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Analysis of influential factors on heat accumulation in structural elements of road underpasses

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ABSTRACT

This study shows the results of field tests on heat accumulation in asphalt surfaces and concrete curbs on two road underpasses in Osijek, Republic of Croatia. The tests were conducted in 9 daytime periods over several months in 2014. The MLR model (multiple linear regression model) was made using measurements from 36 hourly periods and the model was tested in 9 hourly periods chosen at random from the overall data. The conducted research showed that by using the MLR models it was possible to successfully predict heat accumulation in the asphalt surfaces and concrete curbs of the underpasses using varying air temperature and humidity. Finally, a schematic view is shown of critical points in road underpasses in the event of the possible occurrences of slippery road surfaces, freezing road surfaces, plastic deformation of asphalt surfaces and any possible health hazards for pedestrians in the event of great temperature differences between road surfaces.

1. Introduction

The effects of solar radiation directly influence heat build-up in exposed surfaces. Factors which directly cause heat build-up in such surfaces are solar emission, solar reflection and thermal emission. Increased heat accumulation in surfaces of urban areas causes higher ambient temperatures in urban areas compared with surrounding areas. This is known as the "heat island effect" which is mostly caused by urban structures absorbing solar energy, causing their surface temperature to become a few degrees higher than the air temperature. Heat islands are most prominent in central parts of urban areas where the difference in ambient temperatures can be considerable compared to the city outskirts.

The surfaces of urban structures of lighter colours reflect higher amounts of light compared to darker coloured surfaces, resulting in lower heat accumulation. Studies have shown that the use of certain types of pavement surface materials contributes to the formation of heat islands (Asaeda and Vu, 1993; Babić et al., 2012; Doulos et al., 2004; Kleerekopera et al., 2012). The development of urban forestation areas, the use of cold and reflective road surfaces and reflective roofing materials for buildings helps prevent heat islands. Akbari and Taha (1992) reported that developing urban areas with high albedo values and the cultivation of trees can lower summer temperatures.

The European road network consists of over 5 million km of roadways, over 90% of which are covered by asphalt (Asphalt, European Asphalt Pavement Association). The US has slightly less, with over 4.3 million km of paved roads of which 93% are covered by asphalt (NAPA). Especially interesting for this research are road underpasses which represent road structures running under railways or other roads. Such roads were chosen as test objects because these structures show high temperature fluctuations due to their structural elements being exposed to varying amounts of sunlight. Such temperature fluctuations can lead to health hazards for pedestrians using these structures, ranging from differences in how slippery the surface is (sunny side of the road vs. shade) and the varying rate of the melting of snow and ice in winter. These fluctuations can cause surface damage (ruts during high temperatures / strain cracks during low temperatures) and the formation of heat islands due to the exposure of outside surfaces to sunlight.

1.1. Analysis of the effects of heat accumulation on the observed structures

Road underpasses show significant differences in heat build-up between exposed and covered elements due to their unique shape. This may result in air temperature differences along the direction of traffic which may have harmful effects on pedestrians. Ashley

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(2008) stated (Centers for Disease Control and Prevention - CDC) that excessive heat claims more lives in the US each year than hurricanes, lightning, tornadoes, floods and earthquakes combined. Road underpasses can also cause varying rates in the drying of the road surface and in the melting of ice on parts of it due to differences in exposure to sunlight. Dragčević and Korlaet (2003) reported that roads should run along the sunny side (south and west) to facilitate faster drying rates and shorter periods of snow-covered and icy surfaces. According to Safe Winter Roads, over 116,000 Americans are injured and 1300 killed every winter due to icy roads (Asphalt, European Asphalt Pavement Association). According to the Road Weather Management Program, out of the total number of car accidents (5,748,000 every year), 22% (1,259,000) are directly linked to adverse weather conditions (rain, snow, fog, etc.) (Road Weather Management Program).

Asphalt surfaces contract during winter and expand during sun exposure in the summer. Road underpasses can experience increased temperatures of asphalt surfaces during summer if they are exposed to thermal radiation from the sun. Šimun et al. (2013) stated that the average maximum summer temperatures of road surfaces in some parts of Croatia reach 60 °C which may lead to decreased asphalt rigidity and the formation of plastic deformations of the surface, such as ruts. Strineka et al. (2010) reported that ruts are plastic deformations of the road surface in the shape of wheel marks formed under the load of traffic. In contrast, during winter, a drop in the temperature of the asphalt layer leads to thermal strain due to the contraction of Hot Mix Asphalt which may cause strain cracks on the surface (Androjić and Mikulić, 2016). This was established as one of the primary criteria for determining the wear of the road and the need for repair (Jajac et al., 2015).

The difference in the effects of sunlight radiation leads to higher temperature accumulation in the exposed, outside surfaces of underpasses in comparison to inside, unexposed elements. This leads to the conclusion that the outside elements are more susceptible to the formation of heat islands. Measurements performed during the summer of 1997 at 30 locations in Athens, Greece, showed that the daily heat island was found to be close to 10 °C (Santamouris, 2001; Mihalakakou et al., 2002; Livada et al., 2002). The authors maintain that the main cause is the replacement of vegetation with buildings. In their research, Akbari et al. (2001) proposed a change in the application of black bitumen, with an albedo value of about 0.35, instead of a value of about 0.05–0.12. Babić et al. (2012) showed part of the test results from measuring temperatures of road surfaces during the summer of 2011 in Rijeka, Republic of Croatia. The research showed that asphalt is the most adverse material in terms of thermal properties. The authors state that the colour of the material has a significant effect on heat accumulation. Other research has been conducted with the goal of helping to reduce surface heat and to select materials with characteristics more favourable to the environment (Santamouris et al., 2011; Nakayama and Fujita, 2010; Synnefa et al., 2008; Akbari and Matthews, 2012).

1.2. Goals of the research

The main goals of the research are:

- The application of key independent variables on heat accumulation of dependent variables (asphalt road surfaces, concrete road curbs).
- The design and development of multiple linear regression models to achieve the successful prediction of predetermined dependent variables on the basic set of used data.
- The analysis and verification of test results using a multiple linear regression model on an extra set of used data.
- To give a diagrammatic view of critical points in the tested road underpasses.

Critical points in road underpasses are areas with a higher possibility of slippery or icy road surfaces, asphalt surface deformations due to high temperatures, and those with possible health hazards for pedestrians due to a high temperature difference between the road surfaces.

By being able to successfully predict heat build-up in the observed test variables, it is possible to:

- Improve the choice of structural elements in road underpass construction during the engineering process.
- Predict parts of the underpass with a high risk of a slippery or icy road surfaces during winter.
- Predict parts of the road with a high risk of plastic deformation damage in the event of high heat and traffic load.
- Predict parts of the underpass with high temperature differences between road surfaces exposed and unexposed to sunlight which may have negative effects on pedestrians.

2. Research methodology

In the second part of the research, a diagram is presented of the performed tests, the test objects (2.1), the weather conditions during testing (2.2), the selection of dependent / independent variables (2.3) and test cases (2.4).

The two underpasses were chosen as test objects due to the short distance between them (<250 m), their different orientations in space (roughly: north/south, east/west) and our familiarity with all the structural materials used in their construction. The surface temperature of the elements was measured using a non-contact infrared thermometer (Uni-t) from a consistent distance of 24 cm using a special enclosed spacer which helped reduce the effects of sunlight and wind on the testing area. At the beginning of each test day it was performed a parallel trial testing of measuring temperature in the laboratory conditions with other moderate thermometers. Allowed tolerances were established at 0.2 °C between the observed devices which was declared as a negligible difference.

Fig. 1 shows the timeline of the performed research which shows that the first stage started by analysing the initial state (1), followed by the choice and analysis of the effects of each individual independent variable on the dependent variables (2.3). Part 3 shows the formation of the MLR models and gives an analysis of the results of their implementation. Part 4 draws conclusions on the performed research.

2.1. Test objects

Fig. 2 shows the observed structures on part of the D7 road.

Object A is a road underpass used to allow a regional road for vehicles and pedestrians to pass under national road D7 from the east and west. Object A is divided on 7 profiles (Fig. 3a). For the purpose of testing, measurements were performed on the road's asphalt layer and concrete curbs. The asphalt surface and concrete curbs were observed as dependent variables since they both continuously follow the entirety of the observed road length but differ in terms of sunlight reflection properties. Akbari et al. (2001) stated that significant modifications in the pavement temperature can be achieved: a 10 °C decrease in temperature for a 0.25 increase in albedo.

Object B is a road underpass to allow national road D7 to pass under a railway line from the north and south. Object B is divided into 5 profiles (Fig. 3b). For the purpose of testing, measurements were performed on the road's asphalt layer and concrete curbs.