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Research Article

ENERGY HARVESTING FROM BLACK TOP PAVEMENT USING THERMOELECTRIC TECHNOLOGY IN LABORATORY

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ABSTRACT

In this paper energy harvesting is carried out from black top pavementmodel using thermoelectric generator (TEG) in the laboratory. TEG works on the basis of temperature difference between hot and cold side. A prototype model of 350 mm x 350 mm x 100 mm dimension was prepared in the laboratory. TEG hot surface was connected with the vapor chamber inserted in the 20 mm below the slab surface and cold side was exposed in the atmosphere. To simulate the solar radiation 500 W halogen lamp was used. It has been found that the output voltage was 951 mV for the temperature difference of 40°C. An amplifier system was also developed to amplify the output voltage up toapplication limit. This indicates Road Energy Harvesting System (REHS) can produce up to 175 kWh energy from a road of 1 km stretch in 8.5 hours. It has been also found that, this energy can be increased by increasing the bitumen content in the concrete mix and it gives 10% more energy in Bituminous Concrete than Dense Bituminous Macadam. Cost benefit analysis showed that REHS is 13% cost efficient in case of energy harvesting from road.

INTRODUCTION

Global energy shortage, environmental pollution and climate changes are the most urgent challenges to the society. According to statistical review of world energy-2016, world's energy consumption per year is increased by more than 150% in last 50 years. In year 2015, 91% of world's total energy consumption came from non-renewable energy sources. Thus, the development of new energy sources and techniques is needed. Nowadays, energy harvesting from the pavement is a focal point of research in transportation sectors. India is second largest road network in the world. Black top (flexible) pavement is almost 98% of the total road network in India. Due to its black top surface (BTS) it absorbed abundance radiation of solar energy. First effect is that BTS radiates the heat back to the environment which leads to an increased temperature around the bituminous pavement surfaces and contributes to the urban heat island (UHI) effect. Second effect is that bitumen or asphalt is thermo-elastic material which reduces the stiffness of bituminous pavements with increase of temperature. Hence it makes more susceptible to permanent deformation failures (rutting) under traffic [3]. There may be one of the way is energy harvesting from the pavement which will not only promote the use of alternative sources of energy but also help in mitigating the UHI effect and the rutting potential of pavement.

In practice the thickness of Dense Bituminous Macadam and Bituminous Concrete varies from 50 to 100 mm and 30 to 50 mm respectively. In India the maximum atmospheric temperature varies from 19.77°C to 34.8 °C and the minimum air temperature from 7.83°C to 24.53°C [4].Whereas maximum pavement temperature varies from 50.19°C to 68.41°C and minimum temperature varies from -10.84°C to 20.52°C [4]. In the pavement structure underground soil maintains constant temperature beyond certain depth (approximately 80 cm). With the increase of depth in the pavement structure from surface, maximum temperature was observed in between 25 to 30 cm. After that it starts decreasing [7].

There are various techniques for energy harvesting from pavement. They are (a) Piezoelectric methods where mechanical energy is converted to electrical energy [1,5], (b) Photovoltaic method where solar energy is converted to electrical energy by placing solar plates, (c) Thermoelectric technology where electrical energy is generated from temperature difference between two points [2,7]. In piezoelectric technology main problem is road-tire interaction is different for different types of vehicles [5]. Photovoltaic method is depends on various influences like traffic load, traffic flow, rain, snow etc. In thermoelectric technology only problem is low efficiency of the system which depends on the temperature gradient. In spite of that thermoelectric technology

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can directly convert temperature difference into electrical energy. With all the benefits it can mitigate Urban Heat Island (UHI) effect. Urban heat island is an urban or metropolitan region which is relatively hotter than the surrounding areas [3]. The atmospheric temperature reaches its maximum limit in the evening time. This effect generally caused in mid-year or in winter [6]. Through energy harvesting technique this effect can be mitigated by extracting the heat from the pavement to generate electricity.

The objectives of this work are (i) To harvest electrical energy from black top pavement using thermoelectric generator, which can be helpful to reduce rutting and UHI effect (ii) To study the effect of air voids and grading of aggregates on output energy generated from the system (iii) To amplify the output voltage generated from RTEGS up to amplification level.

Thermoelectric Generator

TEG works on the basis of Seebeck effect, so it is also called Seebeck generator. It is a combination of p-type and n-type semiconductor. Two dissimilar electrical conductors are there. In case of TEG the thermal electromotive force is the temperature gradient. The grater the temperature difference, more the energy produced from the system. Moreover the main principle of the thermoelectric generator is temperature difference between its two sides. So the main challenge of the REHS is maintain, the temperature difference between its two sides throughout the investigation.

Design of road Energy Harvesting System (REHS)

Design of REHS (Fig. 1) is based on two principles namely (i) Extract the heat energy from the pavement and channelize the heat to the hot side of the Thermoelectric Generator, (ii) Maximize the temperature difference between TEG hot and cold surface. Two third length of the aluminium strips are inserted in the pavement at 20 mm depth and one third are exposed in the atmosphere. TEG hot side is bonded with the aluminium strip (placed on its top surface). The heat collected from the pavement directly transferred to the TEG hot surface. So temperature difference is created between the hot and cold side of the TEG as cold surface is on the atmosphere. To maintain the temperature difference between two sides of the TEG a water tank with cold water flow kept. The bottom of the water tank is bonded with the cold side of the TEG.

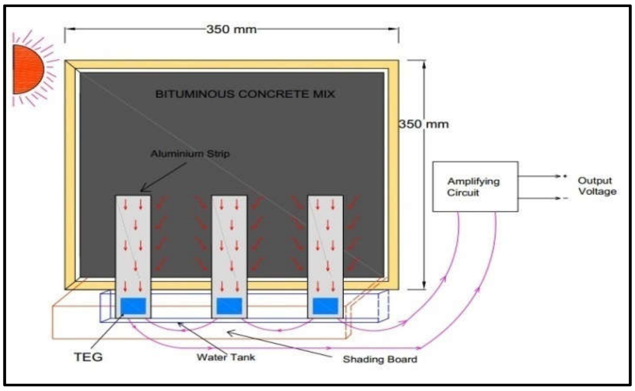

Fig 1 Schematic diagram of experiment

The items used in REHS were (i) Aluminium strip, (ii) Thermoelectric generator (TEG), (iii) Halogen Lamp(iv) Thermocouple (v) Amplifying Circuit (Op-amp circuit), (vi)Mustimeter, (vii) LED Bulb, (viii) Water tank, (ix) Shading Board.In the REHS, when the halogen lamp turned on for the experiment, the bituminous concrete slab starts heating. The heat transferred to the TEG hot side through aluminium strip. As a cold water flow is maintained on the cold side of the TEG, a temperature difference is created between its hot and cold side. This temperature difference produced electricity. This produced electricity is amplified up to amplification limit (Lightening LED bulb) using the amplifying circuit (Op-amp).

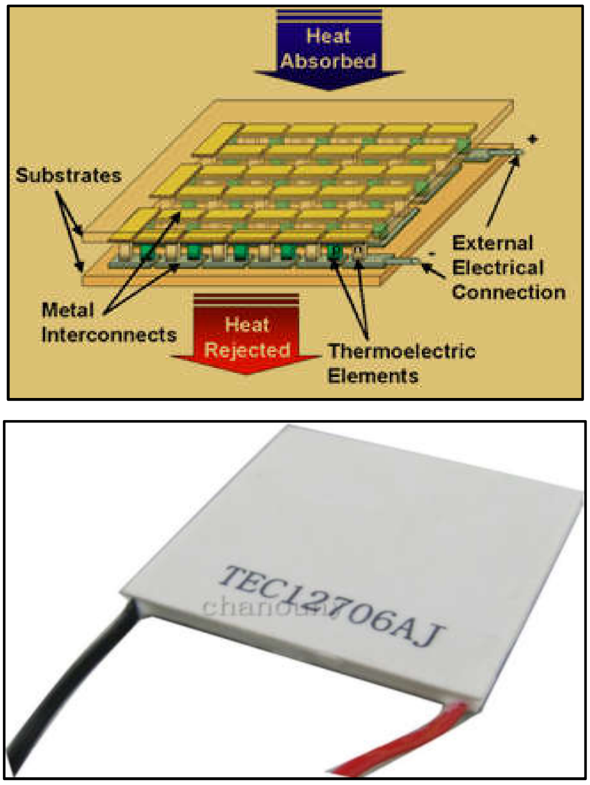

Fig 2 Thermoelectric Generator

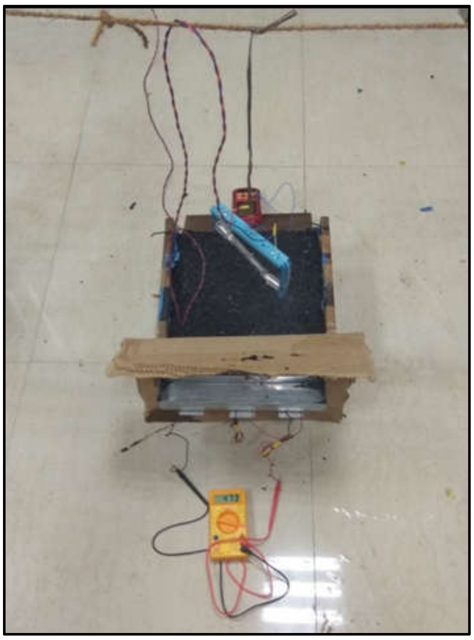

Fig 3 Circuit of REHS

Test Program

MATERIALS

The prototype model of REHS was prepared in the laboratory to generate the electric power using the thermoelectric technology. The prototype model consists of a bituminous concrete slab of 350mm X350mm X100 mm dimension, aluminium strips, thermoelectric generator, heat insulatorand multimeter and water tank for cooling purpose. The bituminous mix slab was prepared for dense bituminous macadam and Bituminous Concrete according to Ministry of Road Transport and Highway (MORTH) specification for Grading 1 (Clause 505.2.5.1 and 507.2.5). The model was prepared with bituminous concrete mix of two layers. Bottom layer has of thickness 60 mm and nominal size of the aggregate was 20 mm. Top layer thickness was 40 mm with nominal size of aggregate of 10 mm. Three aluminium strips of 300 mm × 6 mm × 3 mm were inserted in the concrete slab at 20 mm depth from the top surface. The TEGs was of grade 1 (Model No. -TEG1-SP1848-27145) and size was 40 mm × 40 mm × 3.6 mm. It can be operated in the temperature range of -40°C to 120°C. It can produce 0.97 V voltage and 225 mA current for the temperature difference of 20°C.

METHODS OF INDOOR TEST

A 500 watt of halogen lamp at the perpendicular height of 550 mm from the top surface of the bituminous slab was used to simulate the solar radiation. The pavement starts heating by solar radiation from 08:00 in the morning, the peak value of slab surface temperature reaches at around 03:00 pm. After that pavement starts cooling by radiating the absorbed heat [2]. To simulate this condition experiment was started at 8:00 am by lightening the halogen lamp to heat the bituminous slab. At 03:00 pm (420 minutes from starting) the halogen lamp was turned off. The phase from starting of the experiment up to 420 minutes is known as heating process and after 420 minutes it is known as cooling process. Thermocouple was used to measure temperature at every 30 minutes at five different depths (Surface, 20mm, 40mm, 70mm and 100mm). Multimeter was used to measure the output voltage from the REHS.

RESULT AND DISCUSSION

Temperature Measurement

Fig.4 and Fig.5 shows the variation of temperature along the depth with increase of heating duration in Dense Bituminous Macadam and Bituminous Concrete respectively. Temperatures were measuredat four different depths (Surface, 20mm, 40mm, 70mm and 100mm).

From Fig.4 In case of Dense Bituminous Macadam (DBM) the trend line shows that the temperature starts increasing from the start of the experiment up to 420 minutes. The maximum temperature reaches up to 60°C at slab surface. After that it starts decreases. Temperature at 70 mm and 100mm depth is almost same throughout the experiment. This is because at that depth rate of heat transfer is very less.

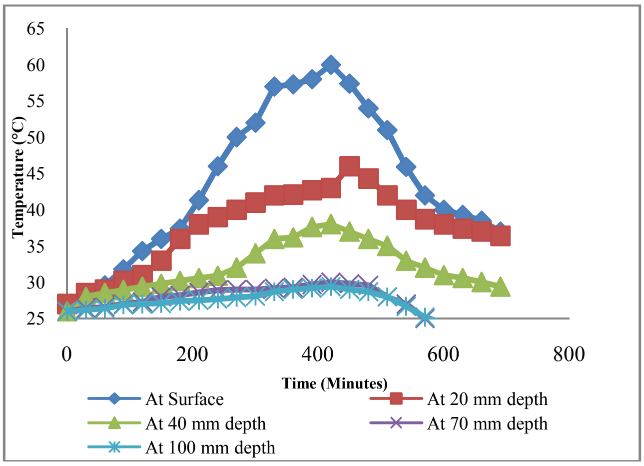

Fig 4 Dense Bituminous Macadam (DBM) temperature at different depth

In Fig.5 the trend line shows that the temperature starts increasing from the start of the experiment up to 420 minutes. The maximum temperature reaches up to 67°C at slab surface.In Bituminous Concrete (BC) temperature at 70 mm and 100mm depth is more than that of DBM. This means in BC the rate of heat transfer is more than DBM.

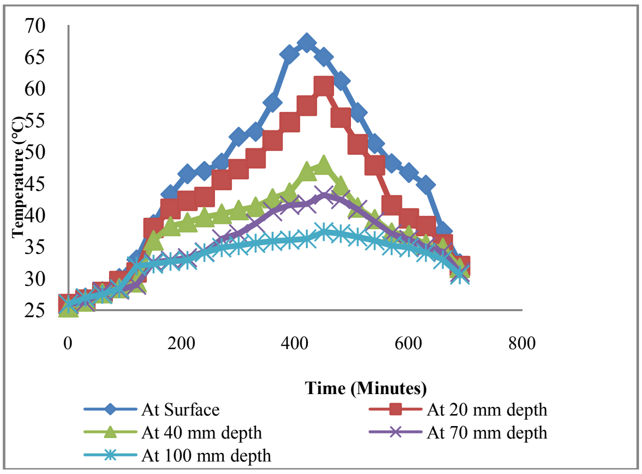

Fig 5 Bituminous concrete slab (BC) temperature at different depth

Temperature Gradient

Fig.6 showsthe variations of thetemperaturein the Dense Bituminous Macadam and Bituminous Concrete slab along the depth after 420 minutes of slab heating. With increase of depth, temperature decreases. This trend can be useful for finding the temperature gradient in the real environment. It can be seen that at a particular depth temperature in BC is more than DBM. At surface (depth=0) temperature in DBM and BC are 60°C and 67°C respectively. This can be also seen in Fig.4 and Fig.5.

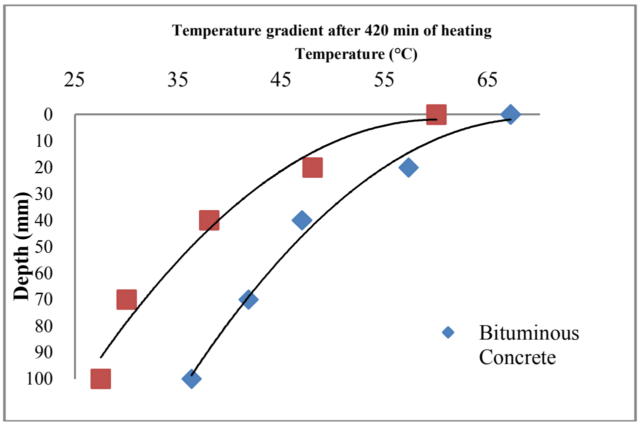

Fig 6 Temperature variation under bituminous concrete slab (DBM and BC)

In the Fig.6 top surface temperature is 60°C and temperature at depth 100mm is 27°C. There is a difference in temperature between top and bottom of prototype model is 33°C. This temperature difference will be used to produce electricity by the REHS.

The relationship is indicated in the Eq.1 and Eq.2 can be used for measuring the temperature in oC at any depth upto 100mm. If D=0, the equations will give the temperature at surface.

$$Temperature°C = 0.0036D^2 - 0.6855D + 60.033 \quad (R^2 = 0.999) \qquad (1)$$

$$Temperature\ (°C) = 0.0026\,D^2 - 0.5667D + 67.072 \quad (R^2 = 0.988) \qquad (2)$$

Voltage and Current Measurement

Fig.7 and Fig.8 show the relationship between temperature difference and Non-amplified output voltage of the system. For both the process, trend lines are parallel to each other. It means follow the linear variation, which will give the voltage with constant rate. Therefore, this investigation can be useful for estimating the voltage during day as well as night time also.

In Fig.7 and Fig.8 for both the cases voltage at the last observation of heating process is less than the first observation of cooling process. At the end of the heating process the output voltage was 878 mV after 300 minutes of heating. But when the cooling process starts the output voltage was 920 mV. This is because when the halogen lamp was turned off, the temperature of the slab surface was at its peak point. But the hot side of the TEG was connected with the aluminum strip placed at 20 mm depth of the slab. So the maximum heat takes some time to transfer from surface to 20 mm depth.

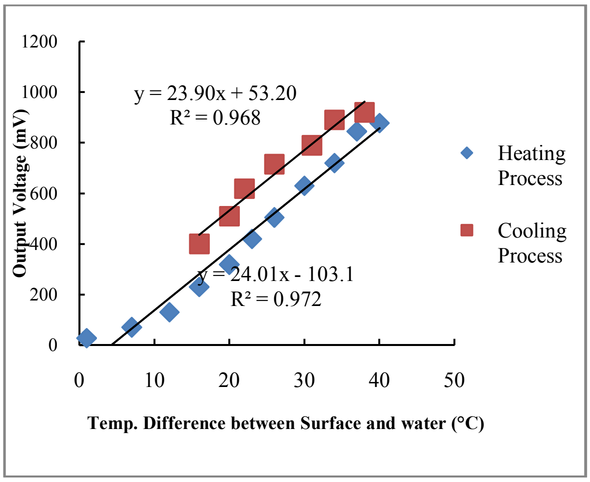

Fig 7 Effect of temperature difference on output voltage in DBM slab

The output voltage (V_{out}) in DBM slab in the heating process is expressed by the Eq.3.

V_out=24.493T_d-109.94 (R^2=0.9702) (3)

The output voltage (V_{out}) in DBM slab in the cooling process can be expressed by the Eq.4.

$$V_{out} = 23.907T_d + 53.206 \ (R^2 = 0.9681) \qquad (4)$$

Where, T_d is the temperature difference between the slab surface of the prototype model and water in the tank.

In Fig.8 it is seen that the peak value of output voltage occurred at the initial stage of slab cooling was 1.017 V, when the temperature difference between slab surface and water in the tank is 47.2°C.

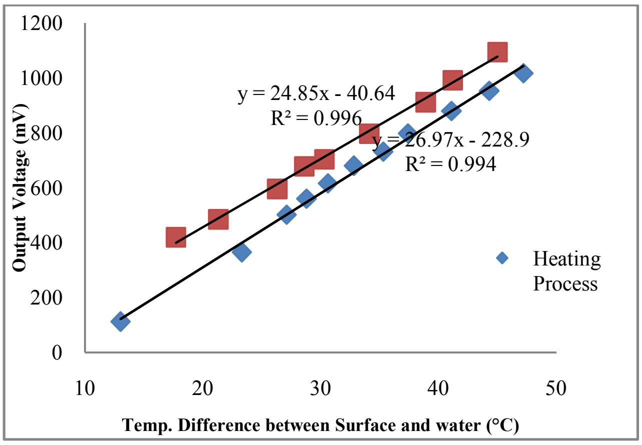

Fig 8 Effect of temperature difference on output voltage in BC slab

The output voltage (Vout) in BC slab in the heating process is expressed by the Eq.5.

V_out=26.97T_d-228.94 (R^2=0.9948) (5)

The output voltage (Vout) in BC slab in the cooling process can be expressed by the Eq.6.

V_out=24.855T_d+40.643 (R^2=0.9681) (6)

Where, T_d is the temperature difference between the temperature at slab surface of the prototype model and water in the tank.

Design of Amplifying Circuit

The REHS is a laboratory prototype model for indoor investigation. So the output voltage is very low to use it in any electronic application. To amplify the voltage up to application limit a circuit (Fig. 9) was designed for energy management. A non-inverting operational amplifier (using IC LM 741) was used to amplify the output voltage. It is a DC to DC converter.

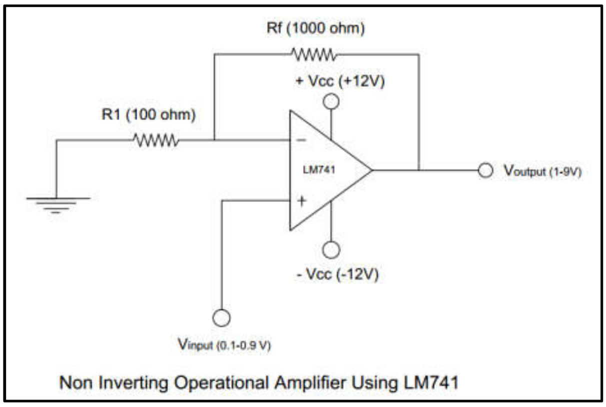

Fig 9 Amplifying Circuit connection diagram

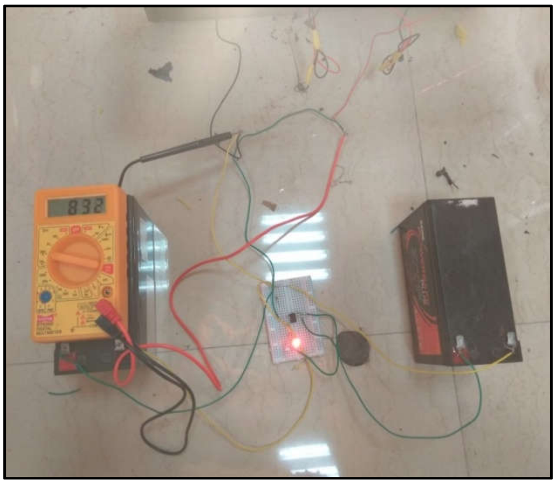

Fig 10 Amplified REHS (lightened LED bulb)

Formula used for voltage gain and output voltage is indicated in the Eq.7 and Eq.8 respectively.

Voltage Gain=1+(Rf/R1) (7)

Output voltage=Voltage Gain ×Input Voltage (8)

Where R_f and R_1 were taken 1000Ω and 100Ω respectively and V_{cc} is the saturation voltage (12V). So the voltage gain was 11 (from eq.7). In the input terminal the generated voltage from the RTEGS was supplied. The amplified voltage from the circuit was measured by the multimeter.

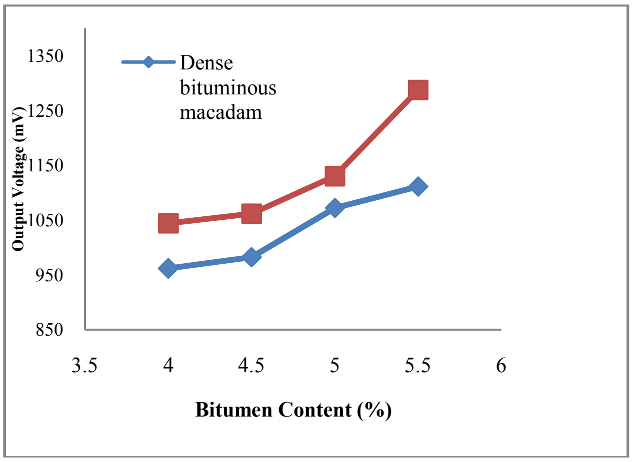

Fig 11 Relationship between Bitumen content (%) and Output Voltage (mV)

In Fig.11, it is seen that output voltage increases with the increase of bitumen content. Output Voltage also depends on gradation of aggregate. At particular bitumen content Output voltage in bituminous concrete slab is more than that of dense bituminous concrete.

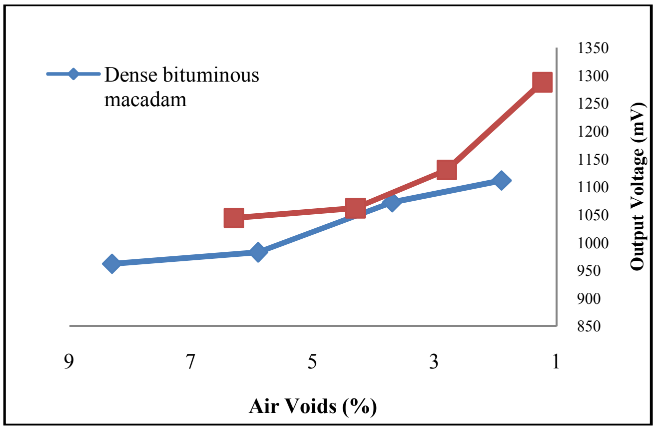

Fig 12 Relationship between Air Voids (%) and Output Voltage (mV)

In Fig.12it is seen that output voltage increases with the decrease of air voids. Output Voltage also depends on gradation of aggregate. At particular bitumen content Output voltage in bituminous concrete slab is more than that of dense bituminous concrete.

Power Generation from the System

From the result of indoor test, there was about 0.878V output voltage gained from RTEGS when the temperature difference is 40°C in Dense Bituminous Concrete and 1.017V output voltage from RTEGS when the temperature difference is 47.2°C in Bituminous Macadam.

The resistance (R) of the TEG used in experiment is about 1.25Ω at 20°C to 70°C. So the generated current (I) and produced Power (P) from the RTEGS model can be calculated using Ohm's Law. For example after 300 minutes of heating of Dense Bituminous RTEGS Model, the current produced can be calculated by eq. (9)

$$I = \frac{V}{R\times n} = \frac{0.878}{1.25\times 3} = 0.234 \text{ A} \quad (9)$$

Where I is the current (A), n is the number of TEG connected in series.The power (P) value can be calculated by the eq. (10)

$$P = V \times I = 0.878 \times 0.234 = 0.2054 \text{ Watt.} \quad (10)$$

Fig.13, shows that with increase of time, the power of REHS increased first (during heating process) and then decreased (during cooling process).

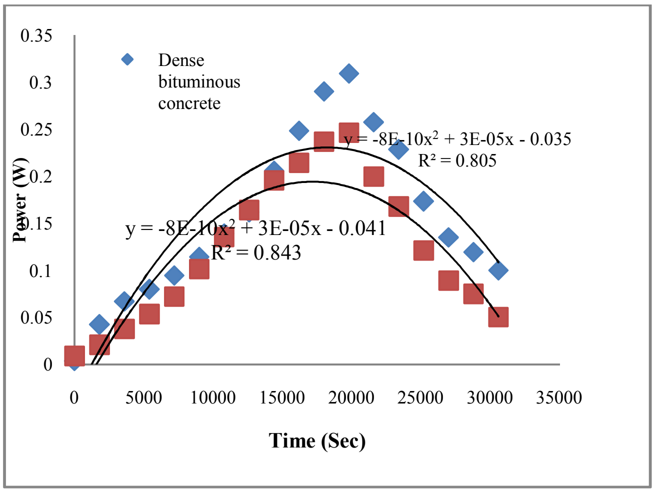

Fig 13 Relationship between Time and Power Generation of REHS

The relationship between power generated and time in Dense Bituminous Macadam and Bituminous Concrete can be described by the polynomial formula using eq. (11) and eq. (12) respectively. Where, t is the time (s).

$$P = -8 \times 10^{-10} \times t^2 + 3 \times 10^{-05} \times t - 0.0415 \qquad (11)$$

$$P = -8 \times 10^{-10} \times t^2 + 3 \times 10^{-05} \times t - 0.0351 \qquad (12)$$

The power output by the DBM and Bituminous Concrete slab of 350 mm x 350 x 100 mm by dimension was about 5134 J and 5330 J respectively in 8.5 h by integral calculation of the eq. (11) and eq. (12).

Which means this RTEGS model system can produce 167 kW hand 175 kW hof electricity from DBM and Bituminous Concrete respectively from a 1 km stretch road in 8.5 h per day.

Cost Analysis

The total cost of the RTEGS system is about Rs. 1500 for indoor investigation. The price of aluminum plate Rs. 200, the price of thermoelectric generator is Rs. 1200 and the cost of materials and production of water tank is Rs. 100.

The cost of installation of a REHS for a road of 1 km length and 10 m width is about Rs. 50,00,000. The main principle of the energy generation from thermoelectric generator is temperature difference between its hot and cold side. But this temperature difference is not same in summer and winter season. So we are considering that the temperature difference in winter (3 months) is 60% of that in summer season (9 months).

Assuming the road service life is 15 years and cost of electricity is Rs. 8 per kWh the cost of total energy generated by the system throughout the road service life is about Rs. 65,00,000 and Rs. 68,00,000for DBM and Bituminous Concrete respectively.

This system is expected to be more profitable in tropical and subtropical region where average annual temperature, average daily temperature and sun radiation is high. Above all the cost of the materials will decreased in huge amount when these will be produced in industrial level. Compared to the pyro electric, piezoelectric, photovoltaic road technology, thermoelectric technology has more environmental and social benefits. This system can be further upgraded to reduce cost and enhance energy output, such as municipal water supply pipeline on the TEG cold side instead of water tank. It is also possible to consider connecting the TEG cold side to one end of aluminium plate and other end is buried at a certain depth in the ground for a relatively low temperature.

In the winter season when the road surface temperature decreases then the temperature difference between hot and cold side of TEG can be increased by flowing cold water in the water tank.

CONCLUSIONS

For energy harvesting from bituminous concrete pavement an indoor investigation was conducted. For this purpose a model of Road Energy Harvesting System (REHS) was developed. The following conclusions are drawn:

1. The output voltage from RTEGS in Dense Bituminous Macadam was 920 mV for the temperature difference of 40°C and in Bituminous Concrete that was 1017 mV for temperature difference of 47.2°C.
2. With the increase in bitumen content the output voltage increases in both DBM and Bituminous Concrete.
3. With the decrease in air voids the output voltage increases in both DBM and Bituminous Concrete.
4. After amplifying the output voltage by Op-Amp amplifying circuit it increased by 9-10 times.
5. From the power output estimation it has been found that this system can generate upto 175 kW-h energy from 8.5 h and 1 km stretch road.
6. For installing this system in the roads the installation cost for 1 km length was estimated Rs. 50, 00,000. But the cost of generated electricity from the system was Rs. 63,00,000 for DBM and Rs. 68,00,000 for Bituminous Concrete.

The energy generated by the REHS system can be stored for further use such as road lighting, communication, traffic signal, wireless monitoring system and other electrical facilities. It is anticipated that in bituminous concrete pavement in tropical and sub-tropical region RTEGS system, will generate more energy. In addition the efficiency of RTEGS system is only 5%- 6% and technology the energy generation can be enhanced.

This laboratory investigation can be further proceeding by conducting this test in field condition. The temperature difference should be monitored in different months and seasons throughout the year. The temperature gradient between the two sides of TEG can be increased by adopting different technique like connecting the cold side with the subgrade of the pavement.

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