INTERNATIONAL JOURNAL OF HEAT AND TECHNOLOGY

ISSN: 0392-8764
Vol. 34, No. 3, September 2016, pp. 364-370
DOI: 10.18280/ijht.340303

A publication of IIETA

IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

http://www.iieta.org/Journals/IJHT

Relation Degree Analysis of Controllable Factors in the Bitumen Foaming Process

Haiying Cheng, Fudong Wei, Tao Yang * and Yongfeng Zhao

Mechanical Engineering School, Inner Mongolia University of Technology, Hohhot 010051, China

Email: yt60168@163.com

ABSTRACT

In the bitumen foaming process, the controllable factors, especially the water consumption in foaming, heating temperature of bitumen and bitumen viscosity can directly affect the technical performance of foamed bitumen. To improve the technical performance of foamed bitumen and reveal the influence rule of the controllable factors, the bitumen foaming mechanism is analyzed and the control model of the bitumen foaming behavior is established. After numerical calculation with CFD software, relation degree analysis of experimental data and simulation data was performed by utilizing the Grey relation analysis method. The average density inside the cavity flow field is used as the reference factor of theoretical analysis. Then the influence of the controllable factors on the foamed bitumen technical performance is respectively tested. The results show that the bitumen temperature affects the technical performance most significantly, water consumption of foaming secondly, and the least influentional is bitumen viscosity.

Keywords: Bitumen foaming, Controllable factor, Foamed bitumen, Average density, Grey relation analysis.

1. PREFACE

Most highways built early in China are approaching the period of repair or replacement. Road maintenance annually generates up to 160 million tons of waste bitumen pavement material, known as reclaimed asphalt pavement, (RAP) [1]. The practice of not reusing the RAP material in a timely manner will cause significant waste. Reasonable recycling and effective use of waste pavement materials has become a very urgent task. Foamed bitumen which is an environmentally friendly luting cement, is an excellent way to solve this problem [2, 3]. Foamed bitumen can be utilized in a variety of construction technologies, such as foamed bitumen recycling construction technology, foamed bitumen warm mixing technology, foamed bitumen cold mixing technology, etc. However, because of various influencing factors of bitumen foaming, controlling the bitumen foaming process is quite complicated. Thus, producing high-quality foamed bitumen is quite difficult. At present, research on bitumen foaming process controlling have mainly focused on the following areas : 1) Determining the test conditions used for obtaining the optimum asphalt foaming effect; 2) exploring the main factors influencing the behavior of bitumen foaming; 3) discussing evaluation index authenticity of foamed bitumen; 4) establishing foamed bitumen recession equation according to different types of bitumen [4-18]. See Table 1 for references.

Table 1. Study on the influencing factors of asphalt foaming behavior [4-18]

Years	Scholars	Academic viewpoint
1982	M.Brennen	Asphalt163°C and 2.0% water dosage
1982	Ruckel	Foaming chamber volume
2003	HE Gui-ping	Asphalt temperature, water dosage, air pressure, water pressure
2003	Mofreh F. Saleh	Soft asphalt foaming effect is better
2006	SHI Fang-zhi	Asphalt type, asphalt pressure, foaming water dosage, water pressure additives
2006	Yongjoo Kim	Asphalt temperature170°C, water1.3%, air pressure400KPa, water pressure 500KPa

All the analysis shows that most of the bitumen foaming mechanism research have used bitumen foaming tests and statistics of relation analysis, regression and fitting to derive a mechanism conclusion. Moreover, similar technical problems often lead to quite different conclusions in some of those research projects. To clarify the influence of the controllable factors during bitumen foaming, CFD software is used for numerical calculation and the Grey relation analysis method is utilized. Finally, the controllable factors' degree of impact is analyzed to provide a theoretical basis for producing foamed bitumen.

2. BITUMEN FOAMING MECHANISM

Hot bitumen and cold water can change into bitumen droplets and water droplets by nozzle spraying. Cold water droplets directly contact the high-temperature bitumen droplets (160 ℃) when they are sprayed into the foaming cavity at the same time. Then the change of the water occurs and generates a large amount of water vapor. Volume increases immediately lead to increasing pressure in the cavity, which makes the gas pressure into the bitumen continuous phase, forming minute foamed bitumen. Finally the minute foamed bitumen is extruded out of the cavity by the pressure in the cavity. Because the internal pressure is greater than the external pressure of the asphalt film, the minute foamed bitumen after volume expansion form a metastable state of the foam asphalt. Injecting some compressed air with a certain pressure into the cavity supports the bitumen foaming. Figure 1 displays the bitumen foaming mechanism [19-22].

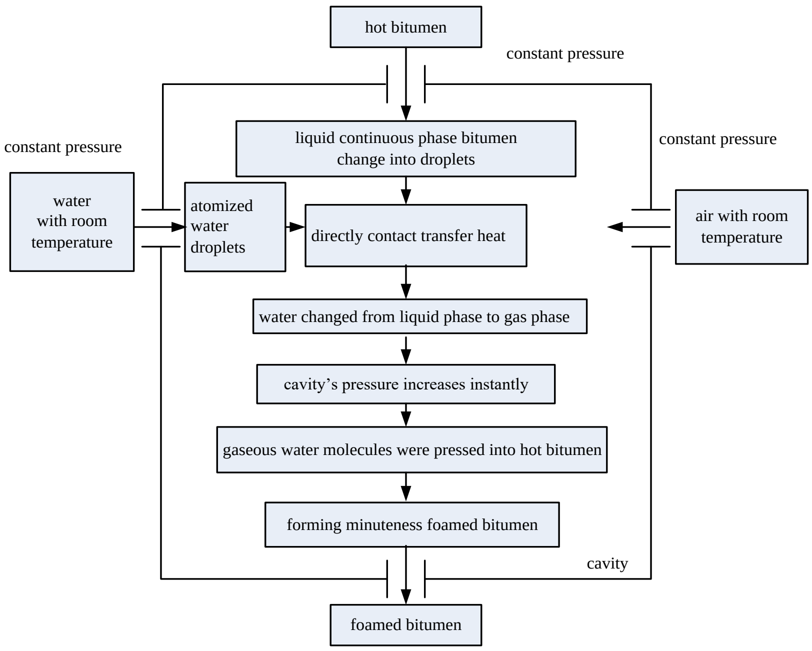


Figure 1. Bitumen foaming mechanism schematic

3. BITUMEN FOAMING CONTROLLED MODEL AND BOUNDARY CONDITIONS

Bitumen foaming is a physical change between multiphase flows. There is a strong coupling turbulent flow field between each phase fluid because each different phase has different velocity. Therefore, appropriately using the mixture model for the fluent is very important. Control equations of bitumen foaming behavior are as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial \tau}+\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0 \tag{1}$$

Momentum conservation equation:

$$\rho\frac{du}{d\tau}=\rho F_b-\nabla P+\mu\nabla^2 u+\frac{1}{3}\mu\nabla(\nabla\bullet u) \tag{2}$$

Energy conservation equation:

$$\frac{de}{d\tau}=\frac{q}{\rho}+\frac{k}{\rho}\nabla^2 t-\frac{p}{\rho}(\nabla\bullet u)+\frac{\mu\varphi}{\rho} \tag{3}$$

Turbulent kinetic energy K equation:

$$\rho\frac{dk}{dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial_k}{\partial x_i}\right]+Gk+Gb-\rho\varepsilon-Y_M \tag{4}$$

Dissipation rate equation:

$$\rho\frac{d\varepsilon}{dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

In the formulas: the ρ represents the density, u_x, u_y, u_z are respectively the velocity component at x, y, z direction; τ is time and F_b is the mass force per unit; p is the stress, e is the internal fluid energy per unit, q is the energy generated by heat exchange, G_k is the turbulence energy made by average velocity gradient; G_b is the turbulence energy made by buoyancy, Y_M is the influence made by compressible flow turbulence expansion on the total dissipation; σ_k is turbulent Prandtal constant; σ_ε is the dissipation ration Prandtl constant; k is turbulent energy; ε is the dissipation ratio.

In numerically simulating of bitumen foaming, the bitumen nozzle, water nozzle and air nozzle are referred to as"Velocity-inlet", and the foamed bitumen nozzle is"Outflow" [23]. The wall satisfies the no-slip condition, using the standard wall function method to set the near-wall region. The mixed flow field inside the cavity is characterized as gas-liquid multiphase mixture unsteady flow, where the main phase is compressed air phase, and the others are bitumen phase, water phase and water vapor phase.

4. BITUMEN FOAMING NUMERICAL SIMULATION AND RESULTS ANALYSIS

The numerical simulation of bitumen foaming can result in many physical flows distribution, such as pressure, speed, temperature, density, etc. A case of foaming water consumption, with 1%, 2%, 3%, 4%, 5% are shown in the stress diagram (Figure 2), velocity diagram (Figure 3), temperature diagram (Figure 4), density diagram (Figure 5).

As Figure 2 shows, when the dosage of foaming water changes, the internal cavity flow field will undergo a corresponding change. After being numerically calculated, the pressure, density, velocity and density averages are shown in Table 2. To date, foamed bitumen is principally measured according to two main parameters: the expansion ratio (ER), which measures the increase of bitumen in volume after being sprayed, and the half-life (HL), which evaluates the durability and stability of the foamed-state before collapsing [24-26]. This paper takes the expansion and half-life as the Grey relation degree reference factors, using HR Yang's experimental data (Table 3) to exchange and analyze. The expansion ratio and half-life test curve with different dosages of foaming water can be drawn. After the pressure, velocity, temperature and average density are numerically calculated under the same condition, the corresponding simulated curve is given (Figure 6). When the dosage of water changes, the expansion ratio, half-life, pressure, density, velocity and average density all change. It is difficult to note the degree of association among the expansion, half-life and numerical simulation of the flow field, as shown in Figure 6. Therefore, the Grey relation analysis method is adopted in order to determine which physical quantity of numerical simulation flow field has the largest relation to the expansion ratio and half-life. The physical quantity with the largest relation will be used as a theoretical evaluation factor.

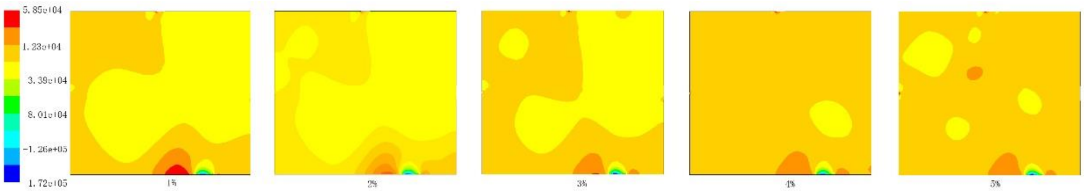


Figure 2. Pressure diagram with different dosages of foaming water

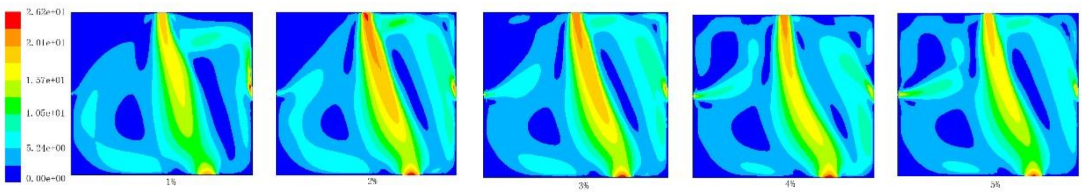


Figure 3. Velocity diagram with different dosages of foaming water

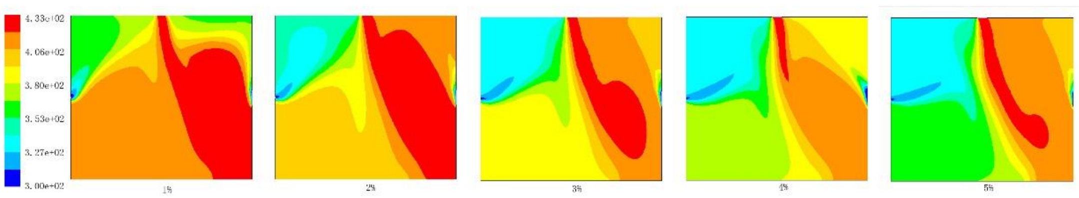


Figure 4. Temperature diagram with different dosages of foaming water

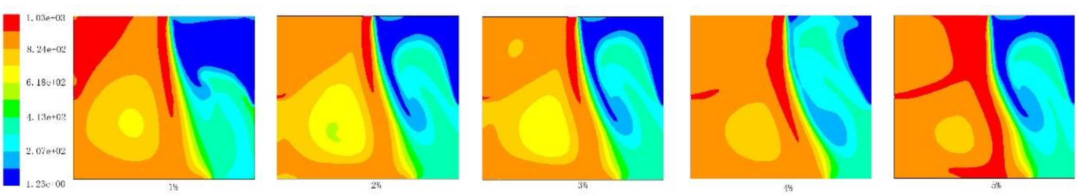


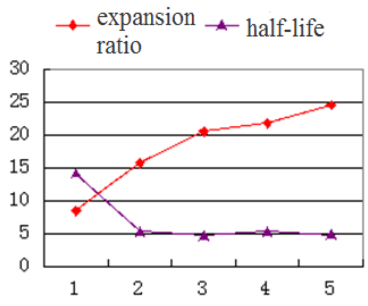
Figure 5. Density diagram with different dosages of foaming water

Table 2. Simulation results of different dosages of foaming water

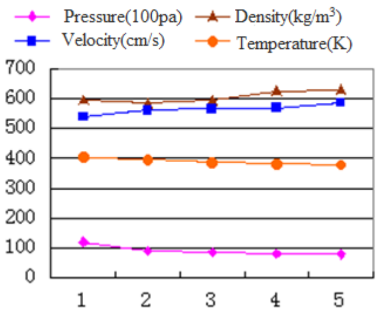
Dosages Of Foaming Water	1%	2%	3%	4%	5%
Emperature(K)	404	396	387	382	378
Velocity(Cm/S)	539	561	565	568	586
Density(Kg/M^3)	595	585	594	625	630
Pressure(Pa)	12007	9140	8567	8188	7919

Table 3. Experimental results of different dosages of foaming water

Dosages Of Foaming Water	1%	2%	3%	4%	5%
Expansion Ratio	8.4	15.7	20.5	21.7	24.5
Half-Life(S)	14.1	5.3	4.7	5.3	4.9



(a) Experimental results



(b) Simulation results

Figure 6. Result of experiment and numerical simulation

5. GREY RELATION ANALYSIS METHOD

The Grey relation analysis method analyzes the effect of all factors on the system by comparing the Grey relation degree [27-29]. The greater the Gray relation degree is, the greater the impact of the factors on the system will be. The Grey relation analysis method can refine the main factors and features that affect the system among many factors, as well as analyze the differences of effects of each factor on the system. This paper uses the Grey relation analysis method twice. First, relation degree analysis of experimental data and simulation data was performed to determine the evaluation reference factors used for theoretical analysis, which clearly characterized the association degree between the numerical results of the flow field distribution and experimental results of asphalt foaming. Second, the relation degree between the controllable factors and the reference factors was determined on the basis of evaluating reference factors used for theoretical analysis. The calculation process is as follows. Firstly, the reference sequence and compared sequence are determined. The reference sequence is a data sequence that reflects the characteristics of system behavior. The compared sequence is a data sequence composed of factors affecting the system behavior. The reference sequences are recorded as $\{X_0\}$ and compared sequences are recorded as $\{X_i\}$ .They are selected as follows:

$$X_0 : X_0 = [x_0(1), x_0(2), x_0(3) \cdots\cdots x_0(k)] \quad (i = 1, 2, 3, \cdots, n) \tag{6}$$

$$\begin{cases} X_1 = [x_1(1), x_1(2), x_1(3), \cdots\cdots, x_1(k)] \\ X_2 = [x_2(1), x_2(2), x_2(3), \cdots\cdots, x_2(k)] \\ \vdots \\ X_n = [x_n(1), x_n(2), x_n(3), \cdots\cdots x_n(k)] \end{cases} \quad (i = 1, 2, 3, \cdots, n) \tag{7}$$

Then, the reference sequence and compared sequence were dealt with using the dimensionless (initialization) method. There is no comparability due to the different units of the original factors. Therefore, sequences were dealt with to eliminate the influence of dimension to form a new sequence with the same starting point, as expressed in Eq. (8):

$$Y_i = X_i / x_i(1) = [y_i(1), y_i(2), y_i(3), \cdots\cdots, y_i(n)] \quad (i = 1, 2, 3, \cdots, n) \tag{8}$$

Then, the relation coefficient of each sequence is solved according to the calculation of Eq.(9) .

$$\eta_i(K) = \frac{\min\min|Y_0(k) - Y_i(k)| + \rho\max\max|Y_0(k) - Y_i(k)|}{|Y_0(k) - Y_i(k)| + \rho\max\max|Y_0(k) - Y_i(k)|} \tag{9}$$

where, $(i = 1, 2, 3, \cdots, k)$, ρ is resolution factor, $\rho \in$ (0, 1), ρ=0.5s, $\min_k\min_k|Y_0(k) - Y_i(K)|$ is the minimum difference between two levels; $\max_k\max_k|Y_0(k) - Y_i(k)|$ is the maximum difference between two levels. To more conveniently compare, take the average value of each sequence as the relation degree of the reference sequence and compared sequence and then calculate the relation degree according to Eq. (10).

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\eta(k) \tag{10}$$

5.1 Determination of foamed bitumen reference factors used for theoretical evaluation

As Table 4 shows, the expansion ratio (ER) and half-life (HL) are regarded as the reference sequence in the bitumen foaming test, the average temperature, average pressure, average velocity and average density of the internal flow field of the foam cavity after the numerical calculation are seen as comparison reference.

Table 4. Bitumen foaming behavior data

Factors	Data sequence(k)				
	1	2	3	4	5
ER X01	8.4	15.7	20.5	21.7	24.5
HL X02	14.1	5.3	4.7	5.3	4.9
Temperature X1	407	399	391	382	383
Pressure X2	87 887	90 853	91 205	91 652	91 776
Velocity X3	6.25	6.52	6.63	6.71	6.84
Density X4	567	573	576	593	599

After calculation, the Grey relation degree between the average values of temperature, pressure, velocity, density and the expansion rate and the half-life are obtained and listed in Table 5. r1, r2, r3, r4 represent respectively the Grey relation degree of expansion ratio with the average temperature, pressure, velocity, and density. r5, r6, r7, r8 represent respectively the Grey relation degree of half-life with the average temperature, pressure, velocity, and density.

Table 5. The degree of relation between numerical calculation physical field and foamed bitumen performance indicators

Factors	Relation	Coefficient					Relation Degree
ER	η_1	1	0.35	0.34	0.37	0.35	r1=0.5275
	η_2	1	0.33	0.32	0.33	0.32	r2=0.5386
	η_3	1	0.33	0.31	0.32	0.30	r3=0.5422
	η_4	1	0.34	0.32	0.33	0.31	r4=0.5369
HL	η_5	1	0.53	0.40	0.38	0.33	r5=0.4822
	η_6	1	0.54	0.41	0.39	0.35	r6=0.4584
	η_7	1	0.55	0.42	0.40	0.35	r7=0.4515
	η_8	1	0.54	0.41	0.39	0.35	r8=0.4604

As Table 5 shows, the factors associated with the relation degree of the expansion ratio in descending order are velocity, pressure, density and temperature fields. The factors related to the relation degree of half-life in descending order are temperature, density, pressure and velocity fields. But as Figure 6 shows, with the increase of dosage of foaming water, the expansion ratio and half-life have the opposite trend, which once again shows that the physical flow field inside the cavity has a relationship with the change trend of the expansion ratio and half-life. A theoretical evaluation of reference factors should synthetically consider both the expansion ratio and half-life as the reference sequence. Obviously, the velocity field and the temperature field are not suitable as a reference sequence. In order to consider the relationship among numerical solutions of the pressure field, density field, the expansion rate and half-life, the average value and variance value of the relation degree among pressure field, density field, expansion rate and half-life have been calculated. As shown in Table 6, the average value of the relation degree between the density field and expansion rate or half-life is the maximum, and the variance of that is the minimum. In consideration of Table 4 and 5, the average density inside the cavity is 500-600kg/m3, the average of the density field is greater than the compressed air density, and less than the density of water and bitumen. This shows that bitumen foaming is a complex physical change process, which generated a certain substance that is different from water, bitumen, and compressed air. Therefore, this paper analyzes the relation degree of controllable factors in bitumen foaming by using the average density as theoretical evaluation reference factors.

Table 6. Relation degree average and dispersion

	Pressure	Density
ER	0.5386	0.5369
HL	0.4584	0.4604
Average	0.4985	0.4987
Dispersion	0.0567	0.0541

5.2 The relational degree analysis of controllable factors in bitumen foaming

The average value of the density field inside the cavity is invoked as the reference sequence. The dosage of foaming water, bitumen temperature and bitumen viscosity are considered as comparison sequence, as shown in Table 7. The Grey relation analysis method was used again to estimate the relation degree of controllable factors. Results are displayed in Table 8.

Table 7. Numerical calculation result

Controllable Parameters			Result
Water(%)	Temperature (℃)	Viscosity (Pa•S)	Density (kg/m3)
1.5	140	0.25	498
2	150	0.16	499
2.5	160	0.11	520
3	170	0.08	528

Table 8. Grey relation degree of the Controllable parameters

Coefficient	1	2	3	4	Degree(r)
η_9	1	0.75	0.60	0.51	0.79
η_{10}	1	0.99	1	0.98	0.88
η_{11}	1	0.60	0.43	0.33	0.60

As Table 8 shows, the Grey relation degree of controllable factors and the internal density field of the cavity are r9=0.79, r10=0.88, r11=0.60. Among them, r9, r10, r11 are the relation degree of dosage of foaming water, bitumen temperature and viscosity of bitumen. All the analysis demonstrates that the dosage of foaming water, viscosity of bitumen and bitumen heating temperature will affect the bitumen foaming behavior. The degree of influence sorted in descending order is bitumen heating temperature, dosage of foaming water and bitumen viscosity. The viscosity of bitumen declines with the increase in the bitumen heating temperature. From the analysis results, within a certain temperature range the impact of bitumen viscosity changing in the bitumen foaming process is lower than that of the bitumen heating temperature. Therefore, when using the method of Grey relation analysis, selection of the range of the comparison sequence is essential. The bitumen foaming process has strong fuzziness and strong coupling characteristics. The Grey relation analysis method can provide a useful way to quantitatively analyze the bitumen foaming behavior.

6. CONCLUSIONS

(1) After the numerical calculation of bitumen foaming, among the velocity field, pressure field, temperature field and density field, the relation between the average value of the density field and the performance of the foamed bitumen is better.

(2) Taking the average density of the inner flow field as the reference standard, by utilizing the Grey relation analysis method, it was determined that that Grey relation degree of bitumen heating temperature, dosage of foaming water, bitumen viscosity respectively was 0.79, 0.88, 0.60. The results show that the dosage of foaming water, the heating temperature of bitumen and the viscosity of bitumen all affect the process of bitumen foaming, and the influence of bitumen heating temperature is greatest. The second greatest influence is the dosage of foaming water, and the influence of bitumen viscosity on the bitumen foaming process is the least influential in the three contrast sequence.

ACKNOWLEDGEMENT

This project is supported by National Natural Science Foundation of China (Grant No.51265033) and Natural Science Foundation of Inner Mongolia (Grant No.2012MS0702).

REFERENCES

[1] Jia Peng, “Research of recycling pavement structure and material for common stem road,” Ph.D. thesis, Beijing Jiao tong University, 2014.

[2] Cheng Haiying and Wang An-Lin, “Research for foam asphalt technology and equipment,” *Construction Machinery and Equipment*, vol. 41, no. 3, pp. 18-22, 2010.

[3] Cheng Hai-Ying, Zhang Yu, Wang An-Lin et al., “Foaming chamber design and evaluation based on the analysis of bitumen foaming essential characteristics,” *Chinese Journal of Mechanical Engineering*, vol. 48, pp. 13, 2012. DOI: 10.3901/JME.2012.13.152.

[4] M. F. C. Van de Ven, et al., “Development of (half-) warm foamed bitumen mixes: state of the art,” *International Journal of Pavement Engineering*, vol. 8, pp. 163-175, 2007. DOI: 10.1080/10298430601149635.

[5] Brennen M., Tia M., Altschaeffl A. G., et al., “Laboratory investigation of the use of foamed asphalt for recycled bituminous pavements,” *Transportation Research Record*, pp. 80-87, 1983.

[6] Mofreh F. Saleh, “Effect of Rheology on the bitumen foam ability and mechanical properties of foam bitumen stabilised mixes,” *International Journal of Pavement Engineering*, vol. 8, no. 2, pp. 99-110, 2007. DOI: 10.1080/10298430601149650.

[7] He, Gui Ping and W. G. Wong, “Effects Of moisture on strength and permanent deformation of foamed asphalt mix incorporating RAP materials,” *Construction & Building Materials*, vol. 22, no. 1, pp. 30-40, 2008. DOI: 10.1016/j.conbuildmat.2006.06.033.

[8] Ozturk, Hande I., and M. E. Kutay, “Novel testing procedure for assessment of quality of foamed warm mix asphalt binders,” *Journal of Materials in Civil Engineering*, vol. 26, pp. 839-844, 2014. DOI: 10.1061/(ASCE)MT.1943-5533.0000924.

[9] He, Gui Ping and W. G. Wong, “Laboratory study on permanent deformation of foamed asphalt mix incorporating reclaimed asphalt pavement materials,” *Construction & Building Materials*, vol. 21, pp. 1809-1819, 2007. DOI: 10.1016/j.conbuildmat.2006.05.024.

[10] Kim, Yongjoo, et al., “Development of mix design procedure for cold in-place recycling with foamed asphalt,” *Journal of Materials in Civil Engineering*, vol. 18, pp. 116-124, 2006. DOI: 10.1061/(ASCE)0899-1561(2006)18:1(116).

[11] Wang An-Lin, Zan Peng-Yu, Lin Fei et al., “An engineering method for parameter sensitivity analysis of asphalt foaming,” *Journal of Building Materials*, vol. 15, no. 2, pp. 218-221, 2012. DOI: 10.3969/j.issn.1007-9629.2012.02.013.

[12] Roberts, F. L., et al., “Hot mix asphalt materials, mixture design, and construction,” *National Asphalt Pavement Association*, 1991.

[13] Feng L. I., Huang S. and Jian X. U., “Foamed bitumen decay equation and bitumen foaming characteristics ev aluation,” *Journal of Tongji University*, vol. 7, pp. 103 1-1035, 2011. DOI: 10.3969/j.issn.0253-374x.2011.07. 016.

[14] Yang Hu-Rong, He Gui-Ping, Han Hai-Feng, “Effect of bitumen viscosity on foamability,” *Highway*, vol. 6, pp. 106-112, 2004.

[15] Nataatmadja, Andreas, “Some characteristics of foamed bitumen mixes,” *Transportation Research Record Journal of the Transportation Research Board*, vol. 1767, pp. 120-125, 2001. DOI: 10.3141/1767-15.

[16] Hailesilassie, Biruk W., M. Hugener and M. N. Partl, “Influence of foaming water content on foam asphalt mixtures,” *Construction & Building Materials*, vol. 85, pp. 65-77, 2015. DOI: 10.1016/j.conbuildmat.2015.03.071.

[17] Iwański, Marek and A. Chomicz-Kowalska, “Laboratory study on mechanical parameters of foamed bitumen mixtures in the cold recycling technology,” *Procedia Engineering*, vol. 57, pp. 433-442, 2013. DOI: 10.1016/j.proeng.2013.04.056.

[18] Crispino, Maurizio, et al., “Effects of foam agents on foaming processes and physical and rheological properties of bitumen,” *Sustainability, Eco-efficiency, and Conservation in Transportation Infrastructure Asset Management,* 2014. DOI: 10.1201/b16730-23.

[19] Yu Liang, Lu Hai –Bing and Shi Fang-Zhi, “Research on evaluation indexes of the foaming feature of

asphalt," *Construction Technology*, vol. 8, pp. 82-85, 2009. DOI: 10.13824/j.cnki.cmtm.2009.08.011.

[20] Shi F. Z., He Z. H., Lu W. M., et al., "Principle and study of bitumen foaming," *Journal of Building Materials*, vol. 2, pp. 183-187, 2004. DOI: 10.3969/j.issn.1007-9629.2004.02.011.

[21] Cheng Hai-Ying, Hu Zhiyong and Chen Wenyan, "The flow control method of foamed bitumen," *International Journal Of Heat And Technology*, vol. 33, no. 3, pp. 145-150, 2015. DOI: 10.18280/ijht.330322.

[22] Hailesilassie, Biruk W., M. Hugener, and M. N. Partl, "Influence of foaming water content on foam asphalt mixtures," *Construction & Building Materials*, vol. 85, pp. 65-77, 2015. DOI: 10.1016/j.conbuildmat.2015.03.071.

[23] Cheng Hai-Ying, Hu Zhiyong and Jia Lei, "Response surface methodology of foamed bitumen expansion ratio," *International Journal of Heat and Technology*, vol. 33, no.3, pp. 35-42, 2015. DOI: 10.18280/ijht.330305.

[24] Martinez-Arguelles, Gilberto, et al., "Investigating physical and rheological properties of foamed bitumen," *Construction & Building Materials*, vol. 72, pp. 423-433, 2014.

[25] Windhagen, Wirtgen GmbH, *Cold Recycling Manual*, 1st ed, Germany, 2012.

[26] A guideline for the design and construction of bitumen emulsion and foamed bitumen stabilised material (Interim Technical Guideline, TG2). 2nd ed. Pretoria, South Africa: CSIR Transportek, Asphalt Academy; 2009.

[27] Liu Si-Feng, "Emergence and development of grey system theory and its forward trends," *Journal of Nanjing University of Aeronautics & Astronautics*, vol. 2, pp. 266-272, 2004. DOI: 10.16356/j.1005-2615.2004.02.027.

[28] Lu, Meng and K. Wevers, "Grey system theory and applications: A way forward," *Journal of Grey System*, vol. 10, pp. 47-53, 2007.

[29] Trivedi, H. V. and J. K. Singh, "Application of Grey system theory in the development of a runoff prediction model," *Biosystems Engineering*, vol. 92, pp. 521-526, 2005. DOI: 10.1016/j.biosystemseng.2005.09.005.

NOMENCLATURE

ρ	Density
u_x, u_y, u_z	Velocity component at x, y, z direction
τ	Time
F_b	Mass force per unit
p	Stress
e	Internal fluid energy per unit
q	Energy generated by heat exchange
G_k	Turbulence energy made by average velocity gradient
G_b	Turbulence energy made by buoyancy
Y_M	Influence made by compressible flow turbulence expansion on the total dissipation
σ_k	Turbulent Prandtal constant
σ_ε	Dissipation ration Prandtl constant
k	Turbulent energy
ε	Dissipation ratio
$\{X_0\}$	Reference sequences
$\{X_i\}$	Compare sequences
ρ	Resolution factor
ER	Expansion ratio
HL	Half-life