

Life Cycle Assessment-based Feasibility Study of Spall Damage Rehabilitation using 3D Printing Technology

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Spall damage to concrete pavement is often caused by heavy vehicles or low-quality construction materials. Spall damage occurs when loads from heavy vehicles are repeatedly applied to the joints between concrete plates, or from internal pressure caused by vapor evaporating from wet aggregates in hardened concrete. Since the damage worsens if it is not promptly addressed, the repairs must be made soon after the damage occurs. The most common existing spall repair method involves placing and curing fresh concrete. According to the unified facilities criteria published by the US Department of Defense, to properly cure a high-quality concrete patch, vehicles must be detoured around the job site for at least seven days. This could cause indirect losses of up to $140,000, based on information provided by the US DoT. This study proposes an alternative means of rehabilitating spall damage that uses the advantages of 3D printing technology. This proposed method involves pre-fabricating a 3D concrete patch that can be inserted into a spall; the result is that the gap from the spall damage is filled faster than it would be if the existing spall repair method (partial-depth repair) is employed. This research also presents results from the Economic Input-Output Life Cycle Assessment (EIO-LCA) that compares the existing and proposed spall repair methods and investigates the feasibility of the more rapid spall repair method.

Key Words: Feasibility, Spall Damage Repair, 3D Printer, Life Cycle Assessment

Introduction

Minor damage to the surface of concrete pavement (such as surface defects, cracks, and spalls) occurs frequently (US DoT, 2003). These minor issues and other surface defects in the road surface do not usually cause substantial inconvenience to drivers, especially since cracks can quickly be repaired with epoxy-based fillers (Caltrans, 2015). However, spall damage repair via existing techniques requires that vehicles be detoured around job sites, often for significant periods of time. With regards to spall damage, the partial-depth repair method is the most commonly applied fix, as the results are more stable and last longer than those produced by the available alternatives (Basham et al., 2001). This repair process begins by separating the damaged area from the undamaged pavement via a concrete sawing machine. The damaged concrete is then broken up and removed by a chipping machine. Before pouring fresh concrete into the cleaned area, bonding agents are applied to increase the bond strength between the new patch produced by the fresh concrete and the existing concrete substrate. Once the fresh concrete is poured into the area where the damage was removed, white-pigmented curing compounds are applied to the surface of the replaced area; this prevents concrete shrinkage. The edges between the undamaged and damaged areas are then filled in with a waterproofing agent to prevent water infiltration (FHWA, 1994).

Drying shrinkage occurs if the concrete contains water after the hydration reaction between the cement and water is completed. The remaining water evaporates from the area where the concrete is cured, resulting in a reduction of the entire volume of concrete the size of the vapor evaporation. Drying shrinkage can lower the elevation of the existing area, creating height differences along the edges of the repaired and existing ranges. The edges of the undamaged concrete can easily be damaged by traffic because the loads repeatedly generated by moving vehicles are concentrated in that area. In contrast, if it rains while the fresh concrete is curing, the material will absorb the rain and sulfates leaked from vehicles. In such cases, the quality of the cured concrete will be poor (Chindaprasirt et al., 2004). The Unified Facilities Criteria (UFC) handbook issued by the US Department of Defense in 2001 recommends that construction industry practitioners wait for at least seven days for complete curing after the curing compound is applied to the top of fresh concrete (Basham et al., 2001).

The existing research on this topic has focused more on repair materials than repair methods. The primary purpose of this study is to compare the results obtained from the most commonly used spall repair method with those produced by the proposed process, which uses a 3D printer; to do so, the Economic Input-Output Life Cycle Assessment (EIO-LCA) was employed to assess this 3D printing method in terms of its social, economic, and environmental aspects. Many studies have explored using 3D concrete printers to “print out” concrete houses, such as the contour crafting system developed by Behrokh Khoshnevis at the University of Southern California (Khoshnevis and Bekey, 2002). However, it is not currently possible to produce a concrete segment with a 1 mm level of precision using this type of printer. Therefore, contour crafting cannot be used to produce the type of concrete segments used to fill spall damage.

Yeon and Kang suggested a rapid spall repair method using 3D printing technology to reduce the time needed for roadblocks (Yeon and Kang, 2017). This spall repair method involves: (1) taking pictures of the spall from various camera positions, (2) creating a 3D spall model using photogrammetry, (3) printing a 3D model for use as a concrete form in which to cure fresh concrete, (4) pouring concrete into the concrete mold, (5) curing the concrete segment tailored to fill the spall, (6) cleaning the surface of the spall damage with an air compressor to improve the adhesion, and (7) inserting the prefabricated concrete segment into the spall, after an epoxy-resin adhesive is applied on top of the spall’s surface (see Fig. 1).

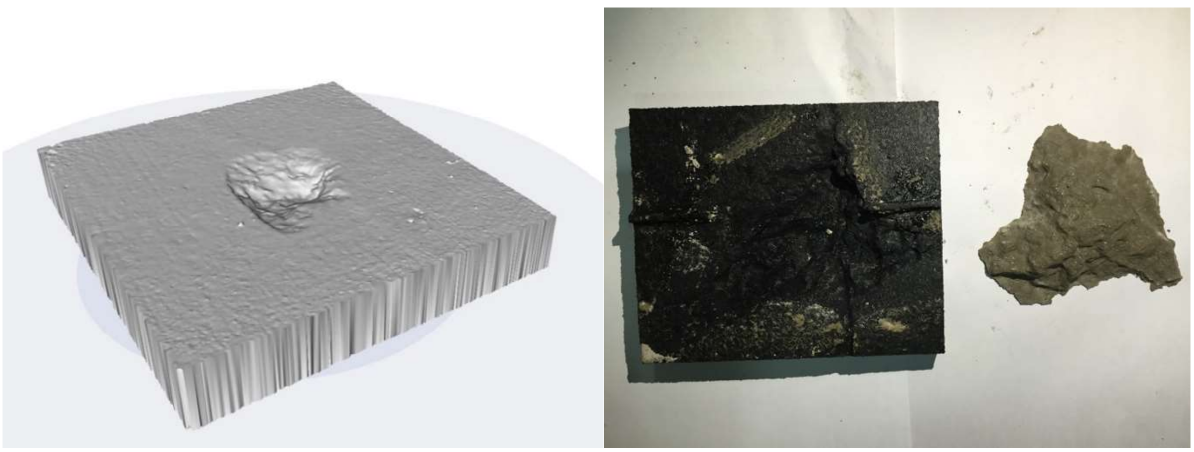

Figure 1: Rapid spall repair method using 3D printing technology (Yeon and Kang, 2017).

Yeon and Kang also provided daily time-related vehicle depreciation information related to the traditional spall repair method. The researchers claimed that their proposed method would allow for spall damage repair with almost no road blockage, because several hours were sufficient to complete the process (Yeon and Kang, 2017). However, the study did not explain in detail the potential impacts of this repair method. Hence, it was necessary to conduct a systematic assessment to determine the effects it would have. In addition, the proposed and existing methods had to be compared. This study selected the Life Cycle Assessment (LCA) process to assess and compare these two spall repair methods.

LCA can generally be summarized in four steps (Guinee, 2002). First, an appropriate scope and set of goals must be defined to determine the reference inputs, system functions and boundaries, assumptions, impact assessment, and analysis method. Second, an inventory analysis should be conducted that quantifies inputs such as raw materials, energy use, etc. Third, an impact analysis must be completed to estimate the economic, social, and environmental implications. Finally, the data must be interpreted to identify areas where improvements can be made, and to conclude the impact analysis. LCA is mainly accomplished by one of two methods: either a process-based tactic or an economical input-output approach. The process-based style separates each product into process flows and quantifies the environmental impacts. This stage is typically limited by data availability, time, and cost (Horvath and Hendrickson, 1998). For this study, EIO-LCA models produced by Carnegie Mellon University were selected. They were based on the US economy's economic input-output matrix and used to determine the economic, social, and environmental impacts when one input data point was applied. This input data point was determined by an inventory analysis of the direct and indirect costs of the project (CMU, 2011).

Problem Statements

Since the size of spall damage on a concrete road tends not to be large, government agencies often do not order repairs in response to single events. In general, once the spall deepens and widens or the number of damaged areas increases to the extent that drivers feel uncomfortable, repair work is ordered. By this time, the periphery of the damaged area has already been weakened by the impact loads of vehicles, environmental influences, and chemical pollutants. Therefore, even if an oval-shaped spall is filled with fresh concrete, the periphery of the spall can be broken off. Hence, the repaired spall must eventually be re-repaired. This is why the partial-depth repair method has widely been adopted for removing damaged areas around a spall (FHWA, 1994). Thus, it is important that the manner of preventive maintenance be considered to prevent wasted money and time.

In addition, while spalls are being repaired, roads must be blocked. Vehicles must reduce their speed and detour around the job site, which results in a depreciation of the value of the planned vehicle flow caught up in the resulting traffic. The actual indirect costs vary significantly based on the work zone configuration, average daily traffic, and other factors. In this research, the vehicle depreciation value was projected based on information provided by the US DoT, who estimated it as reaching as much as $20,000 a day (see Table 1; US DoT, 2015). Assuming that it would take at least seven days to repair a palm-sized spall, it is reasonable to estimate the indirect loss at as much as $140,000 for a single repair job. To avoid incurring this level of cost each time a repair is required, this research introduces a rapid spall repair method using 3D printing technology and investigates its feasibility using the EIO-LCA.

Table 1
Daily Time-Related Vehicle Depreciation (US DoT, 2015)

Vehicle Type	Time-Related Depreciation ($/hr) in 1995 $	PPI 1995	PPI 2015	Adjustment Factor = PPI 2015/PPI 1995	Total Average of Hourly Costs in 2015 $ ($/hr)	Simple Average of Hourly Costs in 2015 $ ($/hr)	Estimated Delay Time for All Vehicles (vehicle-hours/day)	Percentages for Vehicle Types (vehicle-hours/day)	Estimated Delay Time for Vehicle Types (vehicle-hours/day)	Estimated Time-Related Depreciation Costs ($/day)
Small Cars	1.09	134.1	135.4	1.0097	1.1006	1.33912	10,192.6	0.88	8,969.488	12,011.219
Medium-sized to Large Cars	1.45	159	173	1.0881	1.5777					
Four-Tire Single-Unit Trucks	1.9	144.1	219.8	1.5253	2.8981	3.47012		0.08	815.408	2,829.5676
Six-Tire Trucks	2.65	144.1	219.8	1.5253	4.0421					
3+Axle Combination Trucks	7.16	124.5	202	1.6225	11.617	10.6706		0.04	407.704	4,350.4364
3 or 4 Axles	6.41	124.5	202	1.6225	10.4					
5 + Axles	6.16	124.5	202	1.6225	9.99945					
Estimated Time-Related Depreciation Costs for All Vehicles per Day										19,191.223
										20,000

Methodology

Quantitative Analysis: Life Cycle Assessment

The economic, environmental, and social consequences of spall repair throughout the life cycle of the concrete were investigated by applying the EIO-LCA. The existing and new concrete pavement repair methods were then compared and analyzed, as described below. This work also developed a systematic procedure for conducting EIO-LCA evaluations of available spall repair methods to support decisionmakers considering their alternatives with regards to concrete pavement maintenance. Understanding the environmental, economic, and social implications of each selection will assist decisionmakers in choosing the most effective path.

Data Collection for the Two Spall Repair Methods

To determine the LCA input data, the direct costs were determined from cost data provided by Building Construction RSMeans 2011; indirect costs were determined based on the US DoT website (US DoT, 2015). The input data for the EIO-LCA analysis was based on the assumption of one spall repair project in one life cycle of the concrete pavement. Figure 2 shows the inputs and outputs of the EIO-LCA model's main framework (CMU, 2011).

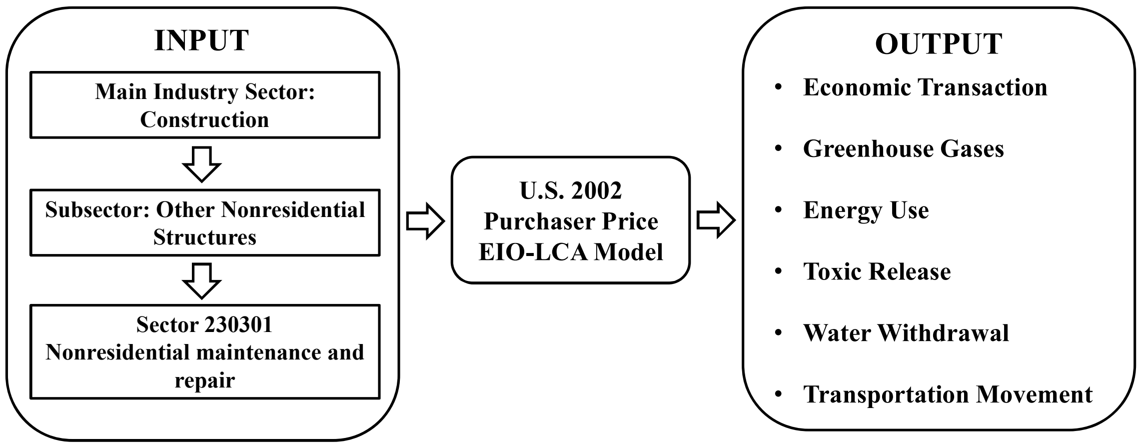

Figure 2: Main framework of the EIO-LCA model.

The input data for the two alternatives were based on the inventory analysis shown in Tables 1 and 2; each dataset was applied to Sector 230301 (Nonresidential Maintenance and Repair) to assess the two spall repair methods. Since the input data for the EIO-LCA was the estimated construction cost, the authors tried to determine the actual cost of a spall repair project. However, when the authors contacted construction companies to gather actual construction cost data, they found that the construction companies would not provide these data. Thus, Building Construction RSMeans was used to estimate the construction costs. Although Heavy-Highway Construction RSMeans was not applied in this study, the results can be meaningful as a preliminary investigation of the economic, social, and environmental impacts of this repair technique, since two alternatives were compared under the same conditions using Building Construction RSMeans.

Assumptions in the Inventory Analysis for the Two Spall Repair Methods

For the partial-depth repair method, the cost of the epoxy-resin adhesive was not provided by Building Construction RSMeans 2011. Instead, the price was assumed to be the same as for an epoxy-based first coat for finishing a floor. Also, in RSMeans the cost data associated with construction equipment referred to rental cost. However, a 3D printer was assumed to have been purchased for this study because the cost of renting a 3D printer was not available via the internet, and thus could not be used to determine the input data for this repair method. If the rental cost of a 3D printer could be determined, the direct field cost would decrease dramatically. Another major assumption was that one person could take the photos necessary for the photogrammetry with a smartphone, and apply the glue to the concrete segment inserted into the spall damage. Another major assumption was that the road would only need to be blocked for about two hours when the proposed spall repair method was applied. The cause for the assumption of two hours is that it takes about an hour to scan the spall damage, and an hour to insert the hardened concrete segment after applying the adhesive. When estimated in terms of days, this equated to 0.085 days (or two hours). The indirect costs incurred when the road was blocked for 24 hours were estimated at $20,000. In contrast, the indirect costs incurred by blocking a road for two hours were estimated at about $1,700. Finally, this input dataset was based on the assumption that there was a single spall in 1 km of concrete pavement. Therefore, the input data point for the partial-depth repair method was approximately $140,125, and $3,778 for the rapid spall repair method. These estimated values were determined based on the RSMeans published in 2011. Thus, the estimated values in 2011 had to be adjusted to be comparable to the values in 2002 because the EIO-LCA algorithm is based on 2002 historical cost data.

Table 2
Input Data for Partial-Depth Repair Method: LCA Analysis (RSMeans, 2011)

Partial-Depth	Activity	Number	Line Item	Crew Number	Units	Quantity	Estimated Cost
Direct Costs	Saw-Cut	03 35 29.35 0186	SAWCUT JOINT in CURED CONCRETE 3/4" wide x 11.5" deep, with double saw blades	C-27	Linear Feet	4.00	68.79
	Chipping	02 41 13.17 5200	REMOVE CONCRETE PAVEMENT to 6"6 thick, hydraulic hammer, mech reinforced	B-38	Square Yards	0.12	23.91
	Cleaning	03 35 29.35 0200	AIR BLAST to BLOW OUT DEBRIS and AIR DRY, 2 passes	C-29	Linear Feet	4.00	26.18
	Adhesive	03 35 29.30 4000	EPOXY-BASED 1 COAT	1 Cefi	Square Feet	0.12	1.09
	Placing Concrete	03 31 05.70 1400	PLACING CONCRETE, Elevated slabs less than 6" thick, pumped	C-20	Cubic Yards	0.01	3.93
	Concrete Cost	03 31 05.35 0350	NORMAL WEIGHT CONCRETE, READY MIX, 4500 psi	None	Cubic Yards	0.01	0.67
	Curing Compound	03 39 23.13 0300	CHEMICAL CURING COMPOUND, sprayed membrane	2 Clab	Hundred Square Feet	0.00	0.25
	Sub-Sum						124.82
Indirect Costs	Detour Around Job Site	US Department of Transportation Work Zone Road User Costs	Estimated Time-Related Depreciation Costs for All Vehicles per Day		Days	7.00	140,000.00
		Total Estimated Cost in 2011 (Unit: $)					140,124.82
		Total Estimated Cost in 2002 (Unit: $)					97,481.43

Table 3
Input Data for Rapid Spall Repair Method using a 3D Printer: LCA Analysis (RSMeans, 2011)

3D Printer Use	Activity	Number	Line Item	Crew Number	Units	Quantity	Estimated Cost
Direct Costs	Cleaning	03 35 29.35 0200	AIR BLAST to BLOW OUT DEBRIS and AIR DRY, 2 passes	C-29	Linea r Feet	4.00	26.18
	3D Modeling		PHOTOGRAMMERTRY using FREE SOFTWARE	1 Laborer	Cubic Feet	0.17	34.35
	3D Printing	Zortrax 3D Printer	Printing 3D-printed concrete mold		Cubic Feet	0.17	2,050.00
	Concrete Cost	03 31 05.30 0350	NORMAL WEIGHT CONCRETE, READY MIX, 4500 psi	None	Cubic Yards	0.01	0.67
	Adhesive	03 35 29.30 4000	EPOXY-BASED 1 COAT	1 Cefi	Squar e Feet	0.12	1.09
	Patching		PATCHING CURED CONCRETE SEGMENT	1 Laborer	Cubic Feet	0.17	34.35
	Sub-Sum						2,146.64
Indirect Costs	Detour Around Job Site	US Department of Transportation Work Zone Road User Costs	Estimated Time-Related Depreciation Costs for All Vehicles per Day		Days	0.085	1,700.00
		Total Estimated Cost in 2011 (Unit: $)					3,846.64
		Total Estimated Cost in 2002 (Unit: $)					2,676.01

Results

Interpretation of Environmental, Economic, and Social Implications

As shown in Table 4, the environmental, economic, and social impacts of the two selected spall repair alternatives were analyzed according to eight subcategories. The EIO-LCA analyses are summarized in Table 4 and Figs. 5 and 6. Economic impact related to economic transactions, social impact correlated with transportation movement and land use, and environmental impact was allied to global warming potential, greenhouse gas emissions, energy use, etc. Figs. 5 and 6 show that through the life cycle assessment of the two spall repair alternatives, the rapid spall repair method caused the least economic, social, and environmental impacts. The 3D printer method can satisfy the equivalent repair requirements with 97.2% less economic cost, 98.1% less social impact, and 97.3% less environmental influence than the partial-depth repair process.

Table 4
EIO-LCA Analysis Results for the Two Alternatives

Impact	Assessment	Units	Type	Concrete Highway Repair Methods	
				Partial-Depth Repair	Repair Using 3D Printer
Economic impact	Year-of-expenditure dollars	$1 in 2002	Year-of-expenditure dollars	179,000	5,000
Social impact	Transportation movement	t-km	Transportation movement	320,000	6,090
	Land use	Ha	Land use	14	-
Environmental impact	Global warming potential	tCO_2e	Global warming potential	61,100	1,670
	Greenhouse gas emissions	tCO_2e	CO_2 fossil	50.20	1.38
			CO_2 process	5.57	0.153
			CH_4	3.54	0.097
			N_2O	0.953	0.026
			HFC/PFCs	0.552	0.015
	Energy use	TJ	Total energy	0.847	0.023
			Coal	0.133	0.004
			Natural gases	0.168	0.005
			Petroleum-based fuel	0.447	0.012
			Biomass/waste fuel	0.033	-
			31% non-fossil fuel electricity	0.066	0.002
	Conventional air pollutants	COt	Conventional air pollutants	0.283	0.008
	Toxic releases	kg	Fugitive air	1.02	0.028
			Total air	5.85	0.161
			Surface water	0.93	0.025
			Underground water	0.94	0.026
			Land	10.80	0.297
			Off-site	4.15	0.114
	Water withdrawals	kgal	Water withdrawals	567	15.6

- **Economic Impact:** From the perspective of economic activity, "Year-of-Expenditure Dollars" represented the complete economic supply chain of purchases needed to finish repairing the concrete pavement. Figs. 3 and 4 clearly illustrate that spall repair using a 3D printer has environmental, economic, and social benefits. This result indicates that the cost of the existing spall repair method was over thirty times higher than that of the proposed spall repair method. The major cause of this difference, as stated previously, is the reduction in time the road needs to be blocked; this has a significant effect on the economics of the transaction.

- **Social Impact:** The transportation movement section of social impact referenced movement in ton-km for eight types of transportation, where 1t-km referred to 1t being transported for 1km of distance. The eight types of transportation evaluated included: air, oil pipe, gas pipe, rail, truck, water, international air, and international water. The partial-depth repair method outcomes were significant in terms of transportation movement, especially as compared to spall repair using 3D printing technology (see Figs. 3 and 4). In addition, the land use analysis, like the transportation movement, indicated that the partial-depth repair method entails larger land use than the proposed repair method. This section was analyzed via the spatial requirements related to soil quantity and land development activities.

- **Environmental Impact:** The environmental implications were measured according to various assessments, including global warming potential, greenhouse gas emissions, energy use, conventional air pollutants, and toxic releases. Heat is captured in the air by greenhouse gases like carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (N_2O), and others. The unit of global warming potential was tCO_2e, meaning metric tons of carbon dioxide or equivalent emissions. It is important to note that the global warming potential showed that nonresidential maintenance and repair sectors tend to be the most responsible for greenhouse gas emissions, producing much more tCO_2e for the total global warming potential than other contributors; this is caused by power generation for construction equipment and curing of the fresh concrete in the repair field. Figs. 3 and 4, therefore, illustrate that the spall repair method using 3D printing technology offers more advantages in terms of global warming potential than does the partial-depth repair method.

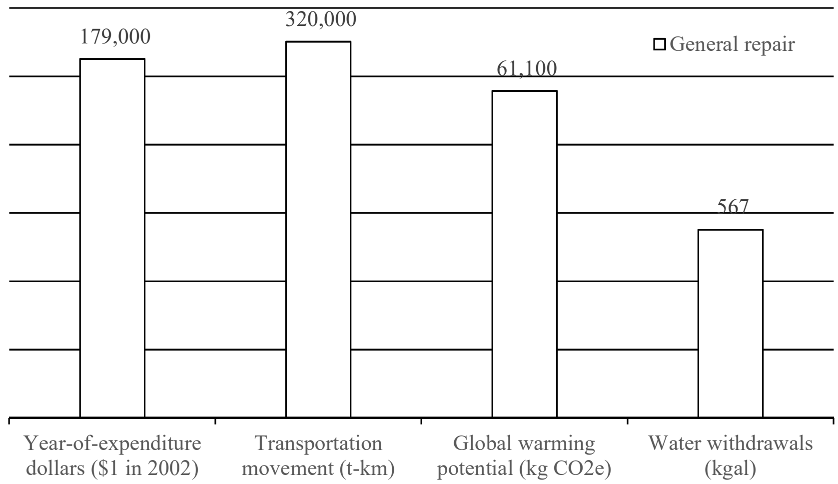

Figure 3: Economic, environmental, and social impacts of the partial-depth repair method.

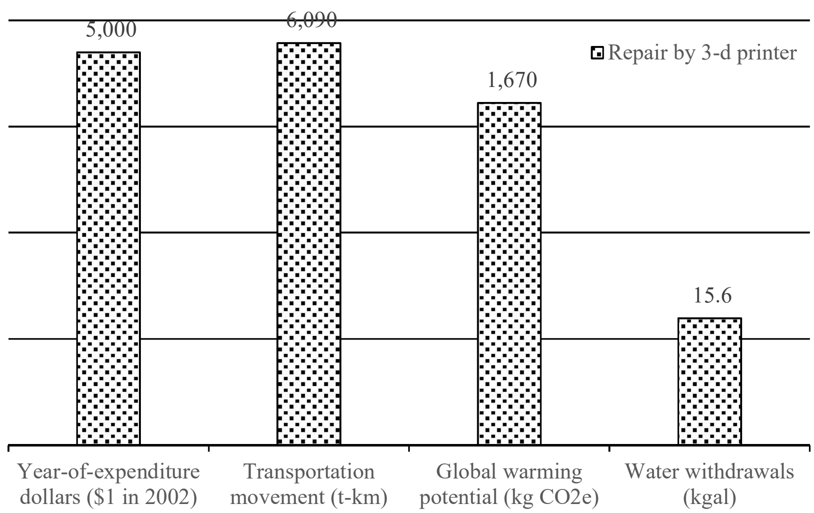

Figure 4: Economic, environmental, and social impacts of the rapid spall repair method using a 3D printer.

Conclusion

The sustainability of cement concrete pavement, which incorporates social, environmental, and economic impacts, is an important element when assessing the benefits of undertaking construction in a particular area. As part of a preliminary investigation, Yeon and Kang suggested a rapid spall repair method using 3D printing technology. Extending this previous analysis, this study applied the EIO-LCA to existing and new spall repair methods to assess their feasibility in terms of economic, environmental, and social aspects. The suggested spall repair method using a 3D printer was determined to be the most effective way of repairing spall damaged to concrete pavement to smooth overall traffic flow. Mitigation of possible social impacts (such as traffic delays and other inconveniences) is one potential benefit of the proposed repair system. Regarding economic advantages, the results indicate that the spall repair method using 3D printing technology meets the equivalent overhaul requirements (such as performance and function) with 97.2% less economic cost than does the conventional concrete spall repair. In terms of social impact, transportation movement and land use were interpreted to compare the two alternatives. The analysis clearly indicated that the traditional partial-depth spall repair method requires greater land use, 97.3% more than the proposed spall repair method (see the social impact column in Table 4). For the proposed method, in terms of the environmental impact, this analysis found that nonresidential structures were the most responsible, producing less than 97.3% of the tCO2e of the total global warming potential, followed by power generation and cement manufacturing. The results also indicate that the CO2 fossil gas produced is mainly from chemical reactions, coal mining, and solid waste in cement manufacturing. For a more accurate EIO-LCA, the actual construction cost data would be required as input data. However, this study is meaningful as a preliminary study comparing two alternative trends in environmental pollutants emitted by materials and energy sources, and other environmental, social, and economic activities. It was determined that the spall repair method using 3D printing technology requires significantly less cost than does the existing method, according to all evaluation indexes. Therefore, the proposed method has demonstrated sufficient feasibility to be applied to actual spall repair projects.

DISCLAIMER: Our proposed method is patent registered in South Korea: "Spall Repair Method using 3D Printing Technology for Concrete Pavement," Registration No. 10-1706626, Korean Intellectual Property Office (KIPO), February 17, 2017.

References

Basham, D., Wright, J., Ferguson, K., and Moy, G. (2001). *Concrete Crack and Partial-Depth Spall Repair*. US Department of Defense.

Caltrans (2015). *Concrete Pavement Guide*. California Department of Transportation.

Carnegie Mellon University (2011). *EIO-LCA: Free, Fast, Easy Life Cycle Assessment*. http://www.eiolca.net

Chindaprasirt, P., Homwuttiwong, S., and Sirivivatnanon, V. (2004). Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cement and Concrete Research 34, 1087-1092.

FHWA (1994). *Partial-Depth Repair of Concrete Pavement*. Federal Highway Administration. https://www.youtube.com/watch?v=b6xWvWCLC5E

Guinee, J. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Springer Science & Business Media.

Horvath, A., and Hendrickson, C. (1998). *Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements*. Transportation Research Record 1626.

Khoshnevis, B., and Bekey, G. (2002). *Automated Construction Using Contour Crafting: Applications on Earth and Beyond*. 19th International Symposium on Automation and Robotics in Construction, Gaithersburg, MD, USA.

RSMeans (2011). *Building Construction Cost Data*. Kingston, MA.

U DoT (2003). *Distress Survey Maintenance and Pavement Management*. US Department of Transportation.

US DoT (2015). *Work Zone Road User Costs – Concepts and Applications*. US Department of Transportation. http://ops.fhwa.dot.gov/wz/resources/publications/fhwahop12005/sec2.htm

Yeon, J., and Kang, J. (2017). *Rapid Spall Damage Repair using 3D Printer*. MAIREINFRA 2017: International Conference on Maintenance and Rehabilitation of Constructed Infrastructure Facilities, Seoul, South Korea.