

FEASIBILITY STUDY ON THE APPLICATION OF HIGH POWER DIODE LASERS IN CERAMIC TILE JOINT SEALING

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Ceramic tiles have been used extensively as an architectural material for covering surfaces due to its good appearance and outstanding properties. One inherent weakness of ceramic tile surfaces is the presence of grouted tile joints that do not have the same properties as ceramic tiles and are susceptible to failures. Most industrial users have turned to epoxy grouts for applications that require high standards of hygiene and resistance to chemicals. Epoxy grouts are nevertheless more tedious to apply and pose health risk to the tilers. This research evaluates the scope and viability of applying an alternative laser-based process for sealing tile grouts by comparing the life cycle cost of the new laser-based sealing process with epoxy tile grouts. Information regarding tile grout performance and cost data for the life cycle costing analysis was collected through a survey of UK tiling contractors. The study found that that laser sealed tile surfaces are generally more economical when compared with epoxy grouted surfaces. Sensitivity analysis conducted indicates that the life cycle cost for the laser sealed tile surfaces is most sensitive to changes in labour costs, tile size, tile laying rate and the laser processing speed. To improve the commercial viability of the laser-based sealing process, it is recommended that the nominal processing speed should be improved and the process automated to provide consistent on-site sealing quality and to reduce its dependence on skilled workers.

KEYWORDS: Innovation, Feasibility, LCC

INTRODUCTION

Ceramic tiles have been used extensively as an architectural material throughout the world because they are extremely cleanable and offer good resistance to water, oil, acids, alkalis and other agents, durable and have very long service life (Elder and Vandenberg, 1984). These properties make ceramic tiles a very popular choice for residential and commercial surfacing. Ceramic tiles are not continuous and their installation requires joints between abutting tiles that are filled with in-situ cement-based grouts. Cement-based grouts, or simply referred to as cement grouts in this study do not have the same chemical and physical resistance as ceramic tiles and therefore are more susceptible to chemical attack, physical abrasion, discolouration and contamination (Potter, 2002). In order to improve the performance of tile joints, specifiers and industrial users have increasingly turned to the use of epoxy resin-based grouts, also known as epoxy grouts which are more difficult to apply and clean off when compared with conventional cement grouts.

Lawrence and Spencer (1999) successfully developed a new two-stage process for sealing tile joints using high-power diode lasers (HPDLs). Experimental results from their study paved the way for further development in the application of laser processing to architectural materials. Consequently, the Laser Processing of Architectural Materials as a New Manufacturing Technology Applied to Construction Processes (LACON) project was launched with the aim of improving the original sealing process and to develop a prototype handheld laser delivery system for applying the process to on-site tiling work. Since the year 2000, the LACON project team has made significant progress in improving the quality and rate of the tile joint sealing process using a HPDL. Subsequent research led to the development of new materials that could be sealed with a single pass of laser and thereby reduces the overall sealing duration (Lawrence *et al.*, 2002). Following the success of the single-stage laser tile sealing, a study was commissioned with the aim of evaluating the feasibility of applying these processes to the tiling industry, in particularly the application of ceramic tiling in industrial buildings. Critical issues such as potential market of the processes, performance requirements, economic feasibility and on-site applications of the processes are examined with the aim of transferring the processes developed to on-site applications. This paper specifically discusses the economic feasibility of applying the process to the UK tiling industry.

PROBLEMS WITH CONVENTIONAL GROUTING TECHNIQUES

A typical configuration for ceramic tile floor system is illustrated in Figure 1. Ceramic tiles are laid directly on a structural base if a good standard of levelness could be achieved. Alternatively a layer of screeds could be laid above the structural base to provide level background for placing tiles. The visible elements in the ceramic tile system are the installed tiles, the grouted joints and the movement joints.

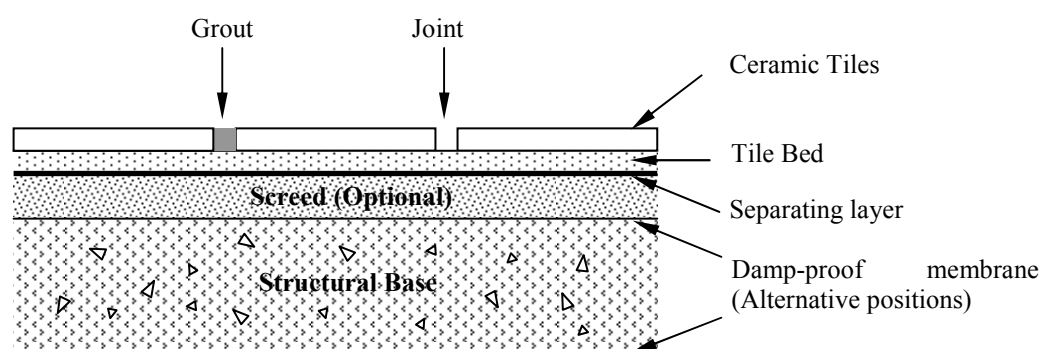


Figure 1: Elements of a Typical Tile Floor System

The joints between adjoining tiles are filled with grouts, usually based on Portland cement, mixed with fillers, admixtures and pigments. The sand-grading limits for cement:sand grouts for joint widths and the recommended widths for installing various tiles are provided in the British Standards. Typical joint widths ranges from not less than 1.5 mm for dust pressed tiles and 6 mm for extruded tiles. Floor tiles are often laid with regular joints of not less than 3 mm and not more than 10 mm. Special installation techniques using vibration tile flooring have been developed which enable ceramic tiles to be jointed at a maximum width of 2 mm (Kemtile, 2001).

Tile grouts should have properties such as good working characteristics, low shrinkages and good adhesion to the sides of the joints. In addition, special properties such as impermeability, resistance to water, heat, cleaning agents and chemical attacks, resistance to mould growth and bacteria, resilience and compressibility may be required depending on the service condition. In addition to the cement:sand mortar grouts, specialised jointing materials have been developed and used in the industry including epoxy and polyester resin grouts, furane resin grouts, silicate grouts, sulphur grouts, phenol-formaldehyde grouts, cashew nut resin grouts and rubber latex grouts (Pye and Harrison, 1997).

The presence of tile joints is one of the weakest links in the performance of tile surfaces. Cement grouts with added fillers, admixtures and pigments are porous and are susceptible to erosion and contamination. The erosion of tile joints grouted with cement grouts can be caused by exposure to corrosive materials, such as hydrochloric acid, use of aggressive cleaning materials and abrasion of grouts (Potter, 2002). Excessive machine scrubbing and the use of highly alkaline cleaners as well as solvent-based systems can have a detrimental effect on grouted joints. The penetration of moisture, chemicals and oils through the porous grout or in the case of sealant, around the edges of the seal along the sealant/tile interface could also cause the joint to break down and/or lose adhesion to the background in normal service condition. The grout surfaces could also be discoloured by materials that splashed or spilled on the tiling. Residues of spilled materials that remained on or seeped through porous joints contaminate the tile joints. Usual cleaning techniques would remove residues from the surface of the tiles but may leave residues on the grout surface which provide nutrient for micro-organisms such as moulds for example *aspergillus niger* to grow (Potter, 2002). In extreme cases, the bacteria could also induce corrosion in the grout (Tatnall, 1981), thus enabling the hyphae of the micro-organisms to penetrate into the grout, making cleaning difficult. As a result of grout erosion or contamination, the life expectancy of fifty years for a typical ceramic tile surface could be drastically reduced, incurring costly and disruptive grout reinstatement or tile replacement work to facilities.

Since the introduction of the Food Safety Act (1990), the potential growth of bacteria in the tile joints has been a major concern in the food and drink processing industry (MBD, 1999). As a result, epoxy grouts have largely displaced most of the jointing materials previously used in chemical resistance application. They are widely used for bedding and jointing tiles in the hygiene industries such as dairies, breweries, pharmaceuticals and general food and meat processing facilities. They have the advantage of high adhesion, impermeability, good resistance to a wide range of solvents and chemicals over a broad pH range, low shrinkage, and good resistance to abrasion and impact (Wittenwyler, 1986). However, due to the high cost of the epoxy and polyester resin grouts, they are usually mixed with fillers such as limestone or dolomite which have poor resistance to acids. They are generally more difficult to apply and could cause skin irritation with repeated use.

DEVELOPMENT OF LASER-BASED TILE JOINT SEALING PROCESS

Lawrence and Spencer (1999) developed a two-stage laser-based ceramic tile grout seal consisting of the amalgamated oxide compound grout (AOCG) that provides a tough, heat resistant bulk substrate, and a HPDL glazed enamel. In the process, the AOCG is mixed with diluted sodium silicate solution to create a manageable paste and placed into the void

between the tile joints. The grout is left to cure for two days before it is irradiated using a HPDL. Next, a thin layer of enamel glaze (250 μm) is placed on top of the AOCCG and left to dry for two hours before being irradiated with defocused HPDL beam to obtain an impermeable seal. Tests conducted on the two-stage laser-based ceramic tile grout seal found that the seal provides an impervious and cleanable surface. Further studies have been undertaken to develop a single-stage laser sealing process that would improve the efficiency of the sealing process. In the earlier two-stage sealing process, it was essential to irradiate the AOCCG to improve enamel/AOCCG wetting and bonding before applying the enamel frit (Lawrence *et al.*, 1999), a time consuming and expensive procedure. By replacing the AOCCG with crushed vitrified ceramic tiles mixed with sodium silicate solution as bulk filler for the joints, the enamel frit could be applied directly onto the crushed tiles and sealed with a single pass of HPDL. Lawrence *et al.* (2002) successfully sealed ceramic tile joints using HPDL with power densities as low as 200 kW/mm^2 and at rates between 100-600 mm/min . Results of tests conducted indicate improvements in the mechanical, chemical and physical properties of the single-stage enamel seal over the two-stage approach with no discernible difference in either the wear resistance or the compressive strength being observed when the joint is subjected to corrosive chemicals. The single-staged joint also indicated marked improvements in wear life over the earlier two-stage process.

In conjunction with development of the single-stage tile grout sealing process, a prototype portable handheld HPDL device has been developed for on-site applications (Lawrence, 2002). The equipment is designed to scan at speeds of up to 600 mm/s , with irradiance levels of between 100 and 300 kW/mm^2 . The variable spot sizes range from 1 to 5 mm diameter with the beam delivered through a fibre optic system. Additional safety mechanisms such as interlock systems, guards, filtration and gas absorption devices will be added as required to meet the Class I safety requirement for laser processing. This development would enable the processes described earlier to be applied safely to any on-site grouting and grout removal works. To improve the quality and consistency of the laser-based sealing processes, Roussos (2002) investigated the feasibility of applying various sensors for detecting surface quality defects in the tile grout sealing and removal processes. In the study, a high-speed CCD camera, an infrared pyrometer and a photodiode were used to detect potential surface quality defects such as bubbles and holes formations, width and surface height variations, discontinuities, edge quality problems and laser beam misalignments. It was found that by combining the three sensors to form an integrated monitoring system, the reliability of defect detection and recognition could be improved significantly.

RESEARCH DESIGN

Ceramic tiles have been used in numerous locations due to their many outstanding mechanical, chemical and physical properties, particularly its ability to provide one of the most cleanable and durable surfaces. Although the initial cost of tiled surfaces is comparatively higher than most types of surfaces, studies have shown that the total lifetime cost of ceramic tiles remains competitive when their longer service life and lower maintenance cost are taken into consideration (Flanagan *et al.*, 1989; Gatfield, 1998). As such, life cycle costing (LCC) analysis is used to evaluate the feasibility of applying laser-based tile grout sealing process when compared conventional grouts.

LCC is often used to support a decision when deliberating upon a selection of options (Dale, 1993). It converts all the cash flows that occur during the life of each option from acquisition

to disposal into comparable form so that the total cost consequences of the options, rather than just then initial cost, can be considered. The concept of LCC is based on the premise that the trade-off between initial cost and operating cost of an asset will give the minimum life cycle cost for the asset. It is nevertheless worthwhile to note that in some instances, the use of more costly materials may results in higher maintenance cost and therefore the trade-off mentioned above would be invalid (Ashworth, 1996).

Several studies have been conducted to study the life cycle cost of ceramic tiled surfaces. Gatfield (1998) compared the life cycle cost of several floor surfaces using the unit rate prices calculated from statistical sample of prices tendered since 1985 and adjusted for inflation and market conditions to represent tender prices in the second quarter of 1995. The studies indicate that although the initial cost of ceramic tile floor is higher, the NPV for maintenance cost is lower than most applied flooring system due to its longer service life. Life cycle studies conducted by Flanagan *et al.* (1989) which compares ceramic tiles surfaces with other wall and floor finishes indicate that ceramic tiles would only be economical if its service life is in excess of 20 to 25 years.

Data Requirements and Collection

The cost of ceramic tiled surfaces can be divided into two basic types: tangible and intangible. The tangible cost is readily quantifiable, but the latter is difficult to measure in monetary terms yet it represents an important aspect of the overall cost. In this study, the primary focus is on the tangible cost, although some aspects of the intangible cost and benefit are considered. The tangible life cycle cost of tiled surfaces includes the initial capital cost and the service or running costs. The initial capital cost is the cost of the tiles, adhesives, joining grout, substrate and other allied construction costs. The service cost includes regular cleaning, annual and recurrent maintenance, replacement of cracked or damaged tiles, and finally disposal. Since some of these cost components are identical for both conventional grouts and laser sealed tile joints, they are excluded from the overall calculations to simplify the overall LCC analysis. The major differences between the laser sealed grout and conventional grouts are the added steps of placing the enamel frit on the grout surface and irradiating the joints with a HPDL and its associated equipment, labour and material costs.

The primary data for the study was gathered through questionnaire survey and telephone interviews conducted with tiling contractors in UK who are members of the Tile Association (TTA) with is the main organisation representing the UK tile industry. The overall response rate for the survey has been good and it represents the tiling industry's interest in alternative grouting technologies. From sixty-four (64) questionnaires that were mailed to tiling contractors throughout UK in mid-October 2002, seventeen (17) or 26.6% of tiling contractors responded to the questionnaire survey. In addition, nine telephone interviews were successfully conducted during the data collection period, resulting in an overall response rate of 35.6% from the seventy-three companies contacted. Data collected from the questionnaire survey and telephone interview include general data regarding the tiling companies, problems relating to grout failures, tiling production rate and responses to the potential introduction of new laser based sealing system were collected in the survey. The SPSS software package is used to analyse the data collected from the survey and telephone interview.

LCC EVALUATION AND RISK ANALYSIS

Assumptions for LCC Analysis

The analysis of the survey data (Table 1) indicates that the difference between the production rates for floor and wall tiling operation are significant. This paper will present the LCC evaluation for floor tiles where the tile laying and grouting rates are comparatively lower and hence more expensive. In addition, floor surfaces are usually subjected to more onerous service conditions when compared with wall surfaces such as spillage, contamination, exposure to corrosive cleaning reagents, higher cleaning frequency and more intense cleaning regime which reduces the grouts' services life. Therefore, the LCC analysis is limited to floor surfaces where laser-based sealing process could potentially replace existing conventional floor tile grouts. The formulation of LCC model for conventional grouts and laser-based sealing process requires a breakdown of all costs associated with the construction, maintenance and disposal of tiled surfaces. Since many of the cost items such as construction costs for background, screed, movement joints, cleaning costs and landfill disposal costs are identical for all the grout types, these costs are not be included in the LCC analysis to simplify the overall evaluation process. In addition, only the labour cost for direct hire workers is used for evaluation as the difference in the hourly rate could be attributed to the lack of additional benefits for contract workers.

Table 1: Summary of data collected for LCC analysis

Grout Types	Cement Grout	Epoxy Grout	LSTJ
Labour rate	£14.32 /hr	£16.58 /hr	£14.32 /hr
Equipment rate	-	-	£8.26 /hr
Additional mobilisation cost	-	-	£50.00
Tile laying rate	2.267 m ² /hr	1.865 m ² /hr	2.267 m ² /hr
Grouting rate	11.016 m ² /hr	3.447 m ² /hr	0.8 × 11.016 m ² /hr
Grout cost	£0.28 /m ²	£4.33 /m ²	4 × £0.28 /m ²
Typical processing speed	-	-	4 mm/s
Grout removal rate	2.491 m ² /hr	1.212 m ² /hr	-
Tile removal cost	£14.50 /m ²	£17.50 /m ²	£14.50 /m ²
Service life	8 years	11 years	30 years
Annual grout failure:	3.34%	2 × 0.33%	0.33%
Percentage of tiled area			

The production and cost data used for formulating the life cycle cost model of the laser-based tile grout sealing process is derived from experimental and survey results. For example, the production rate for laying floor tiles for laser sealed grouts is assumed to be the same as that of cement grouts, while the grouting rate for laser sealed grouts is taken as a fraction of the grouting rate for cement grouts due to the similarity in both the processes. The reduction in the grouting rate stems from the requirement to apply a thin layer of the enamel prior to the laser irradiation process. Two scenarios are considered in the evaluation of epoxy grouts. The first scenario assumes that all the failed grouts are removed and replaced at the end of the

grout service life while the second envisions the complete removal and replacement of the tiled surfaces at the end of the grouts' service lives. These scenarios represent the worst-case outcomes for the conventional tile grouts. For the laser-based grout sealing process, the optimal irradiation speed of 3 mm/s is used for the initial analysis based on the latest results from laboratory experiments.

Comparison of Laser Sealed Tile Joint (LSTJ) with Epoxy Grout

The costs for installing, repairing, replacing and removal epoxy grouts and LSTJ are enumerated in Table 2. The application of laser sealed grout is the most economical of the three scenarios under consideration although the difference between the NPV of LSTJ and intermittent replacement using epoxy grouts is marginal at less than one pound sterling per square meter. The LCC profile of the NPV indicates that LSTJ is more economical than intermittent retiling of the ceramic surface. Results from the analysis show that if the tile surface is required to be replaced once throughout the life of the project, it would be more economical to seal the tile joints with the newly developed laser-based tile grout than with epoxy grouts. LSTJ is only marginally more economical when compared with the intermittent replacement of epoxy grout. However, if epoxy grout is replaced more than twice throughout the life of the project or if the cost of downtime is significantly higher for replacing epoxy grout, then it would be more economical to utilise the laser-based process for sealing tile joint. Sensitivity analysis on the effects of changes in the discount rates indicates that the intermittent replacement of ceramic tile surface is the least economical of the three options when the discount rate is less than ten percent. LSTJ is more economical than the intermittent replacement of epoxy grouts when the net discount rate is less than 4.32% and vice versa.

Table 2: Cost Breakdown, NPV and IRR for Epoxy Grouts and Laser Sealed Tile Joint (LSTJ)

Costs	Absolute Approach			Incremental Approach	
	RegROUT	Retile	LSTJ	RegROUT vs. LSTJ	Retile vs. LSTJ
	(A)	(B)	(C)	(A - C)	(B - C)
Construction	£15,765	£15,765	£25,225	-£9,460	-£9,460
Annual repair	£62	£62	£96	-£34	-£34
Intermittent replacement	£9,446	£25,515	-	£9,350	£24,219
Tile removal	£8,750	£8,750	£7,250	£1,500	£1,500
NPV (4%)	£29,576	£45,723	£29,091	£485	£16,633
IRR	-	-	-	4.32%	11.44%

Risk Analysis

Monte Carlo Simulation

Although the results of the initial LCC analysis are deterministic, there are many uncertainties with regards to the actual cost of the equipment, labour and material in an actual project. Furthermore, variability in the prevailing discounts rate, tile size, production rate and rate of grout failure could significantly affect the outcome of the LLC analysis. Therefore, risk analysis is employed to evaluate commercial viability of the LSTJ relatively to epoxy tile

grouts. The @RISK software is used to perform risk analysis and Monte Carlo simulation of variables in the life cycle cost models. Each uncertainty variable is represented by a probability distribution function in the @RISK software. Three different simulations were conducted to test the consistency of the simulation results and to determine the number of iterations required. The total number of iterations for each simulation was initially set at 1,000. A comparison of the NPV distributions for intermittent regrouting shows that the simulations result is not affected by either the random seeds or the sampling methods used. Therefore, it can be argued that the number of iterations is adequate for the risk analysis results to converge.

Cumulative Probability Distributions

The mean NPV for 500 m² of tile surface sealed using the laser-based process is £28,484. Using the cumulative probability distribution (CPD), the probability of the NPV value falling between any two values could be calculated. In this study, the five percentile and ninety-five percentile are taken as the lower and upper range for all the probability distributions as they represent the main points of inflections for the s-curves that represent the cumulative probability of the life cycle costs. The mean life cycle cost for LSTJ is lower when compared with the mean LCC of epoxy-grouted surfaces (Table 3). The NPV for surfaces that are intermittently retiled is expected to be higher than the NPV for LSTJ under the conditions simulated in the risk analysis at £38,546 and £52,470 respectively. The mean NPV for regrouting and retiling with epoxy grout based on incremental approach are £9,979 and £23,902 respectively. The LCC difference ranges from -£23.79 to £74.79 per square meter for regrouting while the cost difference for retiling versus LSTJ ranges from £2.49 to £108.20 per square meter. The probabilities that the NPVs would be negative are approximately 28% and less than 5% for regrouting and retiling respectively, indicating the advantage of the LSTJ when compared with epoxy grouts. Table 3 indicates that the IRR for regrouting ranges from -1.70% to 28.86% while for retiling, the IRR ranges from 4.07% to 35.23% with the mean at 10.76% and 17.35% respectively. The probabilities that the IRRs are higher than 4% are approximately 72% and 95% for regrouting and retiling respectively. In the current climate of low interest rates, it is advantageous to apply the laser-based sealing process in the UK tiling industry.

Table 3: Summary of Cumulative Probability Distribution

Grouting Methods	NPV			IRR		
	Mean	5%	95%	Mean	5%	95%
Laser Sealed Tile Joint	28,484	18,446	63,756	-	-	-
Epoxy Grouts (Regrout)	38,546	20,350	65,646	-	-	-
Epoxy Grouts (Retile)	52,470	32,700	81,511	-	-	-
Epoxy (Regrout) - LSTJ	9,979	-11,895	37,397	10.76	-1.70	28.86
Epoxy (Retile) - LSTJ	23,902	1,224	54,102	4.07	17.53	35.23

Sensitivity Analysis

The sensitivity of the NPV for LSTJ to changes in the input variables is calculated using regression analysis and the results are displayed in the form of tornado graphs according to

the strength of the relationships between the input and the NPV. Sensitivity analysis of the life cycle cost model (Table 4) indicates that the most significant variables affecting the LSTJ's NPV are the labour cost, tile sizes, tile laying rate and laser processing speed respectively. The changes to the life cycle cost of the LSTJ are mainly affected by variables that directly contribute to the initial construction cost of laser sealed tile surfaces. The cost of labour and laser processing speed are two key parameters that could be improved to increase the efficiency of the laser process. Despite the high initial cost of the laser equipment, the impact of the equipment running cost is not shown to be significant, as the utilisation rate for the laser equipment has been fixed at 80% level. However, the impact of the running cost on the NPV would be significant if the utilisation rate for the equipment is lower than 80%. It is therefore essential to determine that there is sufficient market for the technology prior to its deployment. The NPV for both regrouting and retiling are most sensitive to changes in the cost of labour when grouting with epoxy grouts and to a lesser extent by the labour cost of the laser sealing process. In addition, the life cycle cost of regrouting is influenced mainly by changes in the cost of intermittent grout removal while the LCC for retiling is affected by tile laying and grouting rates.

Table 4: Results of Sensitivity Analysis

Variables	Laser Sealed Tile Joints	Epoxy (Regrout) - LSTJ	Epoxy (Retile) - LSTJ
Rank 1	Labour Cost (+0.587)	Labour Cost – Epoxy (+0.519)	Labour Cost – Epoxy (+0.535)
Rank 2	Tile Sizes – Grout length (+0.410)	Grout Removal Rate (-0.271)	Tile Laying Rate (-0.382)
Rank 3	Tile Laying Rate (-0.367)	Labour Cost – Laser (-0.205)	Grouting Rate – Epoxy (-0.273)
Rank 4	Laser Processing Speed (-0.357)	Discount Rate (-0.157)	Labour Cost – Laser (-0.260)
Rank 5	Tile Cost (+0.134)	Grouting Rate – Epoxy (-0.147)	Discount Rate (-0.259)

CONCLUSIONS

From the LCC analysis, LSTJ is found to be more economical when compared with conventional grouts for surfaces that are intermittently retiled. Although the life cycle cost is sensitive to the discount rate used, the analysis results suggest that LSTJ is more economical under most conditions due to the high cost of tile replacement. Laser-based grout sealing would be the preferred choice if the tiles grouted with conventional grouts are expected to be completely replaced at least once in the building life. When the LSTJ is compared with the option of regrouting using epoxy grouts, the probability that the return of investing is positive is approximately seventy percent thus indicating that the option of LSTJ is generally viable when compared with epoxy grouted surfaces. These estimates are considered conservative as downtime costs from regrouting or retiling work would greatly increase the cost of epoxy grouted surfaces.

In order to improve the commercial viability of the laser seal process, laser sealing should be used in conjunction with larger sized tiles, thus reducing the sealing length required. Secondly, the processing speed should be increased. Alternatively, an automated system could be designed to reduce its dependence on labour as the labour cost is the main variable

affecting the life cycle cost of all tile surfaces. An automated system would also provide better control over the process speed and reduce the risk of laser exposure. However, the cost for developing an automated on-site laser delivery system is expected to be significantly high and may not be commercially viable.

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