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Spall damage repair using 3D printing technology

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ABSTRACT

Concrete road surfaces may crack due to shrinkage from drying. Often, cracks are induced at predetermined locations to solve this problem. However, the impact loads from vehicles are concentrated on these pre-induced transverse joints, often resulting in palm-sized spall damage. Repairing this damage with cast-in-place concrete leads to indirect losses from road blockages that occur during curing. This research presents a new method of repairing spall damage that minimizes indirect loss. A three-dimensional concrete patch is prepared in advance and placed over the damaged area. When using cast-in-place concrete to repair spall damage, road use must be restricted for a minimum of seven days. The proposed method reduces road closure to 2 h. According to the US Department of Transportation guidelines, the proposed method is estimated to reduce indirect losses from road repair from USD $140,000 to USD $1700. A three-dimensional concrete patch attached to a damaged surface can withstand a shear load of up to 15.7 MPa. The proposed method can withstand at least 91% of this load. Moreover, given the friction between the patch and the damaged surface, the structural stability of a concrete patch in response to shear loads may be even greater than 91%. This study presents the proposed methodology and discusses its economic value and structural practicality.

1. Introduction

Portland cement concrete is widely used for road pavement because the physical advantages it offers are numerous. Smith and Maillard (2007) described the following benefits of concrete roads, as compared to roads paved with asphalt. (1) Micro-textures form naturally on concrete road surfaces and artificially create grooves; these grooves reduce the water film phenomenon that causes vehicle tires to “float” on a road when it rains. (2) Concrete road surfaces diffuse light, which is advantageous for night drivers. (3) Noise on urban roads is a social concern, and the Cement Association of Canada (CAC) has experimentally demonstrated that the Sound Intensity (SI) noise values (about 104 dBA–105 dBA) for concrete roads are equal to or less than the SI noise values for asphalt roads (about 105 dBA) [1]. Depending on the texture of the road surface, the noise near concrete roads can be even less than near asphalt roads. (4) Since concrete is durable, the quality of a concrete road can be maintained for a long period of time. According to a five-year survey conducted by the Nova Scotia Department of Transportation and Public Works [2], the Riding Comfort Index (RCI) value of asphalt pavement (approximately 8) is higher than that of concrete (about 7.5), immediately after completion of construction. However, as time passes, the RCI value of the asphalt pavement decreases steadily, and after five years it becomes lower than that of concrete. (5) The Profile Ride Index (PRI), which indicates the roughness of the road surface, increases by a multiple of four for asphalt, from 4.0 to 16.2 over five years, while the PRI for concrete only increases by a multiple of 1.7, from 4.1 to 6.8. (6) According to a report from the Athena Institute commissioned by the cement and concrete industry, asphalt roads consume two to four times more primary energy than concrete roads [3]. Zaniewski (1989) argued that heavy vehicles use more fuel than usual to run on flexible pavements such as asphalt [4]. Experiments conducted by the Federal Highway Administration (FHWA) for the World Bank showed that heavy vehicles driving on concrete roads used up to 20% less fuel than when driven on asphalt roads [4]. The Cement Association of Canada (CAC) did a similar experiment, showing that a heavy vehicle traveling at 100 km/h used 4.1% to 4.9% less fuel when driving on a concrete road than on asphalt [5].

Portland cement concrete also has drawbacks, especially its reduction in volume during the curing process. When concrete is used on slender structures such as roads, the middle part can become cracked due to shrinkage occurring during the curing process. Water caught in these road cracks changes in volume when it freezes and thaws, resulting in even wider cracks. These cracks have an adverse effect on the

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Fig. 1. Representative spall damage on the edge of a concrete slab [7].

road's durability. As a means of prevention, transversal joints are often inserted at predetermined positions [6]. This helps prevent road cracking in undesirable locations. These transversal joints are filled with a stretchable sealant to stop water from penetrating, even if a gap in the joint increases due to concrete shrinkage. If concrete roads crack along an artificially created transversal joint, the concrete slab segments become structurally disconnected and begin to act independently over time. Depending on the condition of the ground, the heights of the two slab segments along the transversal joint may not seamlessly match. As a result, a vehicle passing over this point may rattle and suffer additional shock loads. If this impact load is repeatedly applied, the edge of the slab will break into palm-sized pieces, as shown in Fig. 1.

This type of road damage is called spall. Impact loads are concentrated in areas where spall damage occurs. If spall damage is not promptly treated, the area suffering the initial damage could increase in size. To quickly repair this damage, the injured area is often filled with asphalt. However, in order to properly repair the impairment, the damaged area must be cleaned and fresh concrete placed [8,9]. This method requires cutting the concrete to separate the damaged part from the rest, and then breaking the damaged part with a chipping machine and blowing it with compressed air. Fresh concrete is then poured into the cleaned area; the repair is finished once the concrete cures.

If a project team chooses to repair spall damage by placing fresh concrete, they will need to restrict road use while the fresh concrete is hydrated; this can result in indirect financial losses. The time required to cure fresh concrete depends on the type of cement used, but it generally requires at least seven days [8]. According to the report “Work Zone Road User Costs” published by the US Department of Transportation in 2015, if traffic is blocked for road maintenance, indirect losses of up to USD $20,000 per day can be assumed, as shown in Table 1 [10]. The amount of indirect loss depends on how many vehicles pass while the spall damage is being repaired. If the road is blocked for seven days, the indirect loss can reach USD $140,000. Knowing that such a large indirect loss can occur, the decision to repair spall damage is not an easy one to make. In many cases, decision-makers must wait until the scale of the spall damage is so large that the eventual cost will be greater if the damage continues to go untreated. Until a consensus on this issue is formed, drivers must suffer the inconvenience and danger related to the road damage.

Spall damage is similar to dental cavities in that the damaged area must be filled. One way to treat a dental cavity is to remove the affected area and fill the space with resin or amalgam. It is time-consuming to make a resin or amalgam patch that perfectly fits the area left by the removal. Recently, there has been a dramatic improvement in this process that involves laser scanners and 3D printers [11]. Photogrammetry captures the 3D shape of the damaged area. Then, a resin patch that fits the damaged area is printed in 3D. Romero et al. (2015) experimentally demonstrated that using photogrammetry and 3D printers could repair tooth damage quicker and more accurately than traditional procedures [12]. Liu (2005) introduced new materials that could be used for optimal 3D printing [13]. Williams et al. (2006) attempted to print dentures, as shown in Fig. 2, using a 3D printer [14]. Through this process, they experimentally proved that using 3D printing technology could create sophisticated dentures that would reduce patient discomfort in less time than traditional measures. Fuster-Torres et al. (2009) devised a method of applying 3D scanning and printing techniques to implantation treatments [15]. Kasparova et al. (2013) predicted that dental plaster models printed in 3D would eventually replace traditional plaster models, because they are as precise and less expensive than traditional models [16]. Ciobanu et al. (2013) attempted to produce auditory implants in 3D using photogrammetric techniques, finding that auditory implants fashioned in this way were of a similar quality to those made by expensive 3D laser scanners [17].

Interestingly, the use of laser scanners and 3D printers to treat cavities also has implications for engineers in road maintenance. This method of treating cavities using 3D printers can be used to repair spall damage on roads. This research proposes a method for repairing spall damage on concrete roads by using 3D printers, and analyzes its economic value and structural stability.

2. Proposed method for repairing spall damage using a 3D printer

The main process of spall damage repair using a 3D printer involves prefabricating a 3D concrete patch with the same shape as the damaged area and attaching it to the area's surface. To create a 3D concrete patch, a 3D computer model of the damaged area is required. This 3D model can be obtained by using a 3D laser scanner. With this scanner, one can collect tens of thousands of points that together represent the shape of the damaged surface. By connecting these points to one another, tens of thousands of triangular surfaces are produced that become a 3D computer model of the damaged area. The dense point cloud that is collected can be used to produce a highly precise 3D model. Though this can be expensive, the 3D model needed for spall damage repair does not require the same high level of precision as does the treatment of a dental cavity. Thus, it is possible to substitute photogrammetry as an alternative. This technique acquires the point cloud for the target object by using several pictures taken from various points of view. This method achieves a smaller number of points in the cloud than does a 3D laser scanner, but is significantly less expensive.

The resin or amalgam needed for dental cavity treatment can be printed directly via a 3D printer. However, it is difficult to directly print concrete patches in 3D. This is due to the materials used in 3D printing. The 3D printers currently being developed for the construction industry do not provide the precision needed to produce 3D concrete patches. There are two types of printers currently in use. The first is a contour crafting printer designed by Professor Khoshnevis of the University of Southern California [18]. His printer extracts a fresh concrete string similar to a pasta noodle, with a viscosity similar to that of the clay used to make ceramics [19]. The fresh concrete strings have rectangular cross-sections approximately 40 mm in width and 10 mm in height [20]. Such strings are printed on top of rectangles of other fresh concrete strings that have already been printed and are half-hardened [21]. By repeating this process, one can build a concrete wall without using a formwork [22]. However, it is not possible to produce a 3D concrete patch with a 1 mm level of precision using this type of printer.

The second printer was devised by Enrico Dini. It makes one layer of a 3D structure by gluing evenly-spread sand particles onto a flat surface