Budapest University of Technology and Economics
Faculty of Civil Engineering

Thesis booklet

ASSESSMENT AND ANALYSIS OF THE BEHAVIOUR OF THE RAILWAY SUPERSTRUCTURE IN CRUSHED STONE BALLAST BED STABILIZED BY BALLAST BONDING TECHNOLOGY UNDER STATIC AND DYNAMIC LOADS

Ph.D. dissertation

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1. INTRODUCTION

Since the appearance of the railway traffic demands have been increasing continuously towards higher speed, bigger traffic safety, better travel conveniences and the optimization of running costs. Satisfying these demands is absolutely necessary to maintain and increase the competitiveness of railway public transport. This means that reserving and increasing the competitiveness, functional efficiency and service quality of railway traffic has always remained a challenge. We also have to mention that railway infrastructure – as one of the determining elements of railway materials – is an important cost factor. That is why improving quality, increasing efficiency and cost saving require to develop and adopt those engineering technologies which are of higher standards, more persistent, efficient and cheaper by all means. Because of the listed reasons railway traffic needs to develop and reform continuously that requires in depth-developments. Ballast bonding technology is also a result of a development like this and its turn-out offers many new opportunities in planning, building and maintaining railway tracks.

Ballast bonding technology is a relatively new stabilization method that can ensure the geometrical and structural stability of railway crushed stone ballast bed, the protection against loosening crushed stones and can also increase ballast resistance (lengthwise and lateral ballast resistance). Ballast bonding first appeared in Japan outside Europe till in Europe in Germany in the late 80's. Since then this technology has been used in many countries worldwide among others in Hungary as well since 2001.

Ballast bonding technology in case of railway tracks is usually used when classical railway track construction – rails, rail fastenings, sleepers and crushed stone ballast bed – does not meet the demands for some reason. These demands can be for example preventing crushed stones from moving, reserving the profile and measures of crushed stone ballast bed, increasing the geometrical and structural stability, lengthwise and lateral ballast resistance and strength of crushed stone ballast bed. The advantage and significance of ballast bonding technology reside in satisfying the listed demands directly, and these indirectly result in rising track reserving period and decreasing track reserving costs specifically. Another advantage of the technology is that it can be used in many areas – because of the listed demands of all kinds – and it is used in railways of various forms (high speed railway, railway, tram train, tram and subway).

2. MOTIVATION OF THE TOPIC SELECTION

As ballast bonding technology is a relatively new method, the number of related literature and previous foreign and Hungarian analysis are very low. What is more, companies producing bonding material almost always do only internal quality control, that means analysing and checking of the features of the bonding material and not the parameters of the bonded crushed stone ballast bed's behaviour. These measurements are basically material-approached, solely from the aspect of the bonding material and not from the aspect of the features, demand and behaviour of the railway superstructure of crushed stone ballast bed. As the ballast bonding technology and the bonding material are for satisfying demands in the railway superstructure of crushed stone ballast bed, ballast bonding technology needs to be basically a railway professional question not a bonding technological one. Unfortunately, only a few of the previous analysis that are still of low number can be really evaluated, and what is more they are very one-way (analyse only a tight area in connection with ballast bonding), so they do not examine those questions, technical parameters, features or coherences which would be very important to know the technology based on scientific validity.

Following from the listed above related to the ballast bonding technology – because of the low number of literature and previous measure results that can be evaluated – the railway professional background based on scientific validity is really missing, because railway professionals mostly work by experiences and not by facts supported by science (coherences, consequences and statements combined with measurements and calculations). Furthermore, it is in spite of the fact that ballast bonding technology is used in many countries and more and more places for solving various problems, because this technology has become a relatively widespread technical solution nowadays.

Considering the mentioned reasons, I am really convinced that the subject of my Ph.D. dissertation is very actual, which is the assessment and analysis of the behaviour of the railway superstructure in ballast bed stabilized by ballast bonding technology under static and dynamic loads.

3. AIMS OF THE DISSERTATION

The aim of my Ph.D. dissertation is that through performing different assessments and analysis to determine on a scientific basis new scientific relationships, properties and technical parameters, which have not been determined previously but are essential in the planning, building and maintenance of the railway tracks with crushed stone ballast bed stabilized by ballast bonding technology. I consider the following elements that are need to be determined on scientific basis:

- During the application of ballast bonding technology the low and high quantity limits of materials required for one bonding layer.
- Influence of the application of ballast bonding technology to the functionality of the railway ballast bed (water permeability, elasticity and rigidity).
- Influence of the application of ballast bonding technology to the stress values of the railway superstructure caused by vertical loads.
- How big lateral ballast resistance can be achieved through ballast bonding technology and with this lateral ballast resistance which is the smallest critical curve radius where continuously welded rail tracks can be built.
- With regard to the lateral ballast resistance what is the effectiveness and performance of the application of the ballast bonding technology, the safety caps and the Y steel sleepers.
- What are the alignment keeping and the changes of geometric conditions of the continuously welded rail tracks with crushed stone ballast bed stabilized by ballast bonding technology and fixed with safety caps.

4. METHODOLOGY, SHORT REVIEW OF THE DISSERTATION

The aims were fulfilled through laboratorial tests, track measurements at traffic railway tracks, theoretical calculations and detailed analysis of their results. In order to answer the important questions determined within the aims and to determine new scientific relationships, properties and technical parameters I built up my Ph.D. dissertation in the following logical structure – according to the following chapters:

Following the introduction (Chapter 1) of my Ph.D. dissertation in Chapter 2 I present the ballast bonding technology in a technical point of view. I present the theoretical background of the ballast bonding technology, the conditions of its application, areas of utilization and the history of its development and appearance.

In Chapter 3 first of all I review the major previous foreign and Hungarian laboratorial tests and track measurements in connection with the ballast bonding technology and their results, experiences and observations. Following the review I carry out the critical analysis and evaluation of the presented previously executed tests.

As neither the professional literature nor the previous studies give guidelines for the optimal quantity of the bonding material (which I consider as basic deficiency) in Chapter 4 based on my own laboratorial test and the analysis of the results of my measurements I determine on a scientific basis the low and high quantity limits of materials required for one bonding layer during the application of ballast bonding technology. The technical significance of this is that I define one low quantity limit for the successful and quality ballast bonding and one high limit for the rational and economical ballast bonding.

As ballast bonding can change the properties of the crushed stone ballast bed by bonding the crushed stones together (may have effect on the functionality of the ballast bed), therefore I consider essential the assessment and analysis of the effects of the ballast bonding technology to the functionality of the railway crushed stone ballast bed. Therefore in Chapter 5 based on my own laboratorial tests and analysis of the results of my measurements I determine on a scientific basis firstly the effects of the ballast bonding technology to the water permeability of the crushed stone ballast bed and after the effects of the ballast bonding technology to the elasticity (rigidity) of the crushed stone ballast bed. The technical significance of the measurements and analysis is that it shows the changes of the basic properties of the crushed stone ballast bed as the effect of ballast bonding technology.

As the elasticity (rigidity) of the crushed stone ballast bed has influence to the stress values of the railway superstructure caused by vertical loads, therefore I consider important the analysis of the effects of the change in elasticity (rigidity) achieved through ballast bonding technology to the stress values of the railway superstructure caused by vertical loads. Due to this reason in Chapter 6 through theoretical calculations and analysis of results of my calculations I determine on a scientific basis the effects of ballast bonding technology to the stress values of the railway superstructure caused by vertical loads.

As the lateral resistance is very important in terms of the position safety of the continuously welded rail track for its improvement one option is the ballast bonding technology, therefore in Chapter 7 through own laboratorial tests, own railway track measurements, theoretical calculations and the analysis of their results I determine on a scientific basis the achievable lateral ballast resistance through ballast bonding technology and the smallest critical curve radius where continuously welded rail tracks can be built. The technical significance of this is in the opportunity of converting the joined railway tracks with small radius curves to continuously welded rail tracks.

Besides ballast bonding technology there are other opportunities to increase the lateral ballast resistance, such as safety caps or Y steel sleepers. Each of the three different technologies helps the lateral ballast resistance of railway tracks with crushed stone ballast bed. As the effectiveness and performance of these solutions have not been compared so far, therefore in Chapter 8 through railway track measurements and the analysis of their results I determine on a scientific basis the effectiveness and performance of the ballast bonding technology, the usage of safety caps and the installation of Y steel sleepers with regard to the lateral ballast resistance.

As the value of the lateral ballast resistance has effect on the alignment keeping and the geometric condition changes of the railway track, therefore in Chapter 9 through the processing, assessment and analysis of the results of the mechanical railway track measurements I determine on a scientific basis the alignment keeping and the geometric condition changes of the continuously welded rail tracks with crushed stone ballast bed stabilized by ballast bonding technology and fixed with safety caps.

In Chapter 10 of my Ph.D. dissertation I summarize my thesis according to my statements and conclusions based on my laboratorial tests, railway track measurements, theoretical calculations, their results and experiences and based on the detailed analysis of these results. The technical significance of my thesis is that provides new, scientific-based results for the planning, building and maintenance of the railway tracks with crushed stone ballast bed stabilized by ballast bonding technology.

It should be noted that in my Ph.D. dissertation I only take into consideration the technical aspects, therefore I do not engage in economical tests and my Ph.D. dissertation assumes the existence of the conditions of the ballast bonding technology and their observance in all cases.

5. THESES

THESIS 1

Based on the experiences of the executed laboratory tests I hereby determined that during the structural bonding, the definition of a lower and an upper threshold limit regarding the quantity of the specific bonding material is necessary for the (successful and high quality, as well as reasonable and economic) development of one bonding layer with complete thickness (25 cm).

Based on the results of the executed laboratory tests and the detailed analyses of the results, during the structural bonding at the development of one bonding layer with complete thickness (25 cm) I determined

- **the lower threshold limit in the value of 4,0 kg/m^2 and**
- **the upper threshold limit in the value of 14,0 kg/m^2,**

so the interval of the quantity of the specific bonding material is between 4,0 and 14,0 kg/m^2. [12]

Through laboratorial tests I defined the breaking power of the 25 cm thick ballast bonded (rail) bed test bodies. During the tests the bonding material quantity below 4,0 kg/m^2 seemed to be low for the full bonding of the 25 cm thick crushed stone ballast bed layer, however tests with bonding material quantity above 4,0 kg/m^2 were feasible. During the analysis of the test results I showed a tight relationship between the breaking power and the bonding material quantity (**Figure 1**). I proved through the analysis of the relationship that the quadratic polynomial function shows a decreasing nature (there is lower growth in the breaking power at the same growth of bonding material), therefore I stated that it is not worth increasing the bonding material above 14,0 kg/m^2 as it will not result in significant growth of the breaking power.

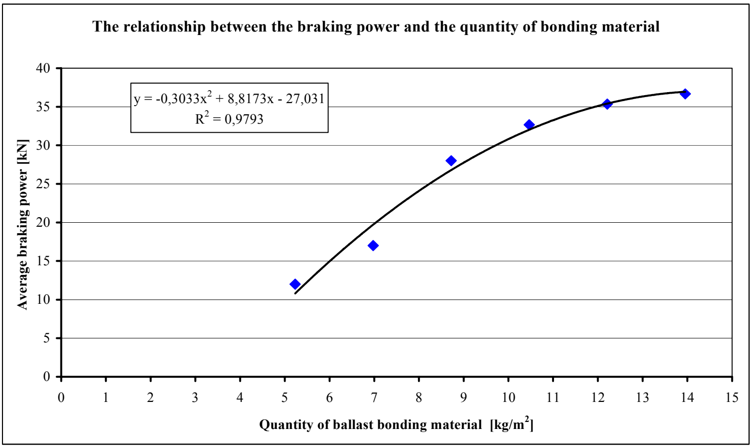


Figure 1: Tight relationship between the braking power and the quantity of bonding material.

THESIS 2

Based on the results and experiences of the executed laboratory tests and the detailed analyses of the results (D [kN/mm] vertical spring rates) I determined that during the usage of the ballast bonding technology, the vertical rigidity of the crushed stone ballast bed is increased

- **in case of the upper bonding (D_{FR} = 46,0 kN/mm) developed with 3,0 kg/m^2 specific bonding material and 20 cm bonding thickness by 61 % (to 1,61 times),**
- **in case of the under bonding (D_{AR} = 47,9 kN/mm) developed with 5,0 kg/m^2 specific bonding material and 30 cm bonding thickness by 68 % (to 1,68 times) and**
- **in case of the total bonding (D_{TR} = 76,4 kN/mm) developed with 8,0 kg/m^2 specific bonding material and 50 cm bonding thickness by 168 % (to 2,68 times)**

compared to the condition without bonding (D_{RN} = 28,5 kN/mm) in case of constant technical parameters.

Furthermore, I determined that during the usage of the ballast bonding technology, in case the quantity of the specific bonding material and the thickness of the bonded crushed stone ballast bed layer are increased, the value of the vertical spring rate increases proportional, i.e. vertical rigidity of the examined crushed stone ballast bed increases proportional, because during the test and the analyses I demonstrated a close connection

- **between the vertical spring rate and the quantity of the specific bonding material ($y = 5{,}69x + 26{,}9$ linear function relation, $R^2 = 0{,}93$) and**
- **between the vertical spring rate and the bonding thickness ($y = 0{,}93x + 26{,}5$ linear function relation, $R^2 = 0{,}95$).**

Due to the fact that the vertical rigidity is directly proportional with the quantity of the specific bonding material and the bonding thickness, I also determined that during the usage of the ballast bonding technology, the wanted ballast rigidity can be developed by using the correct amount of bonding material and bonding thickness. [1], [6], [11]

In order to define the effects of the ballast bonding technology to the rigidity of the crushed stone ballast bed I carried out laboratorial tests where besides static and dynamic loads I performed measurements at four different stages of ballast bonding: without ballast bonding, after upper layer ballast bonding, after under layer ballast bonding and after total ballast bonding. During the tests I defined the values of the vertical spring rates at the different ballast bonding stages (**Table 1**), which feature the vertical rigidity of the crushed stone ballast bed at given ballast bonding stage. I analyzed the results of the tests where I determined tight relationships between the vertical spring rate and the quantity of ballast bonding material (**Figure 2**) and between the vertical spring rate and the thickness of ballast bonding layer (**Figure 3**). The tightness of the stated relationships is also justified by the high square values of the correlation (coefficient of determination).

Bonding stages	Without bonding	Upper layer bonding	Under layer bonding	Total bonding
Spring rate D [kN/mm]	28,514	45,982	47,912	76,429

Table 1: The values of the vertical spring rates D [kN/mm] at the different ballast bonding stages

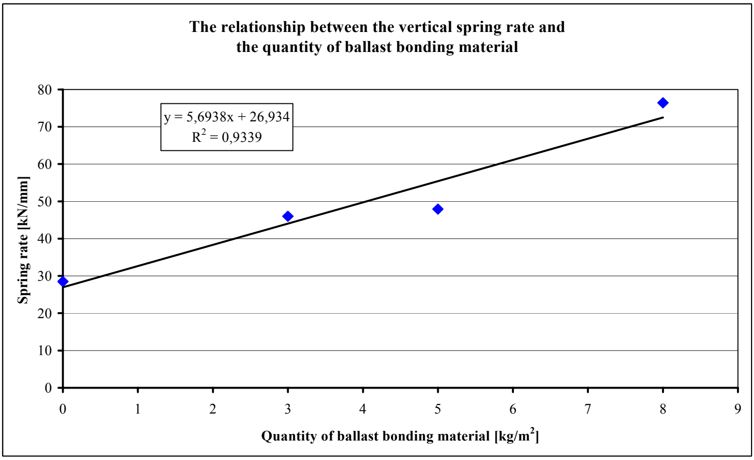


Figure 2: The determined tight relationship between the vertical spring rate and the quantity of ballast bonding material

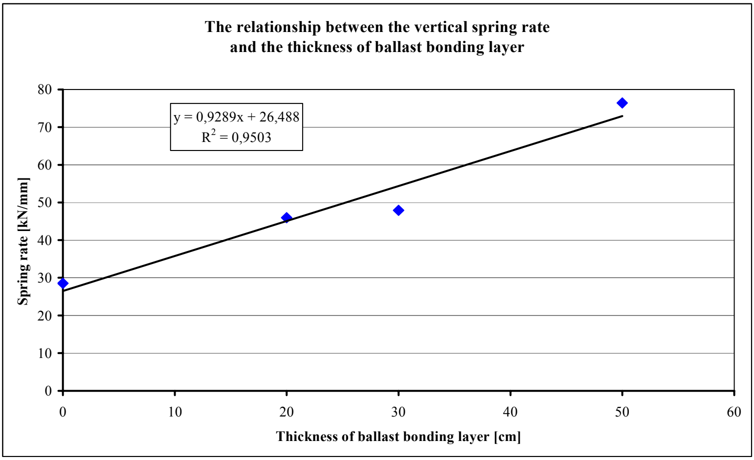


Figure 3: The determined tight relationship between the vertical spring rate and the thickness of ballast bonding layer

THESIS 3

During the detailed analyses of the executed academic calculations and their results I demonstrated that in case of the usage of the ballast bonding technology the value of the settlement is decreased

- **by 29 – 34 % in case of the upper bonding,**
- **by 31 – 36 % in case of the lower bonding and**
- **by 51 – 57 % in case of the complete bonding**

compared to the condition without bonding in case of constant technical parameters.

I also demonstrated that in case of the usage of the ballast bonding technology the value of the moment in the rail is decreased

- **by 7 – 11 % in case of the upper bonding,**
- **by 8 – 12 % in case of the lower bonding and**
- **by 15 – 22 % in case of the complete bonding**

compared to the condition without bonding in case of constant technical parameters.

Furthermore, I demonstrated that in case of the usage of the ballast bonding technology the value of the power transmitting from the rail to the sleeper is increased

- **by 6 – 14 % in case of the upper bonding,**
- **by 7 – 15 % in case of the lower bonding and**
- **by 14 – 31 % in case of the complete bonding**

compared to the condition without bonding in case of constant technical parameters.

Based on the results and the experiences of the executed laboratory tests and the detailed analyses of the results I determined that during the usage of the ballast bonding technology in case of increasing the quantity of the specific bonding material and the thickness of the bonded crushed stone ballast bed layer,

- **the value of the settlement decreases proportional,**
- **the value of the moment in the rail decreases proportional and**
- **the value of the power transmitting from the rail to the sleeper increases proportional,**

because during the tests and the analyses I demonstrated a close connection ($R^2 > 0,94$)

- **between the settlement and the quantity of the specific bonding material,**
- **between the settlement and the thickness of the bond material,**
- **between the moment in the rail and the bonding thickness,**
- **between the moment in the rail and the thickness of the bond material,**
- **between the power transmitting and the specific quantity of the bonding material**
- **and between the power transmitting and the bonding thickness.**

In view of the rail system and the sleeper distance I unequivocally determined the concrete equations of the linear function relations specifying the coherencies. [1], [6], [11]

During the analysis of results of my theoretical calculations I determined tight relationships. From these relationships show examples **Figures 4 – 9** concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems. The figures show the specified equations of the linear functions which feature the relationships.

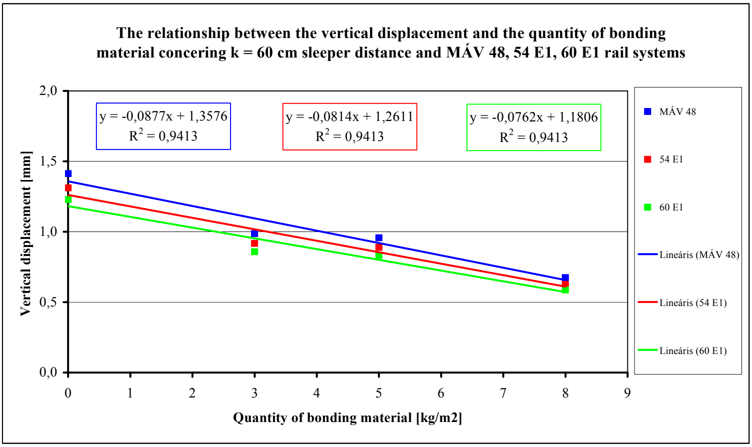


Figure 4: The determined tight relationship between the vertical displacement and the quantity of bonding material concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

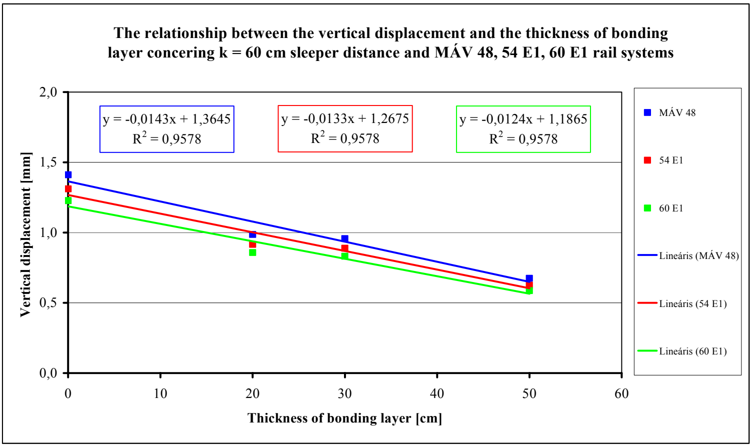


Figure 5: The determined tight relationship between the vertical displacement and the thickness of bonding layer concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

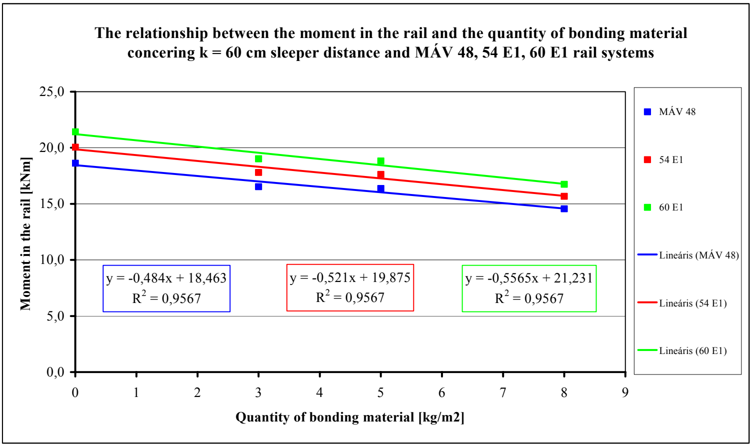


Figure 6: The determined tight relationship between the moment in the rail and the quantity of bonding material concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

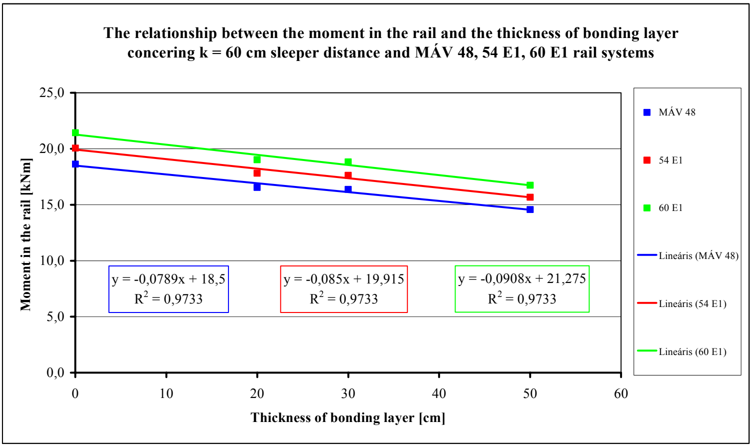


Figure 7: The determined tight relationship between the moment in the rail and the thickness of bonding layer concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

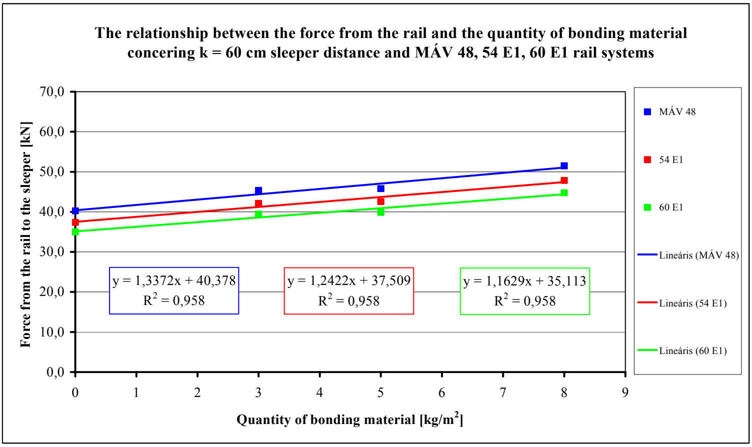


Figure 8: The determined tight relationship between the force from the rail and the quantity of bonding material concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

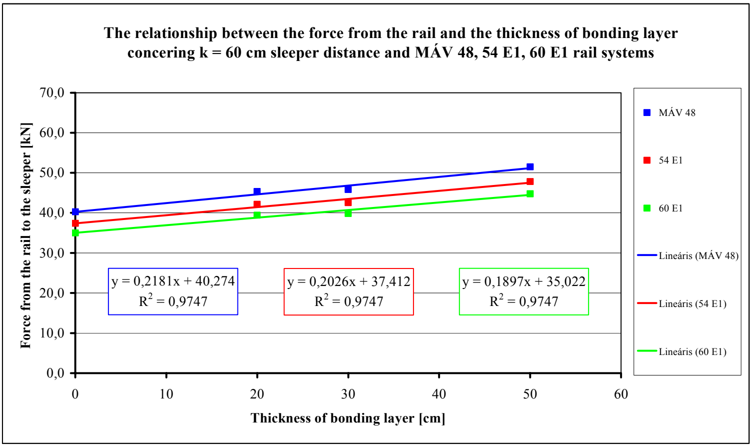


Figure 9: The determined tight relationship between the force from the rail and the thickness of bonding layer concerning k = 60 cm sleeper distance and MÁV 48, 54 E1, 60 E1 rail systems

THESIS 4

Based on the results of the executed laboratory tests and the track measurements, the academic calculations and their results based on these tests and the detailed analyses of the results, I determined the value of the least radius curve, where the stabilized crushed stone ballast bed with crossing sleeper continuously welded rail track can be constructed by ballast bonding technology (with lateral structural bonding of the size of 40 x 15 cm and of the specific bonding material quantity of 5,0 kg/m^2), in case of clean and good quality crushed stone ballast bed, without using a cap increasing the lateral resistance (safety cap), without heaping up the ballast bed shoulder and without using any other structure increasing the collateral resistance,

- **in case of MÁV 48 rail system in the value of R = 200 m,**
- **in case of 54 E1 rail system in the value of R = 220 m and**
- **in case of 60 E1 rail system in the value of R = 250 m.**

[2], [3], [12]

To determine the critical curve radius of crushed stone ballasted and continuously welded rail track stabilized by ballast bonding technology (lateral structural bonding), I made laboratorial tests and track measurements. At first I determined with these tests and measurements the lateral ballast resistance of the ballast bed stabilized by ballast bonding technology. This value was 7,87 N/mm during the laboratorial tests and 7,99 N/mm during the track measurements. After that I made theoretical calculations with the Meier theory and I determined the smallest critical curve radiuses where continuously welded rail tracks can be built with crushed stone ballast bed stabilized by ballast bonding technology (**Table 2**).

Rail system	**MÁV 48**		**54 E1**		**60 E1**	
Lateral ballast resistance [N/mm]	**Track 7,99**	**Laboratory 7,87**	**Track 7,99**	**Laboratory 7,87**	**Track 7,99**	**Laboratory 7,87**
Arc height of the alignment error [mm]	**Critical curve radius [m]**					
1	168,94	171,54	189,66	192,58	210,34	213,58
5	172,52	175,23	193,88	196,93	215,49	218,88
10	177,22	180,08	199,43	202,65	222,29	225,90
15	182,18	185,20	205,30	208,71	229,53	233,38
20	187,42	190,62	211,53	215,15	237,25	241,37
21	188,51	191,74	212,82	216,49	238,86	243,04

Table 2: The values of critical curve radiuses of continuously welded rail tracks built with MÁV 48, 54 E1, 60 E1 rail systems and with crushed stone ballast bed stabilized by lateral structural bonding

THESIS 5

During the detailed analyses of the executed track measurements and their results I demonstrated that due to the effects of the dynamic loads of the (2Z = 165 kN static axel load) M41 series engine (with V = 5, 40 and 60 km/h speed), the horizontal lateral movement of the sleepers in the crushed stone ballast bed

- **is 0,3 – 0,5 mm in the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology (with lateral structural bonding of the size 40 x 20 cm and of the quantity 7,5 kg/m^2 specified bonding material),**
- **is 0,5 – 0,7 mm in the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper fitted by safety caps (on every sleeper) and**
- **is 0,1 – 0,3 mm in the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper constructed by Y steel sleepers (system 230-650-230).**

Based on the results and the experiences of the executed track measurements and the detailed analyses of the results, I determined that the horizontal lateral movement of the sleepers

- **is 30 – 40% less in the continuously welded rail track stabilized by the ballast bonding technology than in the continuously welded rail track fitted by safety caps,**
- **but 70 – 90% more than in the continuously welded rail track constructed by Y steel sleepers.**

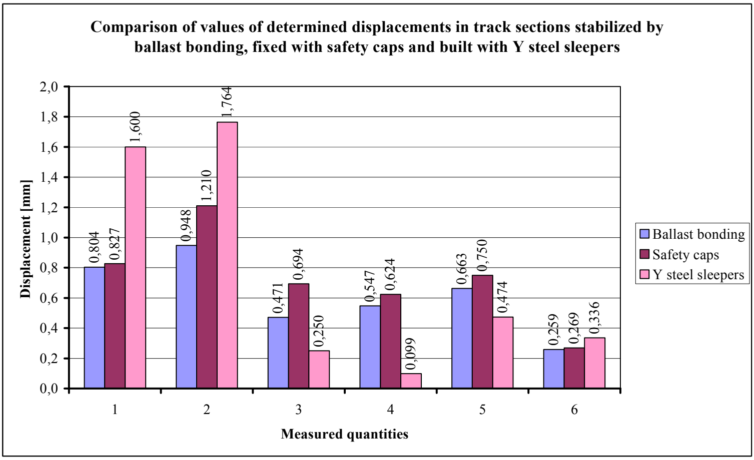
Furthermore, based on the above I determined, that

- **the lateral resistance of the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology (with lateral structural bonding of the size 40 * 20 cm and of the quantity 7,5 kg/m^2 specified bonding material) is more than the lateral resistance of the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper fitted by safety caps (on every sleeper),**
- **but less than the lateral resistance of the continuously welded rail track laying in crushed stone ballast bed with concrete sleeper constructed by Y steel sleepers (system 230-650-230). [4]**

The aim of the tests was to determine what is the effectiveness and performance of the application of the ballast bonding technology (lateral structural bonding), the safety caps and the Y steel sleepers, especially with regard to the lateral ballast resistance. Therefore I measured the displacements of the elements of the track superstructure (rails, sleepers) under dynamic loading of a locomotive, in the track sections stabilized by ballast bonding, fixed with safety caps and built with Y steel sleepers, and after that I analysed the results. The values of determined displacements in the track sections stabilized by ballast bonding, fixed with safety caps and built with Y steel sleepers are shown in **Table 3** and are compared for the speed 60 km/h in **Figure 10**.

Technology	Speed [km/h]	Absolute vertical displacement of the sleeper [mm]		Absolute lateral horizontal displacement of the sleeper [mm]	Relative vertical displacement of the flange (inside) [mm]	Relative vertical displacement of the flange (outside) [mm]	Relative lateral horizontal displacement of the head [mm]
		Outside of the curve	Inside of the curve				
Ballast bonding technology	5	0,646	0,770	0,274	0,599	0,777	0,186
	40	0,746	0,867	0,354	0,573	0,703	0,208
	60	0,804	0,948	0,471	0,547	0,663	0,259
Safety caps	5	0,669	1,043	0,462	0,685	0,884	0,201
	40	0,778	1,179	0,569	0,657	0,793	0,221
	60	0,827	1,210	0,694	0,624	0,750	0,269
Y steel sleepers	5	1,449	1,621	0,127	0,198	0,715	0,446
	40	1,652	1,841	0,207	0,038	0,476	0,338
	60	1,600	1,764	0,250	0,099	0,474	0,336

Table 3: The values of determined displacements in the track sections stabilized by ballast bonding, fixed with safety caps and built with Y steel sleepers



Measured quantities:
1. *Absolute vertical displacement of the sleeper on the outside of the curve.*
2. *Absolute vertical displacement of the sleeper on the inside of the curve.*
3. *Absolute lateral horizontal displacement of the sleeper.*
4. *Relative vertical displacement of the inside flange of the outside rail.*
5. *Relative vertical displacement of the outside flange of the outside rail.*
6. *Relative lateral horizontal displacement of the head of the outside rail.*

Figure 10: The comparison of the values of determined displacements in the track sections stabilized by ballast bonding, fixed with safety caps and built with Y steel sleepers, for the speed 60 km/h

THESIS 6

During the processing and evaluation of the data of the mechanical track measurements executed in the railway track and during the detailed analyses of the results I demonstrated that the speed of the track geometry condition is 35 % less on the continuously welded rail track section (2,48 * 10^{-2} dm^2/day) laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology (with lateral structural bonding of the size 40 x 20 cm and of the quantity 7,5 kg/m^2 specified bonding material) than on the continuously welded rail track section (3,82 * 10^{-2} dm^2/day) laying in crushed stone ballast bed with concrete sleeper fitted by safety caps (on every sleeper).

It means that the track geometry condition change of the continuously welded rail track section laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology is better than the rack geometry condition change of the continuously welded rail track section laying in crushed stone ballast bed with concrete sleeper fitted by safety caps. Based on the above mentioned I determine that in the rail tracks' geometric stability's point of view the usage of the ballast bonding technology (lateral structural bonding of the size 40 x 20 cm and of the quantity 7,5 kg/m^2 specified bonding material) is more favorable than the usage of the safety caps (on every sleeper).

During the processing and evaluation of the data of the mechanical track measurements executed in the railway track and during the detailed analyses of the results I also demonstrated that the speed of the deterioration of the alignment condition on the continuously welded rail track section (2,26 * 10^{-2} dm^2/day) laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology (with lateral structural bonding of the size 40 x 20 cm and of the quantity 7,5 kg/m^2 specified bonding material) is 22% less, than the deterioration of the alignment condition on the continuously welded rail track section (2,91 * 10^{-2} dm^2/day) laying in crushed stone ballast bed with concrete sleeper fitted by safety caps (on every sleeper).

It means that the alignment keeping of the continuously welded rail track section laying in crushed stone ballast bed with concrete sleeper stabilized by the ballast bonding technology is better than the alignment keeping of the continuously welded rail track section laying in crushed stone ballast bed with concrete sleeper fitted by safety caps. Based on the above I determine that in the rail tracks' alignment keeping's point of view the usage of the ballast bonding technology (lateral structural bonding of the size 40 x 20 cm and of the quantity 7,5 kg/m^2 specified bonding material) is more favorable than the usage of the safety caps (on every sleeper). [4]

I determined the alignment keeping and the change of geometric conditions of the crushed stone ballasted and continuously welded rail tracks stabilized by ballast bonding technology (lateral structural bonding) and fixed with safety caps. The track measurements were made by track measuring car and I evaluated and analysed the results.

The change of geometric conditions of a railway track section could be featured by the SAD qualification number changing in time (**Figure 11**) and the alignment keeping of a railway track section could be featured by the alignment measuring number changing in time (**Figure 12**).

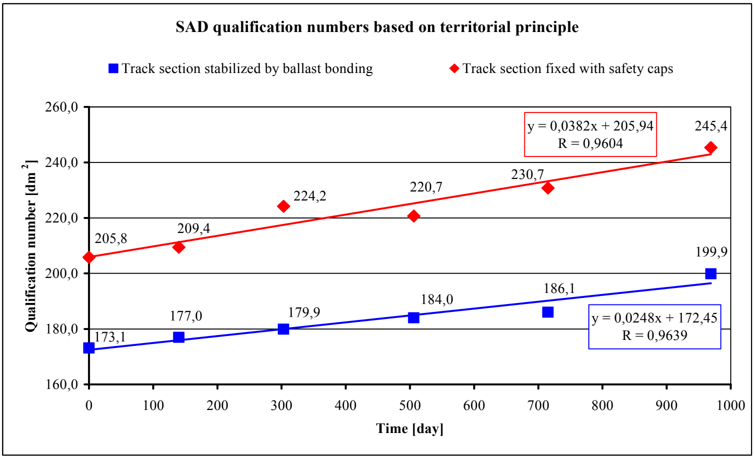


Figure 11: The determined SAD qualification numbers in the track section stabilized by ballast bonding and in the track section fixed with safety caps

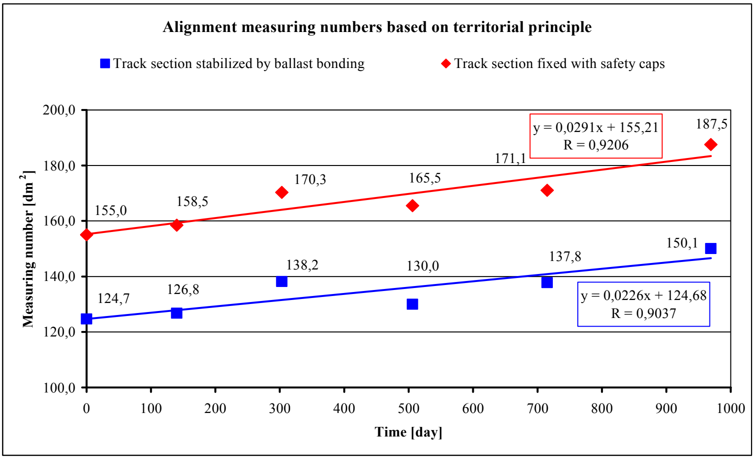


Figure 12: The determined alignment measuring numbers in the track section stabilized by ballast bonding and in the track section fixed with safety caps

6. RECOMMENDATION FOR FURTHER ANALYSIS

In my Ph.D. dissertation through laboratorial tests, railway track measurements, theoretical calculations and their results and experiences I assessed and analyzed in detail the behaviour of the railway superstructure in crushed stone ballast bed stabilized by ballast bonding technology under static and dynamic loads.

My major recommendations for further analysis related to railway tracks in crushed stone ballast bed stabilized by ballast bonding technology are the following:

1. Precise calculation of the theoretical length of the transition section (transition section stabilized by ballast bonding technology at the junction of the crushed stone ballast bed and solid tracks) in case of the transition section with one stage and in case of the transition section with more stages. Connection between the practical length of the transition section and the applied vehicle speed and axle load.

2. The analysis of the effect of the ballast bonding technology to the longitudinal ballast resistance of the crushed stone ballast bed and the practical utilization of this (for example: application at backfill of bridges).

3. Further analysis of the vertical elasticity (rigidity) of the crushed stone ballast bed stabilized by ballast bonding technology, in case of application of supplementary layers with elastic behaviour (for example different repair- and protection layers above ground material substructure).

4. Definition of the (maximum) limit value of the vertical rigidity during the application of ballast bonding technology taking into consideration the mechanical deterioration of the railway track and the definition of the (maximum) limit value of the transferring energy from the rail to the bed especially in case of need for substructure stabilization.

5. Assessment and analysis whether there is any difference in the dirt- and pollution binding capability between the ballast bonded and not ballast bonded crushed stone ballast bed and that how the predisposition for contamination of the crushed stone ballast bed is like in terms of tracks stabilized- and not stabilized by ballast bonding technology.

In addition to the abovementioned five major suggestions other research areas may also be analyzed.

7. LIST OF THE PUBLICATIONS

I.) Proof-read articles in foreign language published in abroad

1. József Szabó – József Szabó Sr.: „Anwendungsmöglichkeiten für die Schotterverklebungstechnologie (Teil 1)”, *Der Eisenbahn Ingenieur (EI), 06/2008, Juni 2008, pp 20-25.*
2. József Szabó – József Szabó Sr.: „Anwendungsmöglichkeiten für die Schotterverklebungstechnologie (Teil 2)”, *Der Eisenbahn Ingenieur (EI), 06/2009, Juni 2009, pp 38-46.*
3. József Szabó – József Szabó Sr.: „Anwendungsmöglichkeiten für die Schotterverklebungstechnologie (Teil 3)”, *Der Eisenbahn Ingenieur (EI), 09/2011, September 2011, (accepted to publication: 20/06/2011)*

II.) Proof-read articles in foreign language published in Hungary

4. József Szabó: „Tests experiences in small radius curves of continuously welded rail tracks”, *Periodica Polytechnica Ser. Civil Engineering, (accepted to publication: 01/06/2011, Ms: PP-20-1121)*

III.) Proof-read articles in Hungarian language

5. Szabó József – Dr. Kazinczy László Ph.D.: „Aljjavítási lehetőségek ismertetése, különös tekintettel a hézagnélküli pályák stabilitásának fenntartására”, *Műszaki Szemle, 32. szám, 2005, pp 45-49.*
6. Szabó József – Id. Szabó József: „Az ágyazatragasztási technológia alkalmazásának lehetőségei – I. rész”, *Sínek Világa, IL. évfolyam, 1-2. szám, 2007, pp 20-29.*
7. Szabó József – Id. Szabó József: „Az ágyazatragasztási technológia alkalmazásának lehetőségei – II. rész”, *Sínek Világa, IL. évfolyam, 3-4. szám, 2007, pp 47-55.*
8. Szabó József – Id. Szabó József: „Az ágyazatragasztás méretezési elvei a kissugarú hézagnélküli pályák stabilitásának tervezésénél”, *Sínek Világa, LIII. évfolyam, 3. szám, 2011, pp 24-33.*

IV.) Articles in Hungarian language with no proof-reading

9. Szabó József: „Zúzottkő felépítmény megerősítése – Ágyazatragasztás az M1 és M2 földalatti vasútvonalakon”, *Mélyépítő Tükörkép Magazin, VI. évfolyam, 1. szám, 2007. február, pp 24-27.*

V.) Hungarian language conference presentations published in proof-read conference proceedings

10. Szabó József: „Ágyazatragasztási technológia alkalmazása a budapesti millenniumi földalatti gyorsvasút vonalán", *ÉPKO 2006, X. Nemzetközi Építéstudományi Konferencia, Csíksomlyó, Románia, 2006. június 14-18., Konferencia Kiadvány, pp 302-305.*

11. Szabó József: „Ágyazatragasztási technológia elméleti és gyakorlati vizsgálata", *BME Építőmérnöki PhD Szimpózium 2007, Budapest, 2007. november 07., Konferencia Kiadvány, pp 147-156.*

12. Szabó József: „Az ágyazatragasztási technológia alkalmazásának hatása, a zúzottkő ágyazat oldalirányú ellenállására", *BME Építőmérnöki PhD Szimpózium 2008, Budapest, 2008. november 28., Konferencia Kiadvány, (accepted to publication: 19/05/2009)*

VI.) Hungarian language conference presentations published in abstracts only

13. Szabó József – Id. Szabó József: „Ágyazatragasztási technológia – Zúzottkő ágyazat megerősítése", *VI. Vasúti Hidász Találkozó, Dobogókő, 2006. július 05-07., Konferencia Kiadvány, pp 56-57.*

14. Szabó József: „Aljjavítási lehetőségek ismertetése, különös tekintettel a hézagnélküli pályák stabilitásának fenntartására", *OTDK 2005, XXVII. Országos Tudományos Diákköri Konferencia, Műszaki Tudományi Szekció, Gödöllő, 2005. március 22-24., Konferencia Kiadvány, pp 217.*

15. Szabó József: „Ágyazatragasztási technológia alkalmazása a budapesti földalatti gyorsvasúti vonalakon", *OTDK 2007, XXVIII. Országos Tudományos Diákköri Konferencia, Műszaki Tudományi Szekció, Győr, 2007. április 02-04., Konferencia Kiadvány, pp 208.*

VII.) Scientific Student Essays

16. Szabó József: „Hazai alkalmazású gyári, illetve helyszíni készítésű szigetelt sínillesztések", *TDK dolgozat és előadás, TDK 2003, BME Építőmérnöki Kar, Tudományos Diákköri Konferencia, Közlekedésépítőmérnöki Szekció, Budapest, 2003. november 11., II. Díj.*

17. Szabó József: „Aljjavítási lehetőségek ismertetése, különös tekintettel a hézagnélküli pályák stabilitásának fenntartására", *TDK dolgozat és előadás, TDK 2004, BME Építőmérnöki Kar, Tudományos Diákköri Konferencia, Közlekedésépítőmérnöki Szekció, Budapest, 2004. november 09., I. Díj.*

18. Szabó József: „Ágyazatragasztási technológia alkalmazása a budapesti földalatti gyorsvasúti vonalakon", *TDK dolgozat és előadás, TDK 2005, BME Építőmérnöki Kar, Tudományos Diákköri Konferencia, Közlekedésépítőmérnöki Szekció, Budapest, 2005. november 11., I. Díj.*

VIII.) Important presentations

19. József Szabó: „Ballast bonding technology in Hungary", *I. International Ballast Bonding Day, MC Bauchemie, Bottrop, Németország, 2007. szeptember 12.*
20. József Szabó: „Scientific research in ballast bonding technology", *II. International Ballast Bonding Day, MC Bauchemie, Bottrop, Németország, 2008. október 16.*
21. Szabó József: „Vasúti járművek futásbiztonságának növelése ágyazatragasztással", *XI. Futástechnikai Konferencia, Harkány, 2007. május 17.*
22. Szabó József: „Ágyazatragasztási technológia lehetőségei a vasút területén", *KTE Vas megyei Területi Szervezet Műszaki Fóruma, Szombathely, 2006. október 19.*
23. Szabó József: „Ágyazatragasztási technológia...", *KTE Hajdú-Bihar megyei Területi Szervezet Műszaki Fóruma, Debrecen, 2007. március 21.*
24. Szabó József: „Ágyazatragasztási technológia alkalmazási lehetőségei a vasút területén", *KTE Fejér megyei Területi Szervezet Műszaki Fóruma, Székesfehérvár, 2007. december 04.*
25. Szabó József: „Ágyazatragasztási technológia...", *KTE Soproni Városi Szervezet Műszaki Fóruma, Sopron, 2008. április 15.*
26. Szabó József: „Ágyazatragasztási technológia Magyarországon", *MC Bauchemie Müller GmbH & Co. Fóruma, Bottrop, Németország, 2007. április 10.*
27. Szabó József: „Ágyazatragasztási technológia Magyarországon", *MC Bauchemie Magyarország Kft. Fóruma, Budapest, 2008. március 26.*
28. Szabó József: „Ágyazatragasztási technológia alkalmazása Magyarországon", *Goldschmidt Thermit Group (GTG) Fóruma, Budapest, 2007. január 24.*
29. Szabó József: „Ágyazatragasztási technológia...", *MÁV Zrt. Vezérigazgatóság, EU Programigazgatóság, Budapest, 2006. november 27.*
30. Szabó József: „Ágyazatragasztási technológia...", *Széchenyi István Egyetem, Közlekedésépítési és Településmérnöki Tanszék, Győr, 2006. november 20.*