Life Cycle Cost Assessment of Engineered Cementitious Composite (ECC) Precast Pavement in Singapore

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Abstract

Heavier trafficked road network in Singapore leads to some concerns about extended road closure during rigid pavement maintenance/rehabilitation process. A quicker pavement repair method using precast panels is potentially good alternative. This paper focuses on the life cycle cost analysis (LCCA) of a proposed precast concrete pavement (PCP) made of Engineered Cementitious Composite (ECC). A precast slab 5.0m x 3.6m x 0.22m is proposed as an alternative for maintenance and rehabilitation of Singapore rigid pavement. With the help of finite element method, this proposed slab is proved to withstand well construction load and has a lifetime of at least 40 years in Singapore heavy traffic condition. User delay cost due to lane closure, one of the key components of LCCA, is estimated with the help of the state of the art microscopic simulation tool for a selected case study area in Singapore. The LCC results show that initial cost contributes mainly on the total cost of ECC PCP whereas user cost is the most significant component in LCC of cast-in-place concrete pavement. ECC PCP can be a very economical solution in term of LCC for concrete pavement rehabilitation and maintenance depends on construction site locations and traffic volume.

Introduction

Heavier trafficked road network in Singapore leads to some concerns about extended road closure during rigid pavement maintenance/rehabilitation process. A quicker pavement repair method using precast panels is potentially good alternative. To determine whether precast pavement is an economical solution, this paper will focus on evaluating the life cycle cost of a proposed precast concrete pavement (PCP) made of Engineered Cementitious Composite (ECC). The life cycle cost assessment (LCCA) takes into account the entire life cycle of the ECC precast pavement from resource extraction, pre-fabrication, transportation, construction, maintenance, to demolition and recycling in Singapore context.

Like many other PCP, PCP made of ECC has the key advantage of minimizing delay to open to traffic and reduces user delay cost. Moreover, owing to the properties of ECC, a unique high performance fiber-reinforced concrete featuring ultra-high ductility and extreme damage tolerance, the resulting pavement is expected to have a much extended service life. It is still unclear whether longer service life and lower user delay cost outweigh the initial cost.

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This paper will firstly propose a high performance PCP slabs using ECC. A powerful traffic microscopic simulation for a case study area in Singapore will be used to forecast user delay cost due to pavement maintenance and rehabilitation. A LCCA platform will be used to evaluate life cycle cost of ECC precast pavement in Singapore.

Precast pavement made of ECC (ECC PCP) as an alternative

Brief introduction about precast concrete pavement (PCP)

PCP systems are the systems that "are essentially fabricated or assembled off-site, transported to the project site and installed on a prepared foundation" (Tayabji, 2011). PCP has been tested, improved and used widely for rapid intermittent repair and rehabilitation in Japan and United States of America (USA) in the last decades. In Japan, after improving the load transfer at joints and support condition, PCP has been used more intensive in the past 20 years (>90 000 m2), and their "very long service life can be expected" (Nishizawa, et al.) (Private communication, Jan 2012). Installed PCP in USA also shows very high on-site performance as CIP concrete (Tayabji, et al., 2011).

The process "fabricated off-site" of PCP will provide a durable and the best quality control concrete. Moreover, concrete curing process is well controlled in plant, therefore early age failures of concrete pavement like cracking due to high temperature change during this curing process (where concrete exhibits shrinkage and expansion) can be eliminated. Because there is no need for on-site concrete curing, weather condition has less impact and delay to open to traffic is minimized.

Engineered Cementitious Composite (ECC) (NguyenDinh, et al., 2014)

Engineered Cementitious Composite (ECC) is a unique type of high performance fiber-reinforced cementitious composite. The most distinctive characteristic of ECC is high tensile ductility which is achieved by the formation of multiple microcracks. These cracks, which carry increasing load after formation, allow the material to exhibit strain-hardening similar to ductile metals (Li, et al., 2004). Figure 1 illustrates a typical uniaxial tensile stress-strain curve as well as crack width development of ECC. After matrix first cracking (at strain about 0.01%), early crack keeps opening to about 60-80μm at about 1% strain. Further loading beyond this point, the straining is accommodated through the formation of additional multiple microcracks. The tensile strain capacity of ECC is several hundred times that of normal concrete. The crack width; however, is seized at a steady value of 60-80μm. After saturation of multiple microcracks, ECC fails with a single localized crack and increased deformation (Li, et al., 2004) (Nawy, 2008).

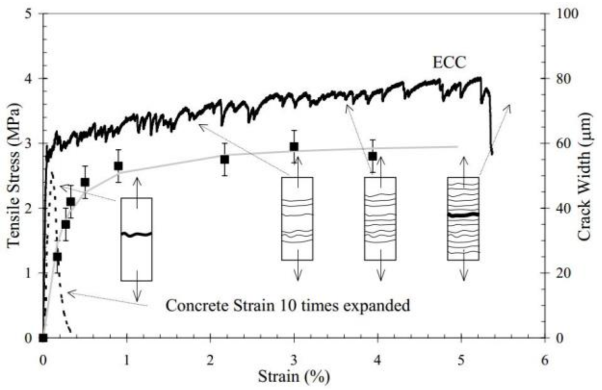


Figure 1: representative uniaxial tensile stress-strain curve and crack width development of ECC material (Li, et al., 2004)

The compression strength of ECC is quite similar to normal or high strength concrete (30MPa to 90MPa). Modulus of elasticity of ECC is about 20-25GPa, which is slightly lower than that of normal concrete due to the absence of coarse aggregate in ECC mix design. The compressive strain capacity, on the other hand, is slightly higher than that of normal concrete (0.45-0.65%). ECC exhibits a very high flexural strength (modulus of rupture or MOR). A MOR of 10-15MPa is "easily achievable and accompanied by a large extent of deflection hardening regime" by altering the brittle failure mode into a ductile failure mode under bending due to the high ductility of ECC material (Nawy, 2008).

ECC used for analysis in this paper is the ECC developed at Nanyang Technological University (NTU), Singapore using materials that are locally available. The main ingredients are cement, ground granulated blast-furnace slag (GGBS), fine sieved river-sand, 12mm PVA (Polyvinyl alcohol) fibers and water. The mix design proportion of the ECC used is listed in the Table 1. This ECC material has a Young modulus of 20GPa, a flexural strength of 12MPa, compressive strength of 55MPa and a bending fatigue resistance as shown in Figure 2.

Table 1: ECC Mix Design Proportions by Weight

Mix designation	Cement	Sand	GGBS	Water	Superplasticizer	Fiber(Vol %)
ECC in Singapore	1.0	0.5	1.5	0.75	0.004	2

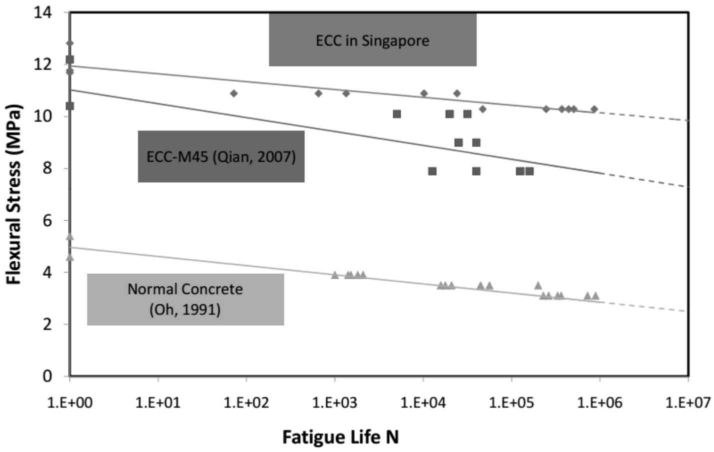


Figure 2: Fatigue response of ECC and normal concrete under four-point bending (Courtesy of Mr. Jishen Qiu, NTU)

Proposed ECC PCP structure

Conventional rigid pavement (PCC) structure in Singapore according to standard details of road elements (LTA, 2014) has thickness of 225mm and slab width of 3.6m. These concrete slab are laid on a 200mm thick layer of graded granite which is supported by a subgrade layer. For replacement of this rigid pavement (PCC) with a precast pavement, the support layers are kept unchanged. The concrete slab will be replaced by a precast slab with dimensions of 220mm thick, 3.6 m wide and 5m long. 5mm thinner precast slab compared to standard 225 slab is meant for bedding and levelling works. The performance of proposed precast slab will be evaluated under traffic load in addition to self-weight and temperature load and construction load (slab lifting during construction).

On Singapore heavy traffic roads, average daily traffic (ADT) is about 50,000-60,000 which converted to about 4.5 – 7.5 million ESALs per year (equivalent single axle load – 80 kN based on ASHTO) (NguyenDinh, et al., 2014). With assumption of 80% traffic distribution in the design lane and pavement lifetime of 40 years, the requirement ESALs is 7.5x40x80% = 240 million.

For temperature loads, ECC is assumed to have similar thermal behaviours to conventional concrete. According to (Lau, et al., 1994), the temperature gradients for day time for 200mm thick concrete pavement in Singapore is up to 0.13K/mm at the depth of 8cm and reduces to 0.09K/mm at 20cm and it is -0.035K/mm at night time.

The performance of proposed precast slab is evaluated with the help of numerical method (FEM - finite element method) which is built in ANSYS. The FEM includes a simplified one concrete slab which is supported by 200mm of grade granite and then a 500mm subgrade material. A calibrated non-linear ECC material model (NguyenDinh, et al., 2014) is one of the most important input of the FEM. Boundary conditions involve a fixed support applied at the bottom of subgrade layer and a small enough elastic support applied at 4 sides of the model only for FEM convergence purpose.

There are 4 combinations of wheel loading location and thermal loading as listed in the Table 2. With a safety factor of 1.2, the wheel load is then 48 kN. Assuming that there is a good load transfer efficiency (LTE) (at least 75%) between slabs. Based on the relation between load applied at the edge of the slab and LTE using FE models, when LTE is 75%, the actual load applied on loaded slab is 32.5kN.

Table 2: Maximum flexure stresses in slab under different load cases

Loading case	Mechanical loading		Thermal loading	Maximum flexure Stress (MPa)
	Loading point	Load value	Warping(W)/curling(C)	
Case 1	Center	48.0kN	W	2.93
Case 2	Edge	32.5kN	C	1.05
Case 3	Center	48.0kN	C	0.52
Case 4	Edge	32.5kN	W	2.73

Table 2 shows that the maximum equivalent stresses in the slab actuated by traffic load, slab self-weight and temperate are clearly higher in day time than in night time. However, the maximum equivalent stress of 2.93MPa is far lower than ECC fatigue strength (Figure 2). The proposed pavement using ECC is unlikely failed fatigue performance. Therefore the pavement lifetime of 40 years or more is expected.

In construction phase of precast pavement, the slabs have to withstand their own weight as well as dynamic lifting load. Tayabji in (Tayabji, et al., 2013) recommends that with four-point lifting, the impact factor of lifting stress should be 1.5. In this paper, the load apply is 2 times of the slab self-weight as a conservative approach. Four lifting points which are located at 1m offset from both longitudinal and transversal edges are used for the proposed slab of 5mx3.6m. The flexural stress during slab lifting by self-weight is computed with FEM and shown in Table 3. It is clear that the flexure stress values are far below the maximum strength.

Table 3: Maximum flexure stresses in slab under lifting load

	Equivalent flexure stress (MPa)	
	at top surface	at bottom surface
5.0m x 3.6m x 0.22m ECC PCP	0.82	1.00

In summary, the proposed 5.0m x 3.6m x 0.22m precast slab made of ECC can withstand well construction load and it can have a lifetime at least 40 years or much more under heavy trafficked road in Singapore.

Life cycle cost analysis (LCCA) of pavement alternatives

Introduction

Life Cycle Cost Analysis (LCCA) is an analytical tool to evaluate the economic performance of alternative pavement investments over a defined analysis period (Swei, et al., 2014). In pavement engineering, the LCCA takes into account the entire life cycle of the ECC precast pavement from resource extraction, pre-fabrication, transportation, construction, maintenance, to demolition and recycling (Smith & Walls III, 1998). Since 1960s, the LCCA has been widely used in the US (Harbuck, 2009) and it has been conducted in nearly 80% US state highway agencies to evaluate pavement alternatives (Chan, et al., 2008).

Many inputs are required and they can be treated as deterministic or probabilistic value in LCCA procedure. In the study (Swei, et al., 2014), the probabilistic LCCA is conducted to evaluate three alternative concrete pavements to conclude that the initial unit-cost is the main variation across all scenarios. Other study (Scheving, 2011) on LCCA between asphalt and concrete pavement has shown that discount rate, asphalt price, concrete price have highest impact on the whole LCCA compared to other parameters such as rehabilitation cost and user delay cost. Therefore, depend on types of pavement investment, the purpose of LCCA and specific condition, the impact of each input can be varied and evaluated differently.

The main cost components could be categorized into four groups (Scheving, 2011): initial construction costs (land procurement, design, equipment costs, material costs, workers salary, etc.), agencies costs (maintenance, rehabilitation cost, workers salary, etc.), and user costs (vehicles operating cost, time delay costs, accidents costs, etc.) and environmental costs (pollution, noise, etc.). General LCCA methodology is to sum up the monetary value of all benefit and cost throughout the analysis period. This could be achieved by performing different economic evaluation, which most common are the Net Present Worth (NPW) or Net Present Value (NPV), Cost-Benefit Ratio (B/C), Equivalent Uniform Annual Cost (EUAC), and Internal Rate of Return (IRR) (Harbuck, 2009). Depend on analysis level and the uncertainty of input parameters, the choice of appropriate method can be different. For pavement alternative evaluation, NPV is considered the most suitable method (Harbuck, 2009).

The Net Present Value (NPV) of two alternative pavements can be calculated using the equation (1) follows:

$$NPV = Initial\_\cos t + \sum_{i=1}^{n} \frac{user\_\cos t(i)}{(1+r)^t} + \sum_{j=1}^{n} \frac{rehbilitation\_\cos t(j)}{(1+r)^t} \qquad (1)$$

Where: t is the year^th of rehabilitation process (minor or major) after construction, i is the number of user cost, j is the number of rehabilitation and r is the discount rate (in Singapore context, discount rate $r=5\%$ (LTA, 2010))

Activity timing of alternative pavements

The selection of analysis period depends on pavement design life but they are two different concepts. The design life of concrete pavement usually in 20 or 25 years while ECC PCP with higher durability can last 40 years or longer (Zhang, et al., 2010). At the end of design life, pavement will be rehabilitated to extend service life out of 50 years (Caltrans, 2007), (McLawhorn, 2004).The analysis period is longer than design life of pavement and should be long enough to include at least one major rehabilitation for each alternative. Therefore, 50 year time period is chosen. In the middle of their service life, minor and major maintenance are required to deal with cracking or joint damage. Detail activity timing is shown in Figure 3

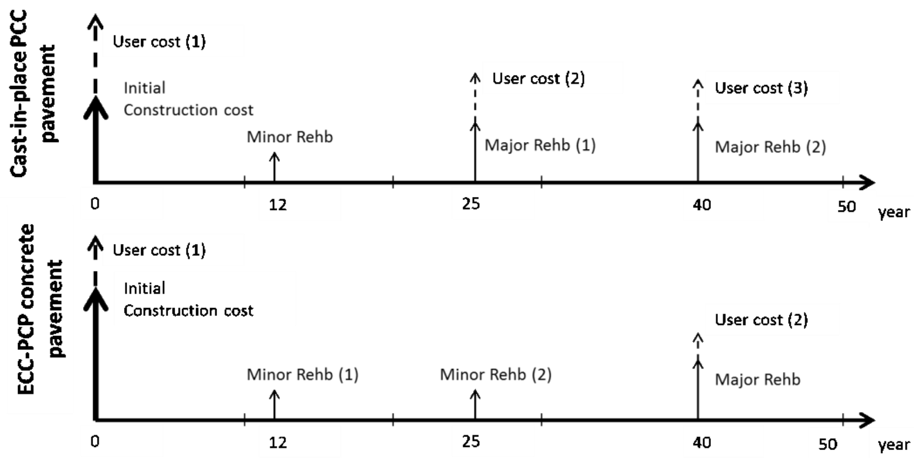


Figure 3: Activity schedule of alternative pavements

From the activity schedule of both pavement alternatives, the initial cost, rehabilitation cost and user cost are the most important elements in LCCA which differentiate two options.

The initial construction cost includes all materials, equipment, staff salaries, etc. required for construction of the concrete pavement. This cost for ECC PCP is higher than that of conventional cast-in-place rigid pavement due to the more complex procedure in construction and also more expensive concrete material. The maintenance and rehabilitation comprises similar cost components as initial construction cost but they are much lower. ECC PCP requires two minor rehabilitations in 12th, 25th and one major rehabilitations in 40th year, while for cast-in-place rigid pavement two major rehabilitations (25th and 40th year) and one minor rehabilitation (12th year) have to be taken into account. User cost is caused by initial construction and major rehabilitation (Figure 3).

User delay cost

User delay cost represents the negative impact of roadwork on travellers by monetization of delay. The impact of work zone can be either an inconvenience when traffic demand is relatively low or significant when the work zone capacity is not able to meet the demand (Smith & Walls III, 1998). Due to this uncertainty and the lack of available standard on user cost calculation, the transportation agencies are hesitant to include this cost into LCCA (Salem, et al., 2013). In the meanwhile, some state transportation agencies in US and Canada by their experiences have simply weighted user cost as 10% of agency cost (Indiana DOT), 50-75% of agency costs (New Jersey DOT) (Salem, et al., 2013). However, the user delay cost contributes mainly on the cost difference between two pavement alternatives (ECC PCP and cast-in-place rigid pavement). User delay cost includes three components:

- Time delay costs. The cost caused by time increasing due to reduced speed or rerouting to other routes. This cost is one of the most controversial parameter as it is difficult to calculate by adding monetary value on delay time of passengers and travellers (Smith & Walls III, 1998). Basically, the time delay costs is calculated by multiplying the estimated delays to of all types of vehicles (car, bus, HGV, LGV) caused by the work zone by the unit cost ($/hr) of travel time.
- Vehicle operating costs. The cost resulted from fuel consumption, tyre wear and other costs related to vehicle operation and maintenance.
- Accident costs. The cost caused by damages, injuries and fatalities.

In general, the delay caused by roadwork can be defined as the difference of travel time between the normal condition without work zones and longer travel time in work zones. Three methods normally used to estimate delay cost are macroscopic analytical approaches, macroscopic simulation approaches and microscopic simulation approaches (Weng & Meng, 2013). In this study the traffic microscopic simulation VISSIM will be used to estimate the travel delay due to roadwork. This commercial tool is able to deliver reliable results.

Traffic simulation using VISSIM

Microscopic simulation models are becoming important tools in modelling of transport systems. The main reason is that simulation is faster, safer and less expensive than field implementation and testing. First released in 1992, VISSIM is a microscopic, time step and behaviour based simulation model developed to model urban traffic and public transit operations. The tool has been used worldwide to simulate traffic control, driving behaviour and develop many scenarios for traffic operation. The microscopic simulation requires huge amount of data (network data, traffic count, signal control, travel time and speed, etc) as well as an adequate calibration and validation process. Regarding to roadwork and incident simulation, many studies have used VISSIM as a reliable platform, generating plausible results for evaluation (Martin, et al., 2011). In Singapore context, VISSIM has been already used to simulate Singapore Queenstown network (S.Y. & H.C, 2007), SCATS operation along Bouna Vista street (Liu, 2013), bus priority schemes in the city (Quing, 2013), traffic light control for multi-junctions (Xian, 2014), etc.

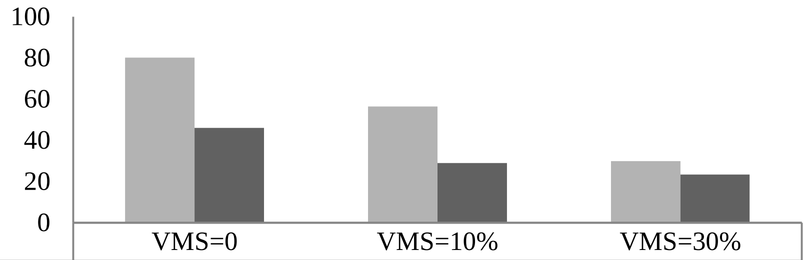
The purpose of this traffic simulation is to estimate user cost between two concrete pavements: ECC PCP and cast-in-place concrete pavement. Clementi network as shown in Appendix Figure 1 is chosen as a case study the roadwork is described as following:

- Work zone length = 50m at the intersection.
- Three-lane urban road in Clementi area and one lane will be close for rehabilitation.

- Vehicle mix: 85% cars, 10% buses and 5% trucks from video recording.
- Traffic demand collected from Land Transport Authority (LTA).

In addition to common circumstance above, certain assumptions are needed for each pavement alternatives. Firstly, the production rate per lane closure is about 15 to 20 repair locations and 122-183m according to (Tayabji, et al., 2013). The 50 meter lane ECC PCP is expected to be constructed in maximum 2 night (10 pm-6 am) lane closures with no traffic diversion strategy. Secondly, cast-in-place rigid pavement requires about 10 days period for construction and concrete curing as a common practise in Singapore (LTA, personal communication, Dec 2012) and there is traffic diversion (VMS) in three levels 0, 10% and 30%. For calibration and validation purposes, travel time, travel speed and queue length are collected from field measurement using video recording and “floating car method” (running a taxi several times during peak hours).

The roadwork is simulated by blocking one lane at the intersection approach for rehabilitation. Delay is measured for all vehicles passing through the construction work at the intersections (coded 4123 and 4105 according to LTA, see Appendix Figure 1). In case of ECC PCP, the delay is minimized due to lowest traffic volume at midnight construction time, which is in contradiction with significant delay for cast-in-place pavement. Therefore the traffic simulation will be used only to simulate traffic delay in the latter pavement alternative. Travel delay at two intersections is shown in Figure 4.



	VMS=0	VMS=10%	VMS=30%
Int_4123	80.18	56.48	29.90
Int_4105	45.99	28.97	23.38

Figure 4: Travel time lost due to construction at intersection_4123 and 4105

Depending on location and level of VMS, travel delay is different. At intersection_4123 all three lanes are used for all types of vehicles, whereas at intersection_4105 one left lane is dedicated to buses. Therefore, closure at bus lane will cause less impact to traffic flow or lower travel delay compared to another case. It is well noted that when the level of VMS = 0, the travel delay is most significant.

The value of travel time and the delay cost

The unit value of time is quite different in various locations. In the US (Smith & Walls III, 1998) this value varies according to vehicle class, ranging from 11.58USD/h (16.2SGD/h) for passenger vehicles to 18.54-22.32USD/h (26-32.24SGD/h) for single-unit and combination trucks. In different states, the value of time also varies in a certain range (Salem, et al., 2013). According to (Scheving, 2011) in Iceland, the average value of the time for passenger vehicle was calculated to be 1695Kr/h (13.25USD/h or 18.89SGD/h), for trucks single unit and combination 2,204Kr/h (17.23USD/h or 24.56SGD/h). This value is similar to that in the US. In Sweden, the hourly time value has been usually assumed to be 10–15EUR (11.4-17.1USD/h or 16-23.94SGD/h) for passenger cars and 20–30EUR (22.8-34.2USD/h or 32-

47.88SGD/h) for heavy vehicles (Mirzadeh, et al., 2014). It is noticed that the value of travel time of trucks is always higher than that of passenger vehicles (1.5 to 2 times). The value of goods transported in these trucks is considered to be the main reason for this difference.

Travel time cost is dependent on a few factors: the number of each type of vehicle, the average occupancy rate of each type of vehicle and the average salary of occupants in each type of vehicle (Pawitra, 2002). There are mainly three types of vehicle: cars, buses and trucks (HGV and LGV). The average car occupancy in Singapore is 1.7, while for buses the maximum carrying capacity for single decker is about 85, double decker is 131 and articulated bus is 143 (with seating is about 50, 90 and 53 respectively) (Menon & Kuang, 2006). In case of goods vehicles, this value is 1.62 (Pawitra, 2002)

The cost of travel time is calculated by the monetary loss of passengers going through the roadwork in one hour (Pawitra, 2002).

$$T = PV_{jk} \times AvSAL_j \tag{2}$$

$$PV_{jk} = VT_{jk} \times OCC_{jk} \tag{3}$$

$$AvSAL_j = \sum_{h=1}^{11} p_{ij} \times MGW_h \tag{4}$$

where:
T = Value of Travel Time during hour k
PV_{jk} = Total number of occupants in vehicle type j during hour k
VT_{jk} = Number of each type of vehicle type j during hour k
OCC_{jk} = Average occupancy of vehicle type j during hour k
$AvSAL_j$ = Average salary of occupant in each type of vehicle
p_{jh} = Proportion of travellers in occupation h in vehicle type j
MGW_h = Mean Gross Wage of occupation h

Types of occupation (MOM, 2014): (1) Managers & Administrators, (2) Working Proprietors, (3) Professionals, (4) Associate Professional & Technicians, (5) Clerical support workers, (6) Service & Sales Workers, (7) Craftsmen & Related Trades Workers, (8) Plan and Machine Operators & Assemblers, (9) Cleaners, Laborers & Related Workers, (10) Others, and (11) Unemployed. The Mean Gross Wage and number of employment of each occupation are presented at Table 4

Table 4: Mean Gross Wage and number of employment of each occupation

	1	2	3	4	5	6	7	8	9	10	11
Mean Gross Wage (SGD)	10,000	3,250	6,974	4,060	2,630	2,100	2,495	1,976	1,265		0
Employment	349,052	156,352	372,252	646,503	421,607	412,707	238,507	302,707	322,307	227,107	81,700

The p_{jh} value is collected from (Pawitra, 2002), in which 4 types of travelers were divided by salary range: below \$2000, \$2000-\$4999, \$5000 to over and no salary. The following table shows the *AvSAL* calculated from p_{jh} and MGW_h data. However, this calculation has not taken the value of goods in the trucks into account, which is different from the fact that the unit cost of truck is always higher than that of cars from 1.5-2 times. Therefore, *AvSAL* of HGV and LGV has to be recalculated accordingly by 1.5 times of cars value.

Table 5: Average delay cost of each type of vehicle per hour

	Cars	Buses	HGV	LGV
Calculated (SGD/h/person)	30.7	17.5	13.4	13.4
Recalculated (SGD/h/veh)	30.7	17.5	46.05	46.05

In total, travel delay cost at two intersections is estimated based on the travel delay and unit cost of travel then being aggregated into price per m^2 as shown in the table below. For the period of 10 days, the travel delay cost for construction without traffic diversion of cast-in-place concrete pavement is 891.2 and 511.1 (SGD/m^2) respectively.

Table 6: Travel delay cost estimation

Location	VMS=0		VMS=10%		VMS=30%	
	delay (h)	delay cost (SGD/m^2)	delay (h)	delay cost (SGD/m^2)	delay (h)	delay cost (SGD/m^2)
Int_4123	80.18	891.2	56.48	627.74	29.90	332.3
Int_4105	45.99	511.1	28.97	322.03	23.38	259.8

Initial cost and rehabilitation cost

The full replacement of 50m short stretch concrete slab using cast-in-place method in Singapore cost roughly 165SGD/m^2 which is about 30,000SGD for one lane of 50m. Data about detail rehabilitation and maintenance costs of conventional rigid pavement in Singapore is not yet accessible; therefore CANPav™ free website tool (Cement Association of Canada, 2015) is used as a reference. With the construction site of 50mx3.6m, the costs are summarized at the Appendix Table 1. The total cost for maintenance and rehabilitation in the period of 50 years is approximately 1,381CAD (1,450SGD or 1,050USD).

With more complex procedures in construction, estimated cost for precast pavement made of ECC is 400SGD/m^2 which is equivalent to total 72,000SGD for one lane of 50m. This cost takes into account the related components of workmanships, materials and machineries/equipment.

Using highly durable material, ECC PCP is expected to have much lower maintenance and rehabilitation cost. However, this cost is taken the same as cast-in-place method as a conservative approach.

LCCA Summary

All the costs of alternatives pavements during 50 years periods are listed in Appendix Table 1, Appendix Table 2 and Appendix Table 3. The Net Present Value (NPV) of those costs are summarised at the Figure 5 and Figure 6 as follows.

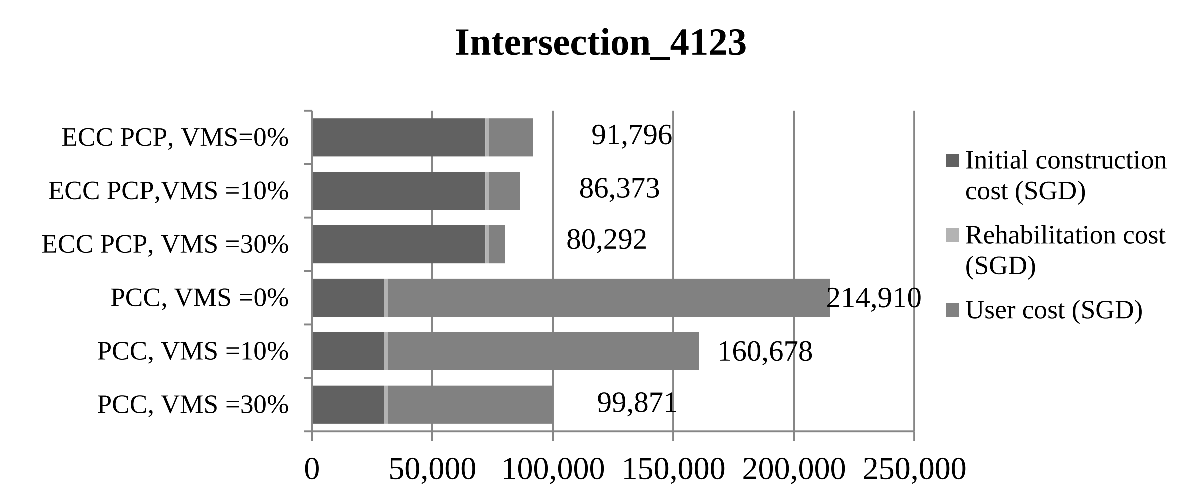


Figure 5: LCC of PCP and PCC at Intersection_4123

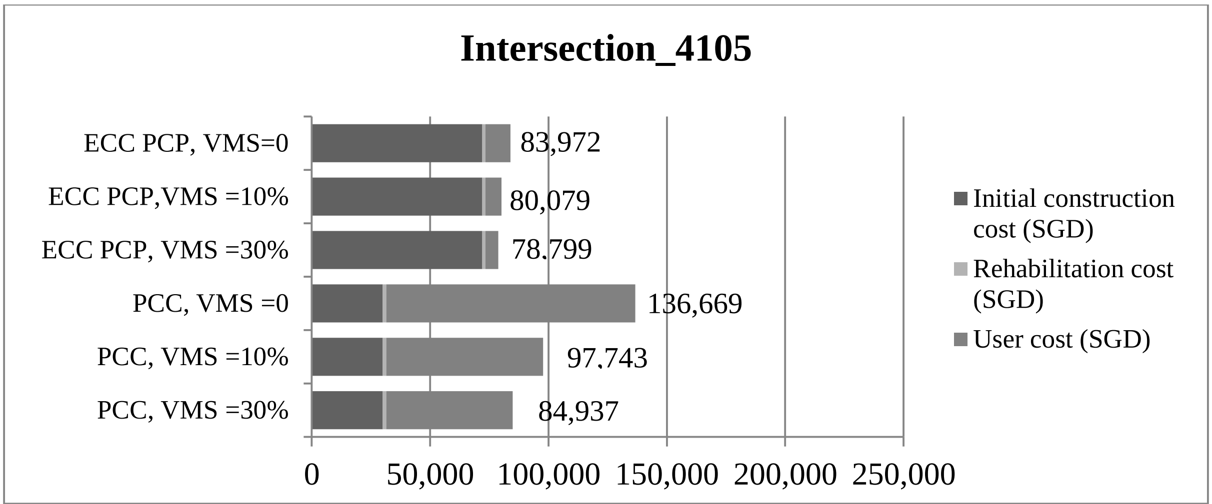


Figure 6: LCC of PCP and PCC at Intersection_4105

Figure 5 and Figure 6 illustrate that the initial cost contributes mainly on the total cost of ECC PCP whereas user cost is the most significant component in LCC of cast-in-place PCC. The results show that LCC varies with construction site locations and traffic diversion ratio (VMS). The more VMS is, the less LCC for both alternatives is. The user cost is reduced to a half when VMS changes from 0 to 30% at the Intersection_4105 and this user cost deduction is more than 2.5 times at the another intersection. However, the PCP alternative has much less dependence on locations and traffic condition. The travel delay cost in PCP occupies from about 4.5% to 15% of total LCC, while with cast-in-place method this value is 63%-85%. In general, with the assumption the construction delay of cast-in-place method is 10 days, the LCC of ECC PCP is still lower than its competitor. The difference in LCC can be as high as 2.5 times in the case of VMS=0. However, when VMS=30% the LCC of the two alternatives are very close to balance.

Conclusion

The study focussed on LCCA of two pavement alternatives cast-in-place concrete pavement and PCP made of ECC.

A precast slab 5.0m x 3.6m x 0.22m was proposed as an alternative for maintenance and rehabilitation of Singapore rigid pavement. With the help of finite element method, this proposed slab is proved to withstand well construction load and has a lifetime of at least 40 years in Singapore heavy traffic condition.

Like many other PCP, PCP made of ECC has the key advantage of minimizing delay to open to traffic and reduces user delay cost, one of the most important components in LCCA. With the help of the state of the art microscopic simulation tool, user delay cost is estimated for a selected case study area in Singapore. The results show that initial cost contributes mainly on the total cost of ECC PCP whereas user cost is the most significant component in LCC of cast-in-place concrete pavement. ECC PCP has higher initial construction cost however due to rapid installation, its user cost is far less than the cast-in-place candidate. In the case study, the LCC of ECC PCP is lower than its competitor. The difference in LCC can be as high as 2.5 times in the case of VMS=0. However, when VMS=30% the LCC of the two alternatives are very close to balance. The results show that LCC varies with construction site locations and traffic diversion ratio (VMS), which translates to traffic volume.

In conclusion, PCP made of ECC can be a very economical solution in term of LCC for concrete pavement rehabilitation and maintenance depends on construction site locations and traffic volume.

Acknowledgements

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Appendix

Appendix Table 1: Maintenance and rehabilitation of PCC

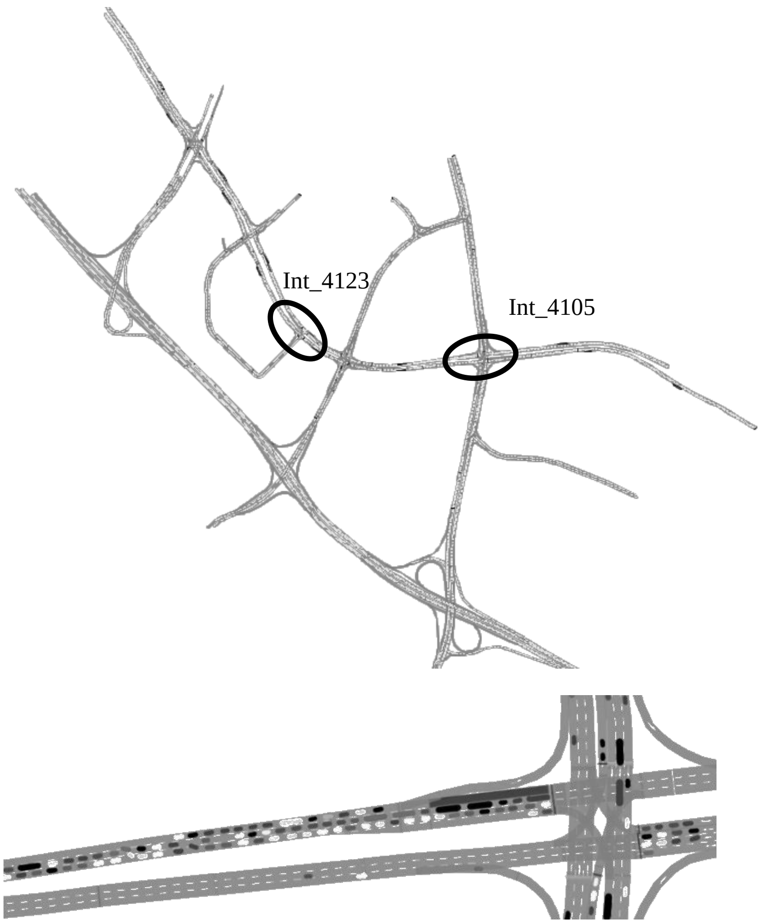
YEARS (after construction)	Activity	Amount		Quantity		Price/Unit of Quantity (SGD)	Cost (SGD)	NPV (SGD)
12	Reseal Joints	20	% length	8	m	$10.60	$85	$48
25	Partial Depth PCC Repair	5	% area	9	m²	$132.50	$1,193	$352
25	Full Depth PCC Repair	10	% area	18	m	$106.00	$1,908	$564
25	Reseal Joints	25	% length	10	m	$10.60	$106	$32
40	Partial Depth PCC Repair	5	% area	9	m²	$132.50	$1,193	$170
40	Full Depth PCC Repair	15	% area	27	m²	$106.00	$2,862	$407
40	Reseal Joints	25	% length	10	m	$10.60	$106	$15
50	Residual Value						$1,386	$121
Total M & R Cost							$6,065	$1,450

Appendix Table 2: LCCA of pavement alternative at Intersection_4123

	Initial construction cost (SGD)	Rehabilitation cost (SGD)	User cost (SGD)		
			VMS = 0 %	VMS = 10 %	VMS = 30 %
Cast-in-place PCC	30,000	1,450	183,460	129,228	68,421
ECC PCP	72,000	1,450	12,231	8,615	4,561

Appendix Table 3: LCCA of pavement alternative at Intersection_4105

	Initial construction cost (SGD)	Rehabilitation cost (SGD)	User cost (SGD)		
			VMS = 0 %	VMS = 10 %	VMS = 30 %
Cast-in-place PCC	30,000	1,450	105,219	66,293	53,487
ECC PCP	72,000	1,450	7,015	4,420	3,566



Appendix Figure 1: Clementi network and detail simulation of roadwork at intersection

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