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Materials study to implement a 3D printer system to repair road pavement potholes

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Abstract

InfraRob is a research project funded by the European Commission's research programme Horizon 2020 that aims to maintain integrity, performance, and safety of the road infrastructure through autonomous robotized solutions and modularization. A specific task of the project is focused on the development of a system 3D printer able to extrude a specific mixture for filling in small cracks and potholes, to be integrated with an existing small autonomous carrier. The first step of the research deals with the definition of the optimal parameters of the system 3D printer/mixture, by studying in parallel the material design and the printer design. This paper presents the study performed on a mixture chosen among those commonly used for road potholes repair. The mixture is studied to achieve and balance the different conflicting performances: consistence, flowability homogeneity, and internal structure. In addition to the basic components, the use of special additives has also been explored to improve the plasticity and adhesivity of the mixture. The first phase of tests is conducted to define the main printing controls: i) Extrudability control: materials for 3D printing need to have an acceptable degree of extrudability, which is related to the capacity of a material to pass continuously through the printing head; ii) Flowability control, to ensure the mixture can be easy-pumpable in the delivery system and easy-usable on the crack or the pothole to be filed-in; iii) Setting time control: printing material requires a certain setting time to maintain a consistent flow rate for good extrudability, thus appropriate additives are needed to control the setting time. The second phase includes in situ tests to verify the compaction of the mixture under the traffic loads. The paper presents the results of the lab and in situ tests, and the features of the chosen mix, suitable to be managed by the 3D printer

Keywords: Road pavement, Potholes repair, 3D printer, Asphalt mixture, Mixture design,

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1. Background

Road potholes are generally caused by moisture, freeze-thaw action, traffic, poor underlying support, or some combination of these factors. Pothole repair is necessary for those situations where potholes compromise safety and pavement ride ability (Sainz, 2016). They can increase the number of accidents resulting in injuries and even fatalities (Hafezzadeh, Autelitano and Giuliani, 2021)

Prompt repair helps control further deterioration and, therefore, can limit the maintenance costs and extend the service life of a pavement. Indeed, patching potholes avoids water can enter the subgrade and cause larger and more serious pavement failures.

On the other hand, the presence of construction sites on the road also causes accidents and in particular poses problems for the safety of workers. For this reason, a system that works on the roads in place of humans and fill the potholes using autonomous equipment is a topic that fascinates many researchers (Krishnamurthy, Kumar and Suthir, 2021).

An innovative approach to pothole repair is underway in the research project InfraRob, funded by the European Commission's research programme Horizon 2020 with the Grant Agreement N. 955337. Its goal is to reduce workers' exposure to live traffic as well as construction machines, reduce the cost of repetitive tasks, and increase the safety of road users, while increasing the availability of the transport network. The perspective of the introduction of autonomous machinery and equipment in the construction sector is making big waves, even if today their penetration level is low and limited to off-road driverless vehicles, machinery, and equipment primarily or exclusively used in closed off-road areas. Yet, stakeholders' interest in autonomous and automated systems is very high, and this is witnessed by the fact that all major construction machine manufacturers (such as Komatsu, Caterpillar, Hitachi Construction Machinery, Volvo Construction Equipment, and more) are all developing autonomous machines. Changing existing equipment to autonomous mode is the growing trend today in the autonomous construction equipment market. To this end, the project promotes significant advances in automating, robotizing, and modularizing the construction, upgrade, and maintenance of the road infrastructure with a focus on roadbed and pavement, which is the fundamental 'continuous' engineering structure that has the duty to carry the whole road traffic throughout kilometers of road infrastructure. By focusing on roadbeds and pavement, and particularly on roads paved with asphalt (the most widely applied type of pavement in Europe), a specific task of the project is to develop an autonomous robotized system for repairing small potholes on the road surface. The machine will be mainly focused on the early stages of road degradation, addressing repair in an integrated approach to road maintenance. It will be composed of an autonomous unit adapted to carry a 3D printer able to repair cracks and potholes having a maximum length of 20 cm and a max depth of a few cm. The pothole repair consists of two operations: the first operation consists in surveying the pothole with a laser scanner for the detection of the point cloud to be supplied to the 3D printer for the construction of the object to be extruded. At a later stage, the robot will be taken to the road and the printer will be able to extrude the filling material with the shape of the pothole being processed.

The first step of the research deals with the definition of the optimal parameters of the system 3D printer/mixture, by studying in parallel the material design and the printer design complying with the constraints given by the dimensions and payload of the autonomous carrier chosen by the project.

2. Methodology

The development of a system 3D printer/repairing mixture for filling small potholes, as well as its integration into an existing autonomous carrier is divided into four different phases:

i) definition of the constraints due to the autonomous carrier;
ii) definition of optimal parameters of the system 3D printer/repairing mixture,
iii) design and construction of the 3D printer, and
iv) system integration with the autonomous carrier.

2.1. Designing constraints

The autonomous carrier chosen by the InfraRob project is a small machine produced by another project partner (Tiny Mobile Robots) able to be easily transported in a normal van and to be deployed on-site by a single operator. These characteristics will noticeably contribute to increase safety in Road Working Zones (RWZs), not only in major road infrastructures but also in the secondary ones, where smaller maintenance operations are the most dangerous for human workers.

Due to the reduced dimensions of the autonomous carrier and the limited space for the printer allocation, the printer mechanics preliminary study led to the available working area of the extruder (printing head) shown in Figure 1 and consequently to the maximum dimension of the potholes to be repaired during the demonstration tests. Indeed, since the printer's tank cannot contain more than 5 kilos of material, the size of the potholes has been limited to 20 cm in diameter and 5 cm in depth. Considering this material quantity, it is possible to fill at least three potholes with a single autonomous carrier operation.

In addition, to reduce the weight on the autonomous carrier, no compaction equipment can be added. Therefore, the study about the suitable mixture was focused on self-compacting material that, immediately after the laying, can be compacted by the wheels of the repairing vehicle itself, and later by the traffic vehicles.

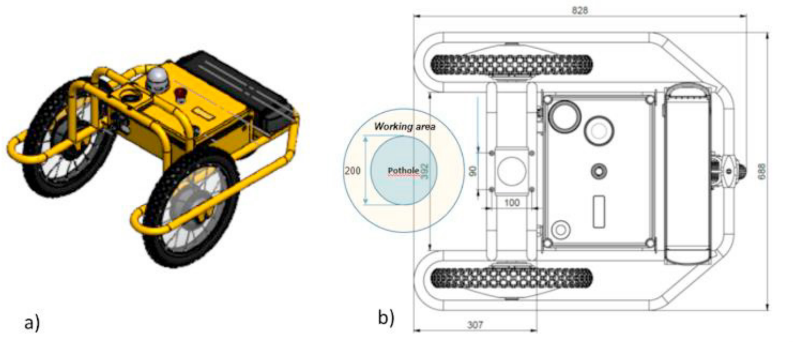

Fig. 1. Extruder morphology. a) The autonomous carrier b) working area; dimensions in mm.

2.2. Parallel study of repairing mixture and specific printer

To achieve the definition of the optimal parameters of the system printer/mixture, a parallel study of both printer and repairing mixture has been launched, starting from an adaptation (Fig.2) of a procedure defined by GuoWei et al. (2018) more oriented to cementitious materials.

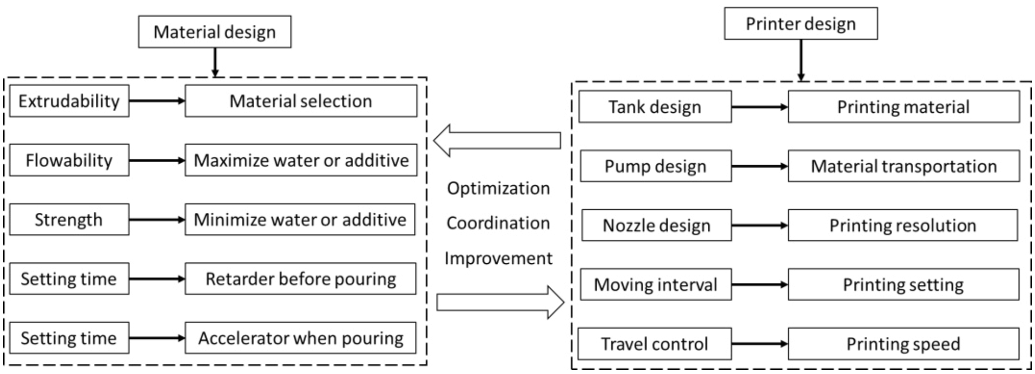

Fig. 2. Parallel design of repairing mixture and specific printer.

The material selection took into consideration the laboratory results for asphalt materials achieved by (Jackson, Wojcik and Miodownik, 2018) in terms of extruder design and printing technology.

2.3. Screening of materials

For the repairing mixture selection, it is necessary to achieve and balance some conflicting performances, like as example consistence and flowability, homogeneity, and internal structure. Materials for cracks and potholes repair include hot, warm or cold mix asphalt, asphalt emulsion mixes, mixes with special blends of aggregate and modified binders, and cement mixtures. The most common materials with their main PROs and CONs are listed in table 1. Many requirements result counterposed, and one of the major difficulties will be to find a good compromise between the main advantages and disadvantages that should be carefully considered to make a sensible decision.

Some materials are especially suitable to be prepared, stored, transported, and extruded by a little robotized machine, because their composition, workability, and extrudability are good, but maybe they are not adequately durable or mechanically resistant. On the other hand, other materials may have good performances with respect to the adhesion, filling and sealing properties, sustainability, and costs, but they are difficult to manage considering their granulometric limits or thermal behavior.

A pre-selection of the available materials for the repairing mixture has been conducted on the basis of a literature review

Table 1. Materials for potholes repair: PROs and CONs.

Material	Main PROs	Main CONs
Hot Mix Asphalt (HMA)	Compatibility/homogeneity with the existing pavement	Temperature management
Warm and Cold Mix Asphalt	Mechanical performances	Viscosity (at low Temp)
Bituminous Mastics	Adhesion, sealing, filling	Compaction energy needed
Cement (and/or concrete)	Costs	Granulometric curve limits
Resins	Compatibility/homogeneity with the existing pavement	Mechanical performances
Polymers, synthetics, ...	Transport, supply	Adhesion

Asphalt-based materials (hot and cold) can be used for both asphalt and concrete pavements and a further pre-selection has been conducted on this type of mixtures. Cold Mix Asphalts (CMAs) are usually used to repair potholes and cracks due to their ease of handling, affordability, few required labor and equipment, long storage time, and low environmental impacts. Many studies all over the world show the good performance of the CMA with different weather conditions and road pavement materials. Generally, the repairing mixtures include some additives to improve the strength and the adhesion to the old materials (Wang, et.al., 2020; Ghosh, Turos and Marasteanu, 2020). In addition, the performance of this material is not affected by the weather. Instead, for example, the application of Hot Mix Asphalt (HMA) in the wintertime is strongly affected by low temperatures, which induce its thermal dissipation during transport to the worksite (Hafezzadeh et al.,2021). Finally, the CMA allows the road to be reopened to traffic in a short time. HMA would also have a particular disadvantage linked to its use in 3D printers: since the amount to be transported is rather limited, there would be great difficulty in maintaining the temperature at the desired levels (160° C), unless the addition of a heater. But this would burden and complicate the robot.

From an environmental point of view, researchers from all over the world are looking with great interest at the use of recycled and reused materials (Rahman, Mohajerani and Giustozzi, 2020). In particular, the use of RAP (Recycled Asphalt Pavement) in the production of asphalt pothole repair is an opportunity of undeniable economic and environmental advantage (Giannattasio et al, 2015). A material used for filling excavations for underground utilities by some municipal administrations is the self-compacting cement concrete and it could be used to repair cracks and potholes with a 3D printer. The self-compacting cement concrete is composed of a mixture of sand, cement, water, and any fluidifying additives (D'Andrea et al., 2011). The aggregate dimension should be well matched and variable to have a continuous grading curve and obtain a slightly waterproof material at the end of the processing. Considering the size of the potholes to be treated in the project, the maximum size of the aggregate must not exceed 10 mm. The material processing temperature corresponds to the ambient one which is advantagous for the use in the 3D printer because the heater can be avoided. However, cement-based materials are commonly used for permanent patches on rigid pavements only. Indeed, the adhesion between the asphalt and cement concretes is very poor.

In conclusion, based on the literature review and the previous considerations, the cold asphalt mixtures seem to be the most suitable for implementing the 3D printer road potholes repair. This choice is also due to the designing constraints previously mentioned, where HMA implies additional devices for maintaining the temperature, thus affecting both the payload and operability of the small autonomous carrier.

The study started with a mixture composed of 100% RAP and recycling agent whose description is in the following paragraph.

2.4. Description of the 100% RAP mix with recycling agent

Reclaimed Asphalt Pavement is the resulting material deriving from the demolition of old pavements which and, according to the high physical-mechanical characteristics, it is totally reusable in road construction, especially in new bituminous mixtures, if properly managed. The recycling of materials deriving from the milling of existing pavements allows to save sources and reduce CO_2 equivalent emissions.

A good treatment of the milled material includes the demolition of the pavement (the separation of the superficial layers from the deeper ones), initial check (presence of foreign materials, dimensions of the elements and environmental compatibility), treatment for crushing and/or screening (chemical and dimensional control of the elements and mixing if deriving from different sources), storage and management of stockpiles and recycling.

The bitumen undergoes a chemical transformation both during the storage and production phases of the bituminous conglomerates, and during the use of the pavement. As recognized, the chemical process involves the oxidation of the bitumen, the loss of volatile parts and the deterioration of the performances. For recycling RAP, it is possible to use two different recycling agents: fluxing product (improves the workability of the mixture containing RAP, to facilitate its use) or rejuvenator (partially or totally reintegrates the chemical components of the aged bitumen contained in the RAP, giving the mixture adequate workability for construction, and restoring the performance of the bitumen, ensuring new service life).

The recycling agent use for this research is composed of different chemical components including rejuvenating agents, anti-aging, plasticizers, moisturizing substances, dispersing additives. It is added and blend to the cold RAP (ambient temperature) until the new mix is completely covered. Generally, the amount is 2.0÷3.5% on the weight of RAP. Some of the given properties are: Colour = black; Density@ 25°C = 0.85÷0.95 g/cm^3;Viscosity at 25°C= 400÷500 cP; Flash point ⩾ 150° C; Pour point ⩾ 0° C

3. Preliminary tests

3.1. Laboratory tests

Grading, Marshall Stability, void content, indirect tensile strength, and particle loss have been studied for the mixture described in paragraph 2.4., with the aim to reach the best performance of the mixture. These characteristics have been studied varying the additive content in the range of 1.5-3.5% and the water content in the range of 3.1-5%. The maximum size of the aggregate was limited to 8 mm, due to the size of the potholes to be treated in the project. Totally eight different mixes were tested. The mixing and compaction process of the specimens were performed at room temperature. The specimens' compaction was carried out with 50 strokes of Marshall's hammer, taking into account the reduced compaction ability of the material in a restricted area. The Marshall Stability and the indirect tensile strength were carried out at 25 ° C after a period of curing of 7 days at the same temperature in a ventilated oven. The particle loss was studied with the Cantabro test according to EN 12697-17 after a curing period of 28 days at 25°C.

Ad hoc tests have been conducted for extrudability and clearness of the mixture 100%RAP and rejuvenator with an equipment specially built for manually operating this kind of tests (Figure 3). The first extrudability tests gave indications on the minimum size of the nozzle that should be three times the maximum dimension of the mixture grain: i.e. for grains of 8 mm the nozzle should have a diameter of at least 24 mm. The dimensions of the conic part of the extruder shown in Figure 3a with respect to the cylindrical one should be adjusted to optimize the internal flowability of the mixture. In addition, a new equipment, based on a horizontal cochlea, is currently under study to have a better extrudability of the mixture.

3.2. In situ tests

Since the Cantabro test does not respond exactly to the damage produced by the traffic, the material has been laid down in some potholes and it was monitored under traffic. Four potholes were dug in the parking lot annexed to the school of Engineering of Sapienza-University of Rome. The choice of the site derives from two reasons: i) the site is private, so the tests were carried out without disruption of traffic and the samples poured on the site were monitored during the time under controlled traffic, and ii) the pavement is made of gravel, so it was easy to dig the potholes.

The potholes are 10 cm deep and 10 cm as diameter (Figure 4) and they were filled with two different mixtures composed of 100% RAP and rejuvenator chosen among those one listed in Table 2: mixtures E and F. The four potholes' repairs were loaded with a road vehicle (FIAT Doblò), immediately after laying and they were monitored after 50 and 100 passages of the vehicle. The surveys were carried out visually to verify that there are no losses of material, even immediately after laying, when the material is not cured and just self-compacted.

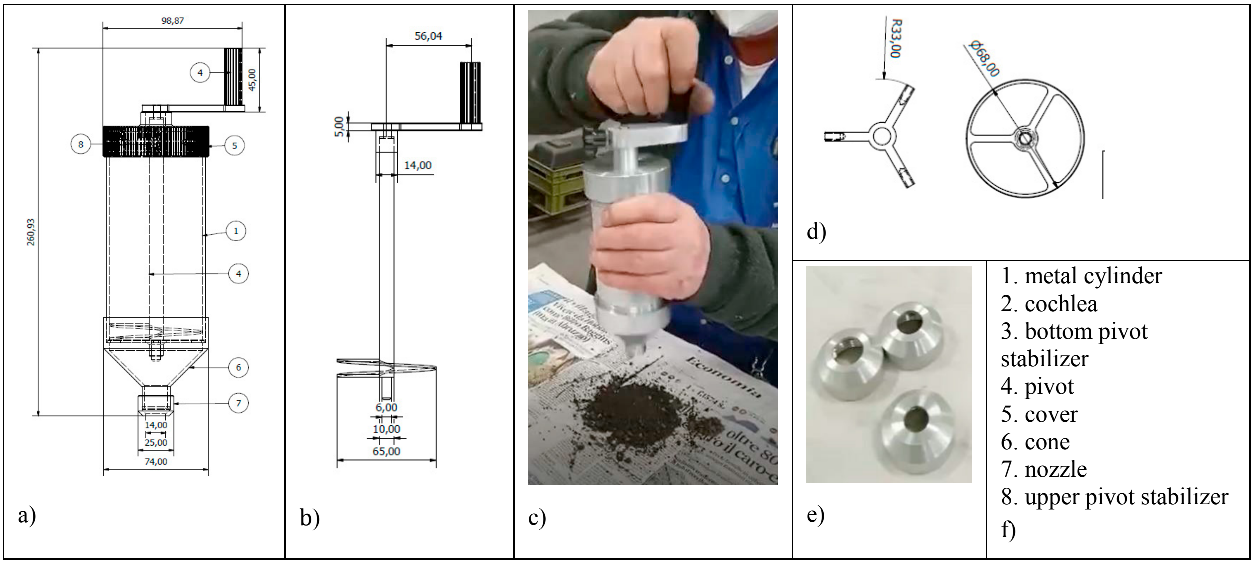

Fig. 3. Manually operated extruder with a capacity for a small pothole. a) section; b)pivot ; c) extruder ; d) bottom pivot stabilizer; f) nomenclature; e) nozzles .

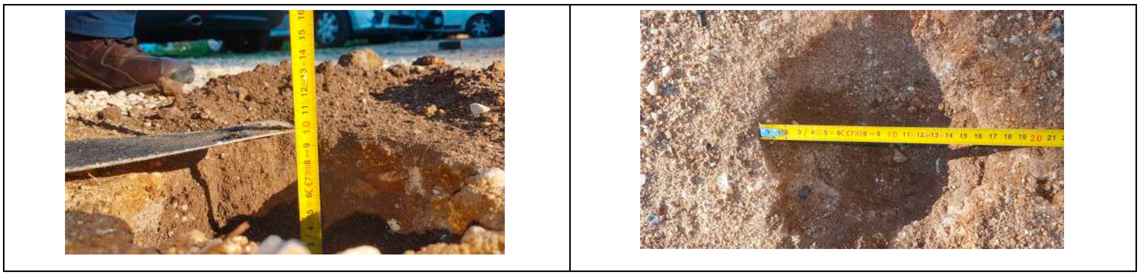

Fig. 4. Potholes dug in the parking lot annexed to the school of Engineering of Sapienza-University of Rome. a) Pothole depth; b) Pothole diameter.

In addition to the initial attempts of potholes repair on gravel, at the moment potholes repair on asphalt pavement is in progress. Some potholes in an urban street close to the school of Engineering are filled with the material under study and its behavior is still under monitoring.

4. Results

For the study of the mixtures, requirements have been defined based on the experiences made on very busy urban streets. They are shown in the last column of table 2. Table 2 lists the laboratory results of the tested mixtures. The percentage of residual voids is quite high, which is due to both the lower compaction energy, and to the lack of fine and very fine material that are hidden inside the milled granules.

All the mixes, except mix G, show the Marshall Stability and the indirect tensile strength very high compared to the target specification. The optimum value of the additive content is 3.0% with the water content of 3.1%. A further increase in the additive produces a significant decrease in the mechanical characteristics in terms of Marshall Stability and indirect tensile strength. The mixture D reaches the highest value of indirect tensile strength and Marshall Stability, but the particle loss is slightly higher than the requirements. Regarding to the particle loss, the best mixtures are E and F which have very low values.

Table 2. Mixtures laboratory test results.

COLD MIX	Reference standard	RECYCLING AGENT FOR 100% RAP (CMA)								Target Specification*
Mixture		A	B	C	D	E	F	G	H	
Recycling agent [%]		1.5%	2.0%	2.5%	3.0%	3.0%	3.0%	3.5%	3.5%	
Water content [%]		3.1%	3.1%	3.1%	3.1%	4.0%	5.0%	4.0%	5.0%	
Bulk density [g/cm³]	EN 12697-6	1.97	2.05	2.08	2.13	2.11	2.12	2.1	2.11	
Maximum density [g/cm³]	EN 12697-5	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	
Air voids [%]	EN 12697-8	20.3	17.3	15.8	13.8	14.6	14.4	14.8	14.8	
Indirect tensile strength 7dd [N/mm²]	EN 12697-23	0.18	0.19	0.19	0.23	0.12	0.12	0.04	0.09	0.05
Marshall Stability 7dd [daN]	EN 12697-34	908	1043	1055	1285	612	603	246	403	400
Particle loss 7dd [%]	EN 12697-17					84	76	84	83	
Particle loss 28dd [%]	EN 12697-17	95	46	20	13	3	5	0	3	10

*Specification of Milan Municipality

The in-situ mix tests show a substantial-good thickening and absence of disintegration of the material or loss of cohesion, even immediately after laying (table 3). Thirty days later, the passages were repeated, and the material was found stable and without distresses. The surveys are visual to check that no loss of material is happened. So far, after one month under traffic, the filling material is in place and no detachment or raveling is revealed. The potholes monitoring is continuing under the passages of actual traffic of the parking lot

5. Conclusions

In this article, the first results of the study of a mixture for road potholes repair using a 3D printer were presented. The mixture is made up of 100% recycled asphalt pavement at ambient temperature with the addition of a recycling agent. The mixture can be laid onto the pothole to be repaired without prior cleaning and without compaction. Grading, Marshall Stability, void content, indirect tensile strength, and particle loss have been studied. These characteristics have been studied varying the additive content in the range of 1.5-3.5% and the water content in the range of 3.1-5%. The maximum size of the aggregate was limited to 8 mm, due to the size of the potholes to be treated in the project. A total of eight mixtures were tested. The laboratory tests carried out with the studied mixture gave excellent results in terms of indirect tensile strength, Marshall stability, and particle loss. The mixture proved to be very stable during on-site tests. Other in situ tests is currently on progress and the results will be presented in a future paper.

This study is part of the European research project Infrarob in which other cold asphalt mixes are currently underway. The one presented in this article seems to satisfy all the requisites of consistence, flowability homogeneity, and internal structure necessary for use with a 3D printer.

Table 3. Mixtures tested in situ.

Pothole	Mix	Immediately after laying		Pothole	Mix	Immediately after laying	
		50 passages of the vehicle	100 passages of the vehicle			50 passages of the vehicle	100 passages of the vehicle
1	E			3	F		
2	E			4	F		

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