Microwave applicator for bituminous surface thermal bonding

Microwave heating has been proven successful not only in the household appliances but also in industrial applications as waste recycling or wood drying. Latest exploration has been also directed towards microwave-assisted thermal bonding of bituminous surfaces, which was proven more effective than conventional methods e.g. in repair of potholes.

This article presents a mobile microwave applicator for bonding of undesirable technological longitudinal joint opening occurring in bituminous pavement. Such defects are typical during road construction when two adjacent lanes are paved sequentially so that they need to be eventually bonded together across the whole depth of the road structure. Typically, after a new lane is deposited, a technological joint between the two lanes is merged with the aid of gas-jet followed by a road roller to improve thermal bonding.

The design of a mobile microwave applicator accounted for coupled electromagnetic-thermodynamic modelling using QuickWave software [4], microwave characterisation of selected bituminous mixtures, control of the exposure to microwave radiation, and heating rates measurements. This work solves significant technological issue of effective bonding of bituminous surfaces, thus, remarkably influencing road durability.

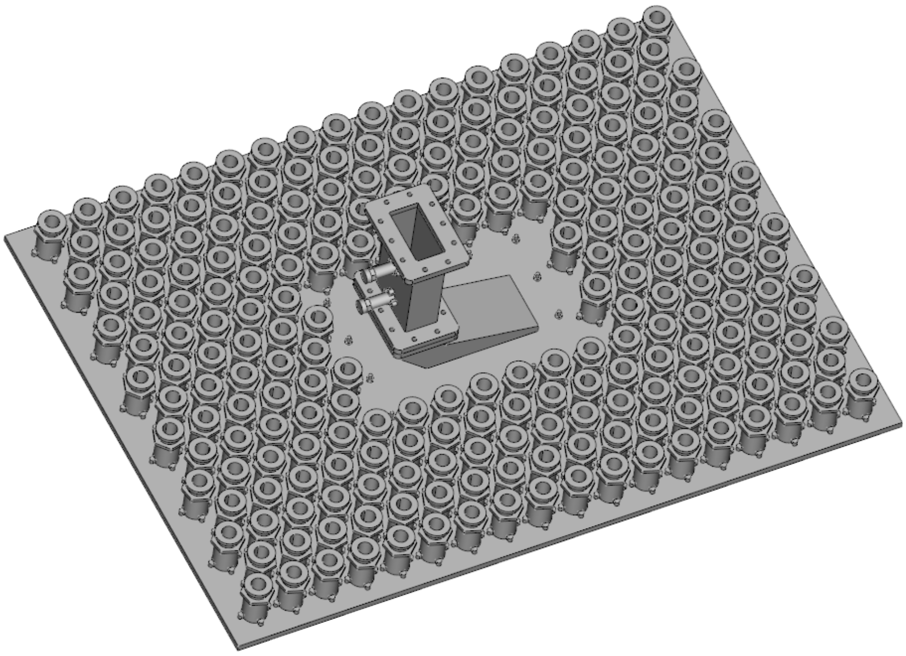

Fig. 1. Top view of microwave applicator.

Simulation scenario

The applicator is an open device equipped with a waveguide nozzle and hexagonal lattice of cylindrical metallic chokes preventing microwave leakage. The model of the applicator is shown in Fig. 2. It presents the applicator equipped with chokes of tuneable height (part of the chokes stands out above base metal plate).

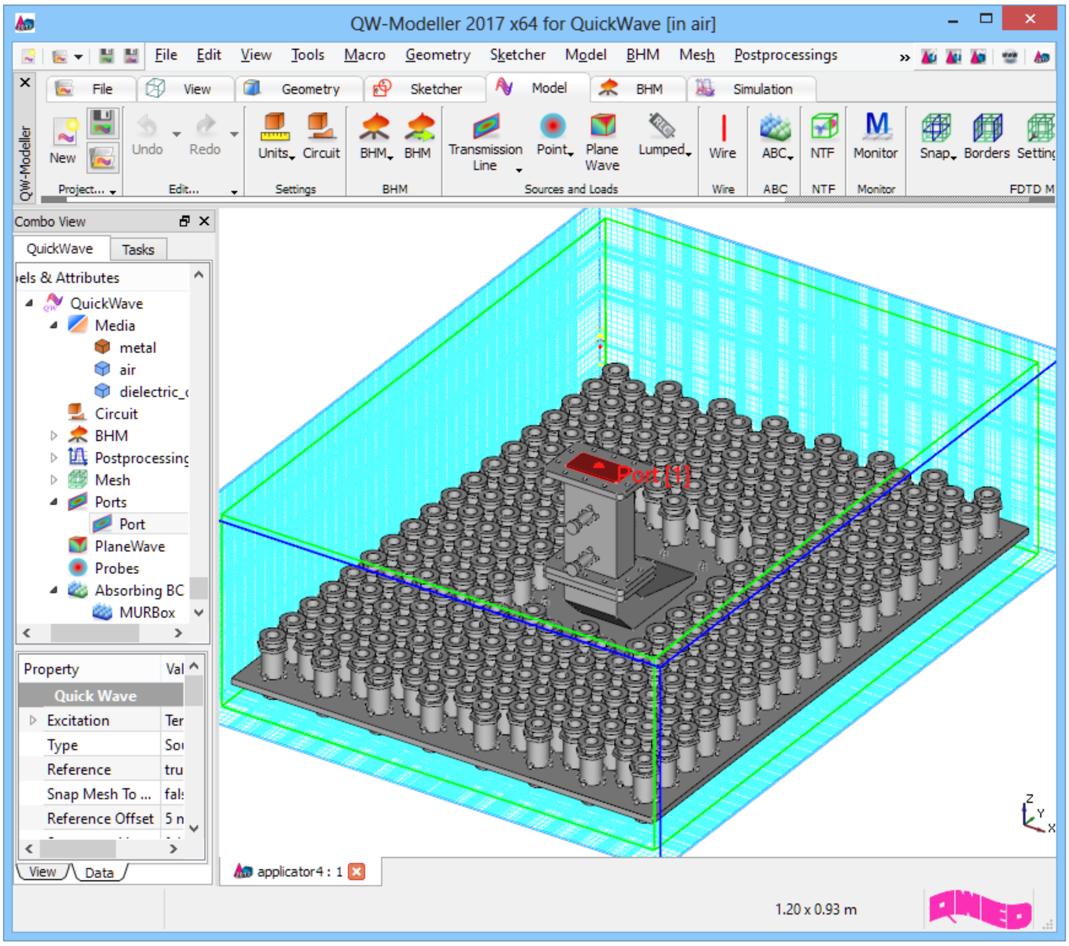

Fig. 2. Model of microwave applicator prepared in QW-Modeller [5].

The device takes advantage of application of non-ionizing microwave radiation at unlicensed ISM band, 2.4 ÷ 2.5 GHz and is fed by 1 kW source. The applicator is placed above the three-layer bituminous pavement structure: surfaces course, binder course, and base course, having the measured dielectric parameters of surface course: $\varepsilon_r = 6.5$, $\tan\delta = 0.052$ [1][3].

The simulation model utilises variable mesh size adjusted to geometry and media parameters variations, with an average cell size enforced by condition $\lambda_{min}/20$, where λ_{min} denotes wavelength at the highest frequency of electromagnetic analysis, which is 3 GHz in this case. The entire model of the microwave applicator and bituminous pavement is surrounded with absorbing boundary conditions, namely MUR with superabsorption.

The simulation scenario occupies around 120 million FDTD cells, which results in 11.5 GB of memory occupation. The FDTD simulation with QuickWave takes around 3 hours when performing multicore computations on Intel Core i7-4930K processor and around 15 minutes when taking advantage of computation option for multiple GPU cards and performing calculations on two GeForce GTX Titan cards with 6 GB memory each.

EM simulation results

Fig. 3. presents magnitude of reflection coefficient of the microwave applicator placed above bituminous pavement structure computed with QuickWave 3D. The reflection coefficient in 2.4 ÷ 2.5 GHz band, which covers the operation bandwidth of typical 1 kW magnetrons, is below -17 dB.

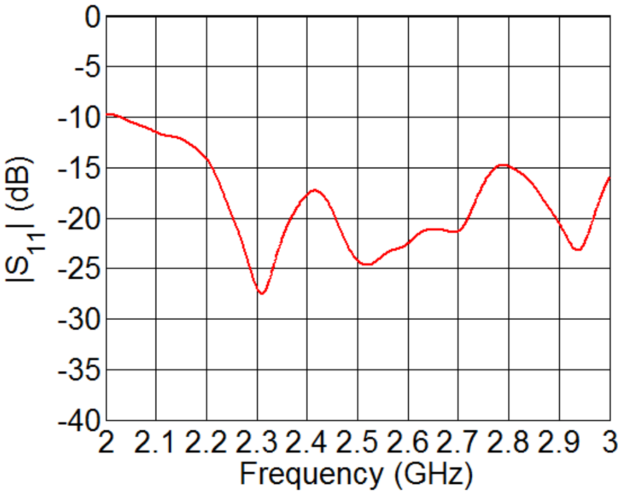

Fig. 3. Magnitude of reflection coefficient of microwave applicator placed above bituminous pavement structure computed with QuickWave 3D.

Fig. 4 shows the distribution of average power density around the microwave applicator in two cases: with cylindrical metallic chokes (a) and after removing the chokes (b). It can be well seen that the hexagonal lattice of cylindrical chokes used in this design significantly reduces the leakage of microwave power beyond device. Shielding effectiveness defined as

$$\eta = 10\log_{10}\frac{P_{radiated}}{P_{input}},$$

where $P_{radiated}$ denotes power radiated by the device into the surrounding space and P_{input} is waveguide input power, is below -40 dB in the entire 2 ÷ 3 GHz band.

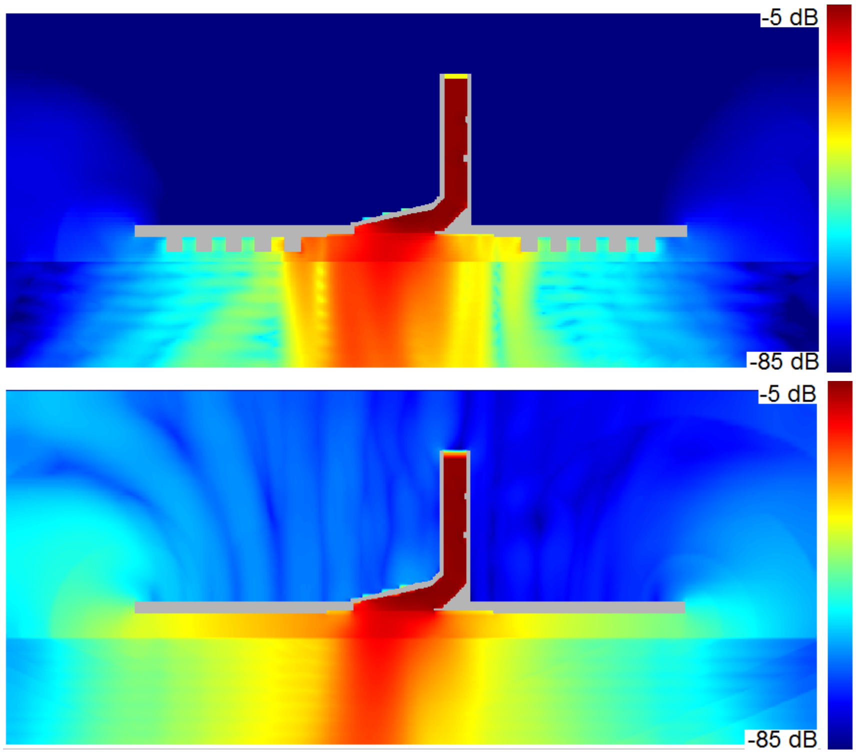

Fig. 4. Distribution of the average power density (W/mm^2) computed with QuickWave 3D, in the cross section of the microwave applicator placed above bituminous pavement structure: with cylindrical metallic chokes (upper) and without chokes (lower).

EM-thermodynamic simulation results

The design and analysis of the microwave applicator accounted also for coupled electromagnetic and thermodynamic simulations, which were performed using QuickWave 3D with its optional microwave heating module QW-BHM. The simulation scenario assumed that the bituminous pavement under the applicator is heated for 15 minutes with a source operating at 2.45 GHz, having 1 kW of mean available power. The analysis with QuickWave 3D and QW-BHM considered both, heat dissipation and conduction. The temperature distribution in the bituminous pavement under the applicator, in the middle cross section of the simulation model is presented in Fig. 5. It is well seen that microwave power is mainly dissipated in the pavement right under the applicator's aperture, in the top layer of few centimetres (surface course). Around 30% of total delivered power is dissipated in the top surface course of the pavement structure (5 cm) and 13.5 % in the volume directly under the applicator's aperture (21 x 9 x 5 cm^3). Based on the simulation data, the estimated heating rate is 4.75 °C/min [1].

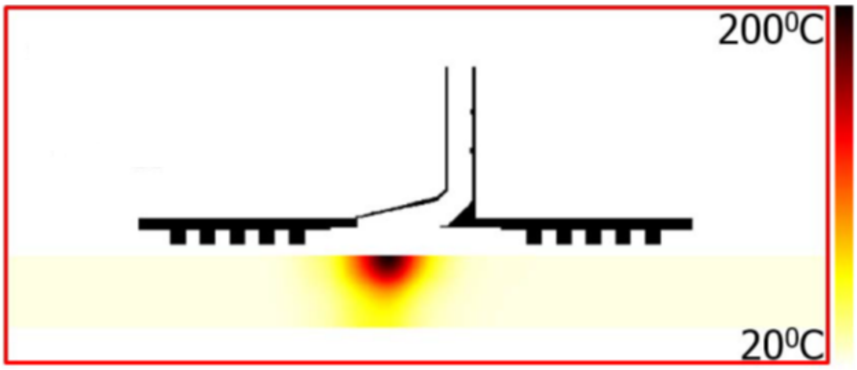

Fig. 5. Distribution of the temperature in bituminous pavement under microwave applicator computed with QuickWave 3D and QW-BHM.

Device prototype

The prototype of the designed microwave applicator has been manufactured and measured. Fig. 6 presents the photograph of an early prototype with 1 kW magnetron source, mounted on a trolley. The prototype was measured in its target operation environment, over the real bituminous pavement.

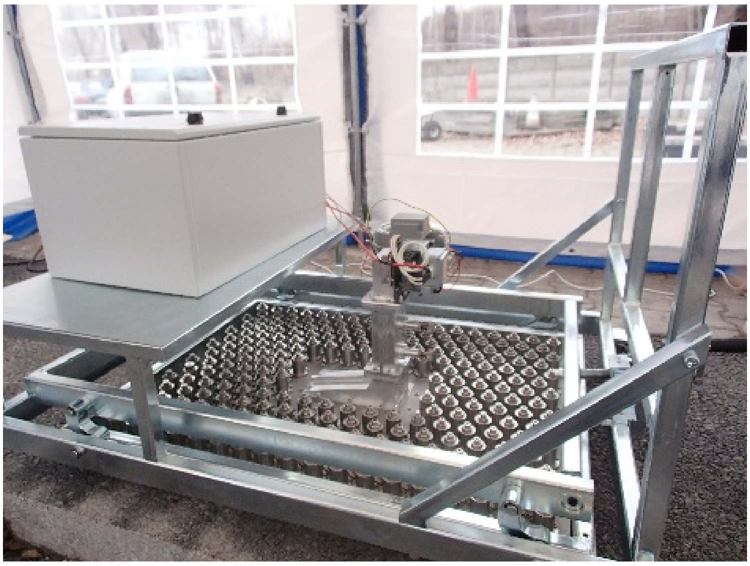

Fig. 6. A prototype of the microwave applicator for thermal bonding of bituminous surface.

Measurements results

Fig. 7 presents the comparison of simulated and measured magnitude of reflection coefficient of the microwave applicator. Ripples in the measurement data result probably from the imperfect de-embedding of long (1.5 m) RF cables operating at low temperature on site, however, a decent agreement between simulation and measurement data has been achieved. Worth indication is the fact that the measured reflection coefficient drops below -20 dB within 2.41 ÷ 2.5 GHz frequency band.

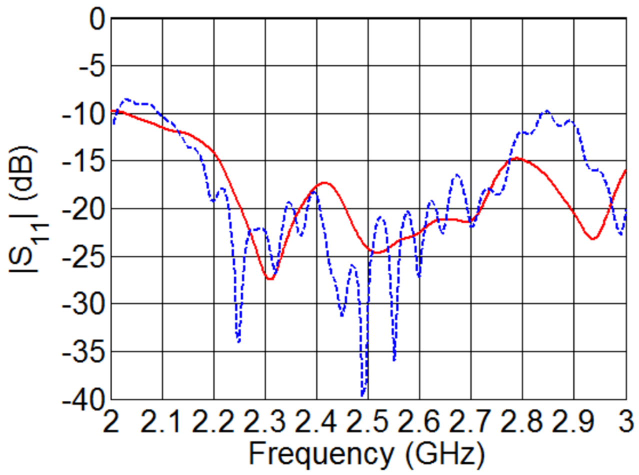

Fig. 7. Comparison of simulated and measured magnitude of reflection coefficient of the microwave applicator.

Level of microwave leakage was measured using spectrum analyser with a dipole antenna. Measured electric field value for vertical and horizontal polarisations is presented in Fig. 8. It can be noticed that the leakage on a side of the applicator is larger than in front of the device, however in both cases its level satisfies European Council occupation exposure limit of 137 V/m with a large margin.

If a power of the source is increased to 30 kW, which is necessary to obtain applicator's speed and heating rate required by the pavement construction process, level of the electric field in the worst case will increase to around 1.2 V/m and 3.6 V/m, in front and on a side of the applicator.

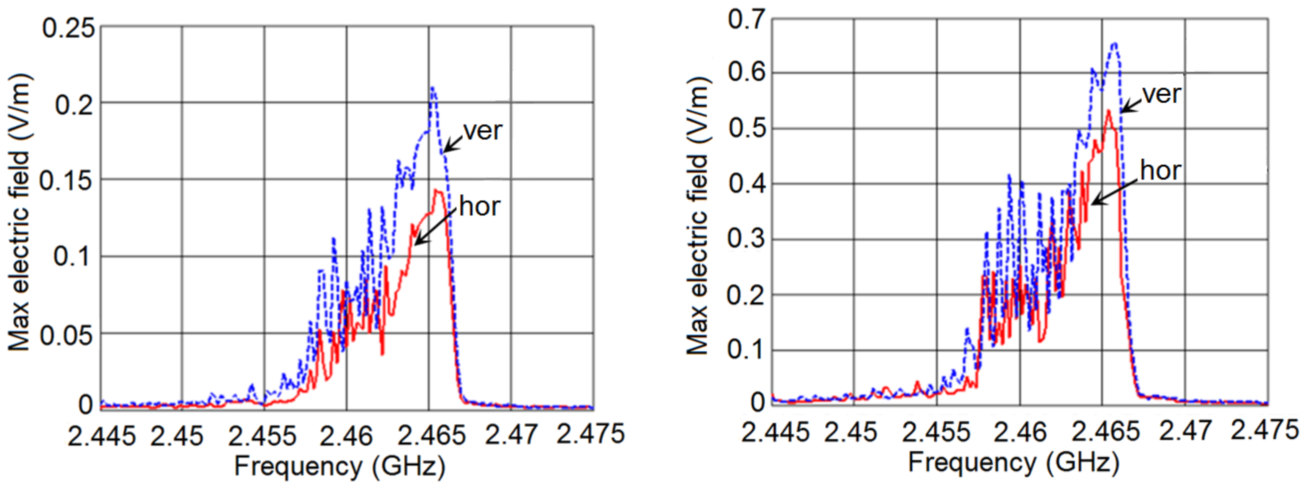

Fig. 8. Time-maximum electric field measured at 0.5 m distance from the front of the applicator (left) and from the side of the applicator (right), for both, vertical and horizontal polarisations.

Fig. 9. presents temperature signature captured with an infrared camera after 10 minutes of heating with microwave source of 1 kW mean available power. The initial temperature of the bituminous pavement was approximately 27 °C and after 10 minutes of exposure to microwave radiation, mean temperature of the pavement raised to 83.6 °C, which results in the heating rate of around 5.7 °C/min. Decent agreement with estimated heating rate of 4.75 °C/min has been achieved, considering the fact that theoretical estimation did not accounted for the bituminous material losses rising with temperature.

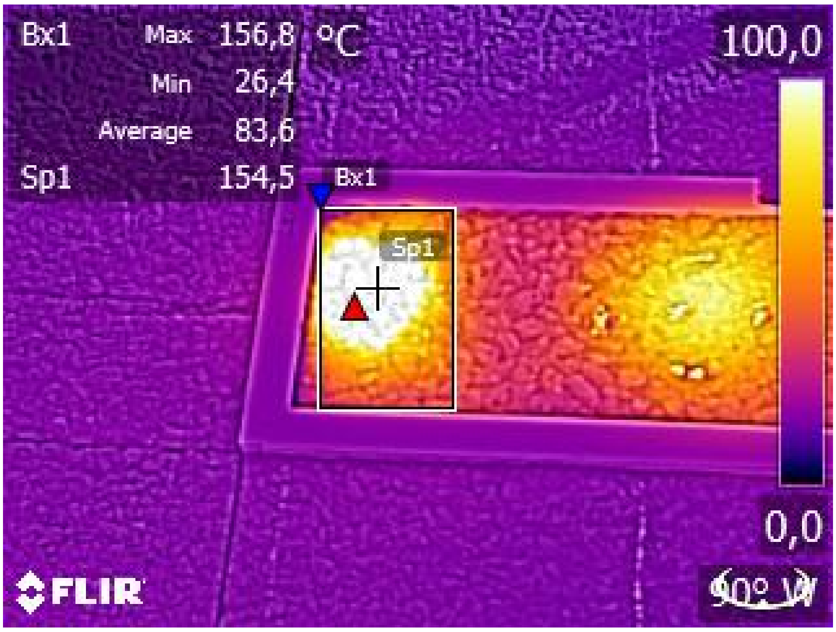

Fig. 9. Temperature signature from an infrared camera, measured after 10 minutes of exposure to microwave radiation.

The article shows a complete design cycle of the mobile microwave applicator for thermal bonding of bituminous surfaces performed with QuickWave [4] software and a set of measurement results confirming the design validity.

References

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