The Experimental Assessment of the Deformability of Cement and Cement-asphalt Matrices with Rubber Powder Additive by Application of DIC System

J Kukielka¹,* and T Sadowski²

¹ Department of Roads and Bridges, Lublin University of Technology, Nadbystrzycka 40 str., 20-618 Lublin, Poland
² Department of Solid Mechanics, Lublin University of Technology, Nadbystrzycka 40 str., 20-618 Lublin, Poland

Abstract. The paper presents an experimental study of deformability of beams made of cement and asphalt-cement matrices with addition of rubber powder 25÷40% in relation to binders. 4-Point Bending (4-PB) tests were performed with series of specimens after 28 days of hardening. Tests were done at various temperatures, i.e. 5°C, 23°C and 50°C. Monitoring of deformation process was fully recorded by Digital Image Correlation (DIC) system ARAMIS up to the final failure. The cracks in the asphalt-cement matrices with rubber powder initiate when stress state exceeded about 50% of their flexural strength (fct, flex2). The obtained experimental results lead to the general conclusion that addition of rubber powder to different matrices causes increase of deformability, from 2 to 3 times in relation to the pure cement matrix. Moreover, it can be stated that composite materials such as asphalt-cement concrete (ACC), mineral-cement-emulsion mixes (MCEM) with rubber powder additive are more flexible in comparison to the pure cement concrete (CC).

1. Introduction

Composite materials, for instance cement concretes (CC), asphalt-cement concretes (ACC), mineral-cement-emulsion mixes (MCEM), as well as those with added rubber powder, are considered to be heterogeneous. Different types of matrices, as a continuous phase of such complex materials and inclusions reinforcing a matrix, are essential components of composite structures. Therefore, the overall properties of considered composites depend on mechanical properties of matrices and inclusions.

In Western Europe and the USA asphalt-cement matrices made by adding asphalt emulsion (AEm) to cement paste are most frequently used in roads recycling; in such matrices the amount of cement in recycled mineral mix usually does not exceed 2%. Cement accelerates asphalt emulsion setting and the initial strength of the mix [1, 2, 3, 4, 5, 6]. The MCEM containing more than 2% of cement have properties similar to those of cement-stabilised mineral mixes [5].

The proposed addition of rubber powder to the MCEM should contribute to improved durability and reduced resilient modulus, as may be concluded from preliminary research [7].

The use of waste tires in road construction was described in the monograph based on the review of national and foreign research [8].

Chippings and granules were used in numerous lab tests of cement concretes intended for the construction of yards and playing fields while crumb rubber was used for instance as an addition to hot asphalt in “dry process” or “wet process” technology [9]. Crumb rubber in “dry process” is added to
mixing plant in the amount of 3±4% of the mix mass. Hot mix-asphalt with added crumb rubber shows increased resistance to temperature changes, for instance to thermal cracks in road pavement layer. Asphalt-rubber binders used for surface treatment and crack relief layers are known from a few industrial technologies, e.g. McDonald [10] or SAMI (Stress Absorbing Membrane Interlayer) [11]. The properties and usability of crumb rubber depend on the rubber type, manner of grinding, shape of particles, specific surface and modification manner [9, 12, 13].

Asphalt pavements are generally designed based on two criteria:
1. asphalt concrete fatigue,
2. subgrade compressive strain.

The asphalt concrete fatigue equation contains calculation of tensile strain in the bottom of asphalt layer [14]. According to this criterion the destructive tensile strain of asphalt mixture should be specified. Different fatigue criteria should be applied to pavement with the MCEM. For instance in publication [15] fatigue equation of pavement with the MCEM was proposed and the minimal level of damage strain which guarantees one million load cycles was established \( \varepsilon_0 = 170 \times 10^{-6} \) m/m – for fatigue damage parameter equal to \( D_t = 30\% \).

In this paper we present results of the 4-PB deformation tests on the above composites with different matrices, starting from purely elastic response, cracks initiation and their further propagation up to the final failure.

In order to test deformation stages we used beams of dimensions 250x50x50 mm made of cement or asphalt-cement matrices with addition of rubber powder. The whole deformation process was recorded using the 3D optical DIC system ARAMIS, which is very useful in case of many different construction materials, e.g. [16-26]. Deformation analysis makes it possible to determine the deformation value in the tested specimen plane from 0.05% to >100% with accuracy of 0.01% [27]. The system allows to locate cracks and trace their propagation from the width of 0.01 mm [16, 17, 28] and was successfully used in works concerning concrete resistance to cracks for the analysis of initial cracks propagation [28, 29, 30, 31].

2. Materials used for matrix preparation

In accordance with Polish requirements concerning the MCEM [3] Portland cement CEM I or Portland composite cement CEM II class 32.5 or 42.5, which complies with the requirements of PN-EN 197-1 standard “Cement. Part 1. Composition, requirements and conformity criteria for common-use cements” should be used. Portland cement CEM I 42.5 R was adopted to make matrices.

Currently, in deep cold recycling slow-setting overstable asphalt emulsion C60 B10 ZM/R as per PN-EN 13808:2013-10 is used and replaces previous C60 B5 R emulsion as per PN-EN 13808:2010. Asphalt emulsion C60 B5 R was adopted to make matrices.

The rubber powder used in tests was made by milling rubber at room temperature to obtain 0/1 mm grading.

3. Specimen preparation and testing

The subject of research were the following compositions of matrices (W – water, CEM – cement, AEm – asphalt emulsion, RP – rubber powder):

A – W:CEM = 1:2 – cement matrix with known properties in the case of concretes [32] is also used in lean concretes and aggregates stabilised with hydraulic binders,
B – CEM:RP = 1.5:1 – cement matrix with added rubber powder used in standard and lean concretes [33, 34, 35],
C – AEm:CEM = 3:5 – asphalt-cement matrix with dominant content of cement which occurs in most mixes used in cold recycling in Poland [3],
D – AEm:CEM:RP = 1:1:1 – asphalt-cement matrix with added 0/1 mm rubber powder with the same content of components (m/m),
E – AEm:CEM:RP = 1:1.5:1 – asphalt-cement matrix with added 0/1 mm rubber powder with increased content of cement (m/m),

...
F – AEm:CEM:PR = 1:2:1 – asphalt-cement matrix with added 0/1 mm rubber powder with the cement content corresponding to the content of the remaining components (m/m).

From each matrix composition 9 beams of 250×50×50 mm in dimensions were made. All the matrix compositions had the W/CEM ratio within the range of 0.5÷0.6 in order to obtain plastic consistence and to prevent segregation of components in the moulds. The specimens were consolidated by gravitational compaction and were left in moulds for 24 hours; after this time they were demoulded and stored for 28 days in room temperature, protected from water evaporation.

To obtain strain fields using the ARAMIS system it is necessary to introduce points pattern on the specimen surface, which is scanned by the DIC system and then its digital image is created. In the experimental tests it was assumed that vertical displacement rate of the loading head during 4-PB process was equal to 0.2 mm/min. The DIC system enables saving the entire deformation test as a video, which makes thee analysis of the whole specimen destruction process possible from the beginning of loading until its destruction [27].

The horizontal tensile strain measurements $\varepsilon_t$ were concentrated in a central bottom part of the specimen, between the points at which loading was applied. The analysed fragment of the specimen has length and height equal to approximately 50 mm and 10 mm, respectively.

4. The results of asphalt cement matrices tests

The flexural strength in the 4-PB tests were performed in temperatures 5°C, 23°C and 50°C. For each matrix composition we prepared 3 beams, which were stored for at least 4 hours in a climate chamber prior to the test. The experimental tests were performed immediately after the specimens were removed from the chamber. The sample deformations $\varepsilon_t$ were measured by application of the ARAMIS and were presented in Fig. 1.

![Figure 1](image-url)

**Figure 1.** The 4-PB flexural strength of the beam made of the F matrix measured in 5°C. The results of experimental measurements and calculations are summarised in Table 1 and Fig. 2.
Table 1. The average values of tensile strains $\varepsilon_t$ and flexural stresses for characteristic points of deformation processes of specimens made of cement and asphalt-cement matrices with added rubber powder.

| Matrix | Temperature of tested beams $[^\circ C]$ | Tensile strain initiating a crack $\varepsilon_t [%]$ | Flexural stress at the moment of cracking $\sigma_{\text{flex2}} [\text{MPa}]$ | Flexural strength $f_{\text{c, flex2}} [\text{MPa}]$ | $\frac{\sigma_{\text{flex2}}}{f_{\text{c, flex2}}}$ |
|--------|-----------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| A      | 5                                      | 0.05                                            | 0.71                                            | 1.29                                            | 0.55                                            |
|        | 23                                     | 0.07                                            | 0.37                                            | 0.67                                            | 0.54                                            |
|        | 50                                     | 0.06                                            | 0.21                                            | 0.33                                            | 0.63                                            |
| B      | 5                                      | 0.08                                            | 0.84                                            | 1.26                                            | 0.67                                            |
|        | 23                                     | 0.23                                            | 0.52                                            | 1.03                                            | 0.51                                            |
|        | 50                                     | 0.17                                            | 0.20                                            | 0.70                                            | 0.28                                            |
| C      | 5                                      | 0.12                                            | 2.50                                            | 2.67                                            | 0.94                                            |
|        | 23                                     | 0.10                                            | 0.88                                            | 0.97                                            | 0.91                                            |
|        | 50                                     | 0.17                                            | 0.52                                            | 0.85                                            | 0.61                                            |
| D      | 5                                      | 0.31                                            | 0.51                                            | 0.89                                            | 0.57                                            |
|        | 23                                     | 0.16                                            | 0.28                                            | 0.64                                            | 0.44                                            |
|        | 50                                     | 0.18                                            | 0.14                                            | 0.34                                            | 0.42                                            |
| E      | 5                                      | 0.15                                            | 0.80                                            | 1.28                                            | 0.62                                            |
|        | 23                                     | 0.13                                            | 0.56                                            | 0.78                                            | 0.72                                            |
|        | 50                                     | 0.14                                            | 0.19                                            | 0.40                                            | 0.47                                            |
| F      | 5                                      | 0.15                                            | 0.66                                            | 1.12                                            | 0.66                                            |
|        | 23                                     | 0.17                                            | 0.29                                            | 0.51                                            | 0.56                                            |
|        | 50                                     | 0.13                                            | 0.18                                            | 0.32                                            | 0.55                                            |

Figure 2. The values of the tensile strain $\varepsilon_t$ initiating cracks during 4-PB strength tests for beams made of matrices: A, B, C, D, E, F after their maturing during 28 days and tested in 5°C, 23°C, 50°C.

5. Conclusion
The performed tests of mechanical properties of specimens taken from cement and asphalt-cement matrices with addition of rubber powder reveal that deformability of the considered composites increased from 2 to 3 times in relation to cement matrix while influencing flexural strength 0.7 to 1.0 times.

The cracks initiation in the AEm:CEM:RP matrices appears when stress exceeded about 50% of their flexural strength \( f_\text{flex} \). In case of the AEm:CEM matrix this stress was about 90% in temperature less than 23°C. In temperature 50°C cracks initiation took place respectively when stress exceeded 40% and 60%.

The tensile strain corresponding to cracks initiation \( \varepsilon_i \) in the cement matrix W:CEM = 1:2 was equal to \( \varepsilon_i = 0.05\% \) regardless of the test temperature. In case of the AEm:CEM:RP = 1:2:1 and AEm:CEM:RP = 1:1.5:1 matrices the appropriate values of strains were \( \varepsilon_i = 0.13\% \pm 0.15\% \). The largest tensile strain \( \varepsilon_i \) was obtained for matrices with high content of the rubber powder, i.e. for CEM:RP = 1.5:1 and AEm:CEM:RP = 1:1:1. The experimentally estimated tensile strain were equal to \( \varepsilon_i = 0.23\% \) and \( \varepsilon_i = 0.31\% \), respectively.

The influence of temperature on the threshold of critical deformations causing cracks initiation is not significant.

One can conclude, summarizing, that the most important factor which influences the deformability of matrices is their composition and the amount of added rubber powder.

It is necessary to formulate a numerical model describing the mechanical response of the beams including formation of the process zone in the crack tip and its propagation, e.g. [36 – 48].

6. References

[1] Asphalt Recycling and Reclaiming Association (ARRA) 2001 Basic asphalt recycling manual, Publication No. NHII01-022 (Annapolis, Maryland, USA)

[2] Merrill D, Nunn M E and Carswell I 2004 A guide to the use and specification of cold recycled materials for the maintenance of road pavements. TRL Report 611, Transport Research Laboratory, (Crowthorne, UK).

[3] General Directorate for National Roads and Motorways 2014 Manual design and embedding of mineral-cement-emulsion (MCE) mixtures. Warsaw, Poland

[4] Xu J, Huang S, Qin Y and Li F 2011 Int. J. of Pavement Research and Technology 4 48–55

[5] Pavement Recycling Guidelines 2003 PIARC Committee C7/8 – Road Pavements.

[6] Road Pavement Rehabilitation Techniques Using Enhanced Asphalt Mixtures 2004 Final Technical Report PARAMIX.

[7] Kukielka J 2017 Civil Engineering and Architecture (Budownictwo i architektura) 16 53-63

[8] Horodecka R, Kalabinska M, Pilat J, Radziszewski P and Sybilski D 2002 Waste tires management in road construction. Book of Road and Bridge Research Institute (Zeszyt Instytutu Bałtyckiego Dróg i Mostów) 54

[9] Epps J A 1994 Uses of Recycled Rubber Tire in Highways Practice. NHRP Synthesis, TRB National Research Council Press (Washington D.C.)

[10] McDonald C H 1969 Asphalt Rubber Compounds and Their Applications For Pavement California Streets and Highway Conference

[11] Hardy T A, Brock L G 1985 Stress Absorbing Membrane Interlayer. Experimental Feature Final Report. Project OR 77-03. Federal Highway Administration.

[12] Monismith C L 1985 Improved Asphalt Mix Design. Proceedings Association of Asphalt Pavenig Technology. 54

[13] Takellou H B 1991 Benefits of Recycling Waste Tires in Rubber Asphalt Paving. Transportation Research Board, (Washington D.C.)

[14] Asphalt Institute 1982 Research and Development of the Asphalt Institute’s Thickness Design Manual (MS-1), 9th edition. Research Report 82-2.

[15] Kuźniewski J, Skotnicki Ł, Szydło A 2015 Bulletin of the Polish Academy of Sciences.
Technical Sciences 63, DOI: 10.1515/bpasts-2015-0012

[16] Sadowski T, Marsavina L, Peride N, Craciun E-M 2009 Comput. Mat. Sci. 46 687-693
[17] Marsavina L, Linul E, Constantinescu DM, Apostol D, Voiconi T, Sadowski T 2014 Eng. Fract. Mech. 129 54-66
[18] Sadowski T, Golewski P 2012 Comp. Mater. Sci. 52 293-297
[19] Nakonieczny K, Sadowski T 2009 Comp. Mater. Sci. 44 1307-1311
[20] Sadowski T, Nakonieczny K 2008 Comput. Mat. Sci. 43 171-178
[21] Marsavina L, Sadowski T 2007 Int. J. Frac. 145 237-243
[22] Sadowski T, Samborski S 2008 Comput. Mat. Sci. 43 75-81
[23] Postek E, Sadowski T 2011 Compos. Interf. 18 57-76
[24] Sadowski T, Golewski P 2012 Comp. Mater. Sci. 64 285-288
[25] Marsavina L, Linul E, Voiconi T, Sadowski T 2013 Polymer Testing 32 673-680
[26] Sadowski T, Marsavina L 2011 Comput. Mat. Sci. 50 1336-1346
[27] ARAMIS v6 User Manual, GOM mbH, Mittelweg 7-8 D-38106 Braunschweig
[28] Ajdukiewicz C, Gajewski M and Mossakowski P 2010 Logistyka 6 28–35
[29] Goszczyńska B and Tworzewska J 2014 Przegląd Budowlany 12 44–49
[30] Golewski G, Sadowski T 2014 Constr. Build. Mat. 51 207-214
[31] Golewski G, Golewski P, Sadowski T 2012 Comput. Mat. Sci. 62 75-78
[32] Brandt A M 2010 Concrete diagnosis based on structure testing. 56 Konferencja Naukowa Komitetu Inżynierii Lądowej i Wodnej PAN oraz Komitetu Nauki PZITB. Kielce – Krynica. p 57–71
[33] Oldakowska E 2015 Ecological Engineering. 43 49–54. DOI: 10.12912/23920629/58902
[34] Sadowski T and Pietras D 2014 Solid State Phenomena 216 67-72
[35] Sgobba S, Marano G P, Borsa M and Molfetta M 2010 Use of Rubber Particles from Recycled Tires as Concrete Aggregate for Engineering Applications. Second International Conference on Sustainable Construction Materials and Technologies. Università Politecnicadelle Marche, Ancona, Italy. Vol. 1 465 p 47–58
[36] Gajewski J, Sadowski T 2014 Comp. Mater. Sci. 82 114-117
[37] Dębski H, Sadowski T 2014 Comput. Mat. Sci. 83 403-411
[38] Ivanov IV, Sadowski T, Pietras D 2013 Europ. Phys. J. Special Topics 222 1587-1595
[39] Marsvina L, Sadowski T, Kneč M 2013 Eng. Fract. Mech. 108 139-151
[40] Birsan M, Sadowski T, Marsavina L, Linul E, Pietras D 2013 Int. J. Solids and Struct. 50 519-530
[41] Balawender T, Sadowski T, Knec M 2011 Arch. Metal. Mat. 56 439-446
[42] Balawender T, Sadowski T, Golewski P 2011 J. Adhesive Sci. Technol. 25 2391-2407
[43] Sadowski T, Bec J 2011 Comput. Mat. Sci. 50 1269-1275
[44] Burlayenko V, Sadowski T 2012 Comput. Mat. Sci. 52 212-216
[45] Burlayenko V, Sadowski T 2012 Finite Elements in Analysis and Design 62 49-64
[46] Marsavina L, Sadowski, T 2008 Polymer Testing 27 941-944
[47] Samborski S, Sadowski T, 2010 Jour. Amer. Cer. Soc. 93, 3607-3609
[48] Sadowski T, Golewski P, Kneč M 2014 Comp. Struct. 112, 66-77