Energy Harvesting from Road Pavement: A Cleaner and Greener Alternative

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Abstract: *The energy demand has consistently been snowballing worldwide and with depleting reserves of fossil fuel, it is becoming increasingly necessary to develop novel ways to harvest energy from non-conventional sources. Over the last two decades, the emphasis on energy harvesting has increased to the extent that it is being considered as one of the paramount challenges of 21st century. Although energy harvesting is in its nascent state, it has the potential of reducing carbon footprint and dependency on battery power. The procedure of energy harvesting includes capturing, conversion, and storage of energy using efficient devices. The potential ambient sources through which energy can be harvested may include heat and light from the sun, and vibration, weight, and movement of vehicles and pedestrians. Until recently, energy harvesting has been focused on sunlight through photovoltaic cells (PVC). However, due to the dearth of solar energy at night, costly maintenance, and difficulties with glass panels, the attention of researchers is shifting towards piezoelectric and pyroelectric materials. A piezoelectric material utilizes physical pressure and converts it into electrical energy. While a pyroelectric material converts thermal energy into electrical energy due to the charge produced when the temperature of the material is altered as a function of time. These methods have immense potential to become the desirable future energy generating alternatives. Lately, roads have been identified as a promising energy harvesting domains as they are spread over a large area of land, carry high traffic volumes of heavy vehicles, and their temperature may escalate to around 60℃. Majority of energy consumption takes place in urban areas where pavements cover large tracts of land; hence, piezo and pyroelectric devices may be embedded under the pavements, sidewalks, stairwells, etc. As the vehicle or person hit the surface, an electrical charge is produced which can be used for* direct supply to nearby devices using transmission lines from a common source point or can be stored through suitable devices such as batteries and capacitors. This study presents a review of technologies being developed worldwide for energy harvesting from pavements, their efficiencies, and prospects to meet future energy demand. It also presents case studies of major projects undertaken globally to harvest energy from pavements.

Keywords: Piezo-electric and Pyro-electric Technology, Energy Harvesting, Clean and Green Energy

INTRODUCTION:

The energy consumption is growing exponentially every year, which in turn increases demand on fossil fuel reserves. Overconsumption of energy has led to the depletion of natural resources and it has been observed that these resources are being consumed at a rate 100,000 times faster than these are being replenished [**1**]. Also, studies have shown that the fossil fuels, especially oil and gas are expected to get depleted by the end of the 21st century [**1**]. This is by far the only reason why researchers have been looking for other renewable and green energy alternatives. This made us look for other sustainable and green energy alternatives. It was stated in an IISD report that the G7 countries, a group of finance ministers and central bank governor's agreed to phase out the usage of oil, gas and coal by the end of 2100 [**2**] .The endeavor for alternative energy sources has also led to the exploration of piezoelectric and pyroelectric technologies. The use of these technologies in pavements and urban roads may create a significant source of energy. Shift to the energy generated by integrated piezo- and pyro-electric pavements from traditional fossil fuels offers a clean, green and sustainable energy harvesting method, which will not only reduce the carbon footprint but will also lead future generations to use a more feasible and reliable source of energy.

Piezoelectric devices are used for harvesting energy from external loads under roads, walkways, dance floors, and so on. The applied mechanical stress caused by the wheel loads produces storable electric charge. Piezoelectric technology used in pavement generates electricity by the means of a piezoelectric crystal which are implanted few centimeters below the road surface. Their deformation under the load of traffic produces electric current. Such devices are used by the East Japan Railway Company (under pedestrian subway station gates) and by Innowattech (under roads in Israel), Pavegen, among others. According to Innowattech, if these devices are planted along a one-kilometer stretch of road then it could provide an average of 400 kW of power which is enough to power 162 U.S. homes [**3**] [**4**]. This example suggests that piezoelectric energy harvesting is a viable alternative. Observing the beneficial traits of this technology, in 2011 California state assemblyman Mike Gatto proposed Assembly Bill 306 to develop this technology for Californian roads [**5**] [**6**].

The pyro electric effect is the ability of a material to generate a temporary voltage when heated or cooled. This change in temperature modifies the positions of the atoms within the crystal structure, leading to change in polarization of the material. This polarization leads to accumulation of free charge on the material surface termed as pyro electricity. Heat sensors used on roads and pavements are important parts of energy harvesting by pyro electric devices. Heat sensors are triggered by very small change in temperature producing electric potential, due to material's pyro electricity. The pyro electric current generated is directly proportional to the rate of change of temperature. In other words, heating followed by cooling or cooling followed by heating will produce charge accumulation in different directions [**7**].

This paper presents the working principle, materials and case studies of piezo- and pyro-electric technologies.

1. Piezo-electric Technology

1.1 Working principle:

When a piezoelectric material is subjected to external force it converts the force or stress into electrical charge. The voltage generated by piezoelectric material is an AC voltage which is then rectified and stored as DC voltage in battery [**8**].

1.2 Piezoelectric Materials:

There is a long list of piezoelectric materials. Some of them are crystals like clear quartz and amazonite. Also a variety of artificial crystals are formed by chemical compounds such as Barium Titanate, Lead Titanate, Lead Zirconate Titanate, among others [**9**]. Lead Zirconate (PZT) is a popular piezoelectric material since it is known to achieve a high degree of piezoelectric effect, along with the ease of fabrication to any desirable shape, high material strength, durable surface, and resistance to humidity and temperature of over 100°C [**10**]. The efficiency of a piezoelectric material is greatly influenced by the properties of crystal used. Some of these properties include geometry, thickness, fixation, and crystal structure [**11**]. Thinner and tapered geometry is suitable for better performance. If fixed at one end, it produced more energy under external load as opposed to fixed at both ends. Bimorph crystal structure produces double the amount of energy as compared to unimorph structure.

1.3 Factors Affecting Efficiency:

In addition to the properties of materials, speed and weight of the vehicle also affect the energy output. In a study on the power output due to vehicles like bus, car, and motorcycles running at speeds of 45mph and 65mph has shown that power output is always greater for vehicles with higher speed [**12**]. Higher speed results in higher input frequency, which results in higher decay [**13**]. Also, heavier vehicles tend to deform the crystal more, resulting in more power output. Thus a truck generates more energy compared to car which generates more energy compared to a motorbike and so on [**12**]. In view of the above factors, it is recommended to implement this technology on roads with high traffic volume, preferably of heavy vehicles [**14**].

Case study-1: Israeli roads harvesting energy using piezoelectricity.

Currently numerous projects on piezoelectric based energy generation are being constructed. In 2009, in Israel, a company named Innowattech used this concept at the Avalon, Coastal, and Trans-Israel Highway and embedded the pavements with piezoelectric material 5cm below the pavement surface. They then tested the energy harvesting capacity of the pavement for 1km long stretch, for single and a for 4-lane road, in terms of energy produced by moving vehicles [**15**]. The amount of energy produced approximations met the required amount of energy. It was stated that the single lane road produced 200kWh and the 4-lane road produced 1.0MWh at that time from a 600v/h traffic flow [**12**]. This setup consisted of a ten-meter strip of asphalt, with generators lying underneath, and batteries are placed in the close proximity. The piezoelectric materials as per expectations converted the mechanical energy exerted by the weight of passing vehicles into electrical energy. The driving experience was the same as before on any normal road and was not affected by integration of piezoelectric material [**16**]. The estimated service lifetime of the mentioned system is approximated to be 20 years and the cost of implementing such a system is reported to be 500,000 $/km if the cost of electricity amounts to 0.1$/kWh [**17**].

Figure 1: Piezoelectric material embedded in the pavement.

Figure 2: Piezoelectric road built by Innowattech.

Case Study-2: Pavegen systems (United Kingdom).

In United Kingdom, a company named Pavegen came up with an innovative and a profitable idea. It developed a system for energy harvesting by harnessing the kinetic energy produced by the footsteps. It designed pavement blocks or slabs which were then placed in the crowded urban environment where the solar energy was not feasible, such as sidewalks, staircases, floors of malls, sports complex and even on the football ground, and these blocks are based on the piezoelectric principle. These pavement blocks are multifunctional and along with harvesting kinetic energy from people's footsteps they also provide wireless data output and charging points integrated within the slab. These piezoelectric blocks produce about 7 watts at 12 volts DC energy in a single step, which is sufficient to light a LED street light for 30s [**18**]. These blocks are being used all over the world; they were also used at sporting events like Paris marathon in 2013 and during the London Olympic games in 2012 at West Ham underground station. It has also being placed at schools and in malls at U.K and in the Riverdale Country School in New York City [**18**].

Figure 3: A typical pavegen slab.

Figure 4: A football pitch in Brazil, powered by over 200 tiles.

2. Pyroelectric Technology

2.1 Working principle:

It is an inherent property of some dielectric materials to develop spontaneous electrical polarization due to a change in temperature or due to creation of induced thermal potential due to polar point symmetry. This leads to the development of electric charge on the opposite faces of asymmetric crystals of the pyroelectric material. The direction of alignment of charge is mostly constant except for ferroelectric materials. However, all the ferroelectric materials exhibit pyroelectric behavior. Although, all the pyroelectric materials show piezoelectric effect but the converse of it may not be true, since, some of the piezoelectric materials have a crystal symmetry that does not allow pyroelectricity to be generated [**16**]. The amount of pyroelectricity is measured as the net change in polarization proportional to the change in temperature.

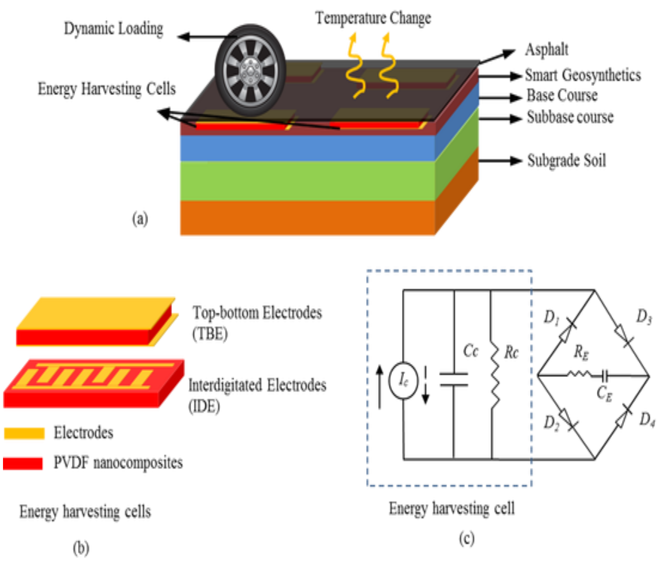

Figure 5: Schematic Diagram showing pyroelectric pavement and pyroelectric cells containing PVDF.

2.2 Pyroelectric Materials:

There is a wide range of materials exhibiting pyro electric properties. They may be classified into four types: crystal, ceramic, polymers, and biological materials. Some pyro electric materials possess high performance of pyro electricity, which include triglycinesulfate (TGS) family, lithium tantalite (LT), barium strontium titanate (BST), polyvinylidenefloride (PVDF) and its co-polymers, modified Lead ZirconateTitanate (PZT), and poly(vinylidenefluoride-trifluoroethylene) P(VDF-TrFE) [**19**].

PVDF and PZT are widely used as pyro-piezo hybrid crystals. They are more beneficial as far as output of energy harvesting and its efficiency is considered as it harnesses a major part of the energy that was better than nothing but only waste in the form of the energy produced due to the applied load of the vehicles, the pyroelectricity generated due to the deformation produced in the crystal, the heat generating due to the irradiation of the sun rays and the temperature rise caused at the surface of the pavements as a result of frictional losses between the tires of the vehicle and the pavement surface and due to the contact forces [**20**].

Case study 3: Energy harvesting in Wooster, Ohio using embedded Hybrid PVDF crystals in pavements.

The site for this project was located in Wooster, Ohio. In this study, a typical pavement section 3.7m long and 24cm wide was selected as specimen [**21**]. The Traffic data (Wheel load, Tire pressure, contact radius and traffic volume per day) and the Temperature were systematically recorded for 2014 [**22**] [**23**] [**24**] [**25**] [**26**]. Energy harvested every day was also recorded. Energy output every day was greater than the individual piezoelectric and pyroelectric outputs recorded in the laboratory. During the day when the surface temperature of the pavement was significantly high, higher energy output was recorded as compared to the same duration during night, when the surface temperature was low.

The results were recorded over a year and they showed that, no matter whether the pyroelectric charges generated in the crystal are far lesser when compared to that of piezoelectric charges generated, but, if both the surface temperature and the temperature difference due to air are used then the pyroelectric charge generation is almost equal to that of piezoelectric charges. This means that the pyroelectric charges generated cannot be neglected and they offer a great opportunity to harness the energy that was on the verge of being wasted.

CONCLUSION:

Traffic volume and wheel loads have continuously been increasing and the energy that could otherwise be tapped using pyro- and piezo-electric technologies is being wasted away. Embedding highways with piezoelectric and pyroelectric devices is one of the effective and futuristic dimensions of harvesting energy. The power generated by this method is environmental friendly, sustainable, and it would be instrumental in alleviating carbon footprint. Unlike solar roads, which incur hefty initial and maintenance costs, these methods provide cheaper and beneficial-in-the-long-run options. It has the added advantage of being a continuous source of supply, which will be available throughout the year, unaffected by the climatic conditions. India has a vast network of highways, which can be made self-sustainable and smart, leading to a new revolution in power generation in the country. This power can be easily utilized for street lights, powering toll collection centers and other small-scale uses. Previously it was considered that the energy generated by the pyroelectric effect was very less as compared to the piezoelectric effect, so investing in harnessing the waste energy generated by pyroelectric effect was considered unprofitable, but some recent studies have shown that the sum of the pyroelectricity generated due to the temperature difference and the deformations in piezo-pyro hybrid crystals is almost equal to the energy harvested by the piezoelectric effect, so it can't be neglected. However, implementing these technologies in real-time situations is challenging as most of the technologies in this area are still in the stage of development and evaluation. Only one (i.e. Pavegen) technology is commercially available in market. However, harvesting energy using embedded piezo-pyro electric pavement, offers a new dimension to power generation and holds a great potential for highways and roads to also act as an active power generation system along with providing access to destinations.

Scope for Future Studies:

From the literature review, following areas for further study have been identified:

- New hybrid piezo-pyro electric materials can be found out which have better efficiencies of power generation.
- Experimental studies can be carried out to find the optimum distance from the surface below which these materials provide better efficiencies.
- Experimental studies can be done to find out the laying pattern for embedding the crystals below the surface of the pavements, in order to get better outputs but at the same time being economical,.
- Further studies can be done on durability of such embedded layers.

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