens under monotonic and fatigue loading at $0,8\sigma_{ult}$ e $0.7\sigma_{ult}$, respectively

3.3 Finite Element Model for Overlay Analysis

JSLAB-2004 is an FEM program developed for analyzing jointed concrete pavements. In this study, this software was used for estimating the overlay critical tensile stress under traffic loading. The program can analyze two-layer systems of up to nine slabs, considering fully bonded or unbonded conditions. The model used for simulating the concrete, PVAECC and PPECC overlay. For this investigation, the overlay system was simulated as a two-layered material – with a top layer of PPECC, PVAECC or plain concrete applied over a bottom layer of concrete substrate with bonding. The slab dimensions were 6.1 m by 3.66 m (20 ft by 12 ft). The cracks in the substrate were modeled by introducing a row of soft elements with 10% of the stiffness of the surrounding concrete. The stiffness of the liquid foundation (modulus of subgrade reaction) was taken as 27 MPa/m (100 pci). An equivalent single-axis load (ESAL) of 80 kN was applied over four rectangular areas, each one having dimensions of 230 mm by 158 mm. The maximum tensile stress at the bottom of the overlay slab, directly underneath the loaded edge, was obtained varying the overlay thickness.

4. Integration of experimental and numerical data

After the experimental tests and the finite element analysis, the results were integrated into a deterioration model establishing the relationship between overlay thickness and fatigue life, as shown in Figure 6. From the figure, it can be observed that the concrete overlay required is much thicker to achieve the same performance as PVAECC and PPECC. The typical thickness range of concrete overlays suggested by the Michigan Department of Transportation (MDOT) is 150 to 200mm for a design service life of 20 years, a similar value to the model prediction. As mentioned before, the PVAECC show a better fatigue performance than PPECC. However, to make a proper comparison between solutions, a life cycle cost analysis needs to be done, as described in the following section.

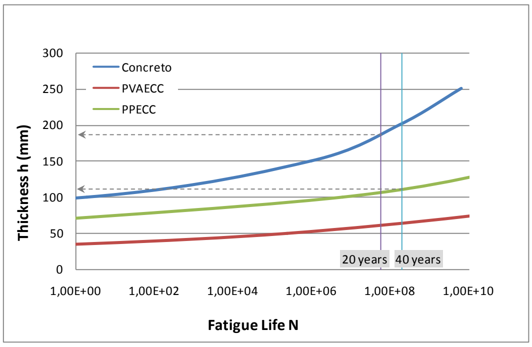

Fig. 6: Fatigue life prediction

5. Life Cycle Cost (LCC) Analysis

A comparison among the LCC performance of concrete, hot mix asphalt, PVAECC and PPECC overlays is presented next. The service life model for ECC overlays was proposed and developed by Zhang *et al*.[17], and is also reported on Zhang *et al*. [18].

Michigan Department of Transportation [6] has developed service life models for unbonded concrete overlay and HMA overlay on rubblized concrete for LCC use. The service life model was developed in the form of distress index (DI) with pavement age relation. The service life for unbonded concrete overlay and hot mix asphalt (HMA) overlay is 21 and 20 years, respectively, requiring major refurbishment or new construction after this period. The distress index is an index that quantifies the level of distress that exists on a pavement section based on 1/10 mile increments. The scale starts at zero and increases numerically as distress level increases (pavement condition worsens). Once the DI reaches 50, the pavement is considered to exhaust its service life. The maintenance schedules reflect the overall maintenance approach that has been used by MDOT for a specific fix (concrete overlay or HMA overlay) based on historical maintenance and pavement management records. It is important to mention that HMA and concrete overlays may last over 20 years. However, in this research, MDOT data was used as reference.

The service life model for ECC was based on the current MDOT service life models. The assumption of 40 years service life of for ECC was based on the fatigue response of those materials and considering the resistance of such systems to reflective cracking and higher energy absorption capacity compared to normal concrete and steel fiber reinforced concrete overlays. Besides of that, ECC material has shown outstanding performance for repair and rehabilitation applications in shrinkage behavior freeze thaw exposure, abrasion and wear testing, long term material performance and accelerated weather tests, indicating the potential for extended service life of ECC [4, 10, 11]. Therefore, as pointed out in the deterioration model above, ECC overlay may achieve the established service life of 40 years with a slight increase in the thickness prescribed to reach a 20-year service life of concrete overlays. The LCC model considered the standard situation of a 10 km long overlay, subjected to a traffic flow of 70.000 ESALs/day, over a four-lane two-way road.

The results obtained suggest that the use of a PPECC overlay system may reduce total life cycle cost when compared to concrete, hot mix asphalt, and PVAECC overlays. The reduced thickness, the extended service life and the need for less frequent repairs favor economically the ECC alternative. Meanwhile, the lower cost of the PP fiber compared to PVA results in an economic advantage of PPECC overlays applications. To clarify this point, Table 5 presents the material production costs for both PVAECC and PPECC. It can be seen that the unitary material cost of production PPECC is half that of PVAECC.

Tab. 5: PVAECC and PPECC material

Components	PVAECC		PPECC	
	Proportion by weight	Cost ($/m3)	Proportion by weight	Cost ($/m3)
Cement (c)	1	64.04	1	45.42
Sand (s)	0.8	76.89	0	0.00
Fly Ash	1.2	16.90	2.8	27.99
Water (w)	0.99	0.47	0.89	0.53
Super	0.016	28.70	0.016	27.06
Fiber	0.02	156.00	0.02	54.37
Total Cost		343.00		155.37

Table 6 shows the total service life costs of HMA, concrete, PVAECC and PPECC overlays. Table includes agency costs, user costs and environmental costs. More details on transportation related costs can be found in Zhang *et al*. [17] Uddin *et al*. [19].

Based on the results, it can be observed that PPECC overlay may reduce in 2%, 40%, and 50% the total cost when compared to PVAECC, concrete and hot mix asphalt overlays, respectively. The total cost performances of PPECC and PVAECC overlays are quite similar when the whole service life cost is considered. However, when only the agency costs are considered, an important difference is observed. The agency cost for the PPECC overlay is reduced in about 24%, 40% and 160%, compared to the costs for PVAECC, concrete and hot mix asphalt overlays. This significant difference results from the easier maintenance and reconstruction activities during the 40-year horizon. Thus, in terms of direct investment, a critical factor when limited budgets are taken into account, the PPECC solution presents significant economic advantages over the other overlay systems considered in this analysis.

Tab. 6: Total life cycle costs analysis of concrete, hot mix asphalt, PVAECC and PPECC overlay systems

Costs	HMA	Concrete	PVAECC	PPECC
Total Agency	6.91	9.23	6.98	5.32
User	109.99	88.77	52.98	52.98
Environmental	0.66	0.88	0.57	0.59
Total	117.56	98.87	60.53	58.89

6. Conclusions

This paper presents an integration of experimental investigation and finite element analysis of different overlay systems from the life cycle point of view. The results of this study show that PPECC meet the required material properties for pavement applications in terms of compressive strength and flexural strength, according to Federal Highway Administration manual [12]. Tests results have proved that PPECC have a better fatigue resistance than concrete as well, proving that polypropylene fibers may be used as reinforcement of ECC for pavement application. In addition, the cracking pattern of PPECC may be a very promising parameter to enhanced material durability due to the tiny crack widths developed under monotonic and fatigue loading. This may also contribute to extend the service life and sustainability of rehabilitated pavement systems.

Life cycle cost analysis suggests that PPECC may result in a significant economic advantage over PVAECC, concrete and hot mix asphalt overlays, especially when agency costs are evaluated. Although the initial production costs of PVAECC and PPECC are higher than cost of concrete overlays, the use of ECC allows a reduction in material volume due to the reduced thickness required to ensure the overlay performance. At the same time, ECC may extend the service life of the pavement, reducing global costs and improving the sustainability performance. The resulting life cycle model may be tool for decision makers to evaluate pavement infrastructure projects from a long term perspective. In this sense, PPECC might be a feasible alternative material for pavement rehabilitation techniques.

7. References

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