Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 14 (2016) 3953 – 3962

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

The design and composition of expansion joints on big-span bridges with intensive heavy-duty traffic

Alexei Busel [a], Radziyen Krotau [b,]*

[a]dean of the Faculty of Transport Communication, the Belarusian National Technical University, Minsk, Belarus
[b]director of Progressive Technologies of Concrete, LLC, ul Gvardeiskaya -35, 220035, Minsk, Belarus

Abstract

In the Republic of Belarus the roads with a high intensity of transport most widely employ expansion joints with rubber and steel compensators fastened to the reinforced concrete base with embedded therein studs. While operated expansion joints are exposed to various kinds of operational and climatic impacts causing their damage. Expansion joints destruction results in a sharp increase in dynamic effects of transport on the structural elements of a bridge with the pavement most affected in the area of the junction. Since the greatest stresses occur in the area of the expansion joints fastened to the concrete base leading to its destruction it is suggested using high-strength concrete able to receive elastically the dynamic loading. In this case the content of joints comes down to a timely tightening of nuts and their sealing.
The article deals with obtaining high-strength concrete with activated crushed stone, fine fillers and fibers for expansion joints base. Having studied experimentally the reinforcement of both the concrete and the technology of making foundations we have summarized here the results.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Expansion joint; rubber compensator; high-strength concrete; studs

* Corresponding author. Tel.:+375298597585; fax:+375172034258.
E-mail address: 150869@mail.ru

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.488

1. Introduction

Expansion joint is a structural element on bridges and overpasses designed to compensate for the movement of the span ends resulting from thermal strains/deformation, live load (transport) and long-term deformation (concrete creep and shrinkage) [Department "Belavtodor", 2011]. Service life of the entire bridge structure depends largely on their reliability and durability.

According to [A.V. Ephanov et al. 2005] the contemporary design of an expansion joint must provide reliability, durability as well as aesthetic, technological and operational requirements.

Reliability and durability requirements to the materials of expansion joints are aimed at enabling the spans' ends to move without overstrain and damage to their elements, structural layers of the deck and the road pavement. In accordance with the performance requirements they need to ensure a smooth passage of vehicles, resistance of the joint material to any impact and abrasion caused by vehicle wheels, to resist corrosion resulting from deicing agents and road maintenance in general. Technological requirements are designed for the joints to be manufactured, installed and their elements replaced at the lowest cost.

2. Expansion joint design

Expansion joints with rubber compensators 120 are used on the road stretches with a high intensity of transport (for example, there are more than 100 thousand cars per day on some stretches of the Ring road around the city of Minsk). When a wheel brakes and meets a joint (Fig. 1) the expansion joint experiences the following stresses: the weight of the vehicle; braking power [Verenko V, Mytko L, 2010] and the stress resulting from the compensator - 120 being stretched or compressed caused by temperature changes. [Zverinski, P. et al., 2013] These stresses are transferred to the concrete base through the studs and the rubber plate under the joint. The expansion joint module is fastened to the concrete base with five studs at each side, the distance between the studs being 200 mm.

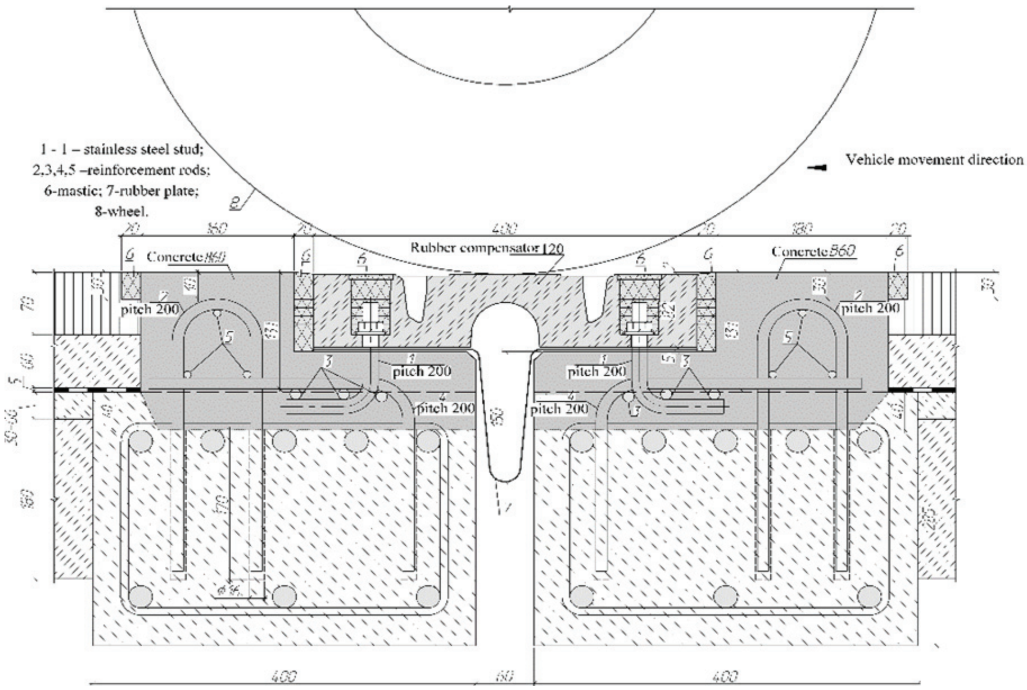

Fig. 1. Expansion joint with a rubber compensator 120.

We took a physical model of wheel interaction with a joint attachment to assess concrete stresses (Figure 2)

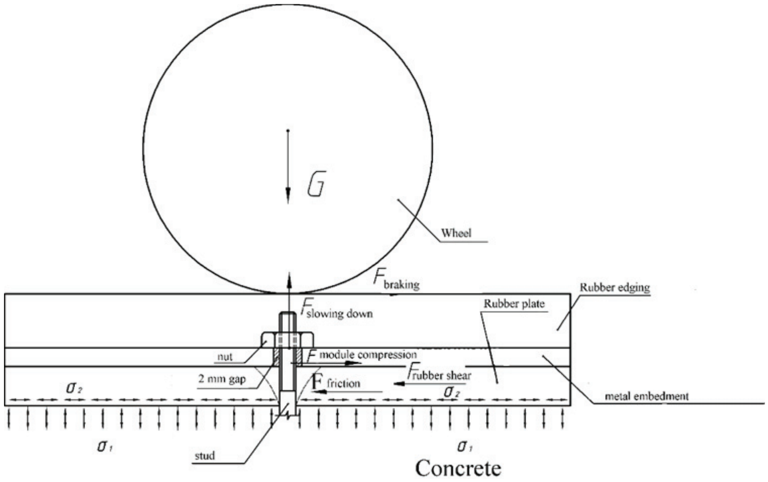

Fig. 2. A physical model of wheel interaction with expansion joint attachment.

We took into account the load of 14 tons (for bridges) per axle of a standard vehicle assessing the stress resulting from the car's own weight. The force of braking was considered in two ways. Firstly, we considered the total weight of the vehicle and the friction factor at the time of braking. Secondly, we evaluated the work of braking forces according to the STB 1641 [Transtekhnika,BelNII, 2006.], taking into account the standard slowing down and the length of the braking distance.

Besides we calculated the force occurring in a rubber plate under a module of a rubber compensator-120 when the plate shears during braking. The thickness of the rubber plate is 7 mm.

As a result, we obtained the following data.

The stress resulting from the own weight of the car G, kN, in the place where a stud is embedded taking into account the dynamic factor made up

$$G = F_{tr} \times k_d / 2 \quad (1)$$

where F_{tr} is a load experienced by the axle of a standard vehicle.
k_d – dynamic factor that equals to 2, according to [Uglova E.et al, 2014.]; 2 – the number of wheels on the axle.

Thus, G = 140 000× 2/2 = 140 kN. This force as shown in Figure 3 effects half of the module of the expansion joint (S = 150 mm (width of the embedded plate) • 200 mm (a step of the studs used to attach the module) = 30 000 mm^2).

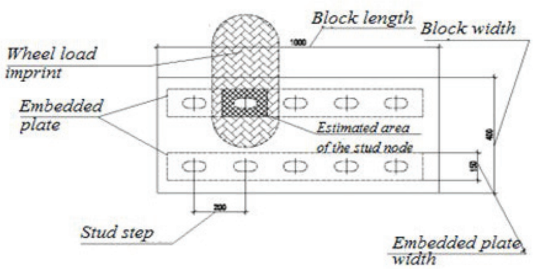

Fig. 3. Rubber compensator module design (top view).

- The stress resulting from braking (F_{br}) will be calculated in two different ways.
  In the first case, taking into account the friction factor between the wheel and the rubber compensator.

$$F_{br}=G\times\mu \tag{2}$$

where μ is a tire-to-surface friction factor. We take it for asphalt roads, μ = 0.4 according to [Leonovich I.I., S.V. Bogdanovich, 2012.], then we get Fbr = 56 kN. Given that this load effects half of the module of the expansion joint, one stud has to experience the force of 56 kN: 5 = 11.2 kN.

In the second case, we took into account the length of the standard braking distance and the standard speed of the train according to the STB 1641 [Transtekhnika, BelNII, 2006.] and [Leonovich I.I., S.V. Bogdanovich, 2012.]:

$$F_{br}\times S_{bd}\times n=(mv^2)\ /\ 2\times S_{bd}\times n \tag{3}$$

where m is the train mass, m = 40t; v - the standard speed, which is equal to 40 km / h (11.1 m / s);
S_{bd} – the braking distance, S_{bd} = 15 m;
n - number of train wheels, n = 14.

After calculating we obtain F_{br} = 11,7 kN. In this case the stud experiences the force of 11.7 kN: 5 = 2.34 kN. Therefore, we take the stress resulting from braking as equaling to 56 kN.

- Under the influence of the braking load the lower rubber plate under the metal embedment is being deformed and the reactive force F_{shear} appears preventing the shear

Based on the design of the joint the gap between the metal embedment and the bolt makes up 2 mm and the thickness of the rubber plate makes up 7 mm (Figure 4).

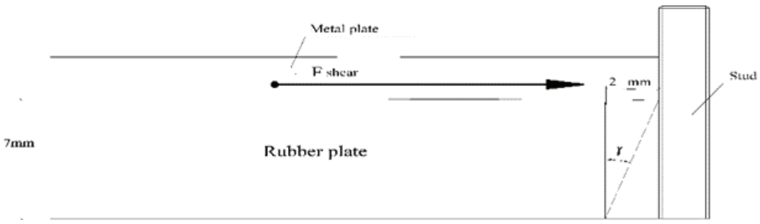

Fig. 4. Rubber plate's shear.

Shear stress τ_{shear} appearing in the rubber with the shear being 2mm is defined by the following equation:

$$\tau_{shear}=G_{shear}\times\gamma \tag{4}$$

where *G* is the shear modulus which for the rubber plate under [Guidelines] makes up 1.8 MPa;
γ is a shear angle of the rubber plate, in our case γ = 0.286 rad.
Thus shear stress τ_{shear} makes up 0.5 MPa.
Shear force F_{shear} compensated by rubber deformation is calculated using the following equation

$$F_{shear}=\tau_{shear}\times S=0,5\times 0,03=15kN \tag{5}$$

where S is the area of a rubber plate under the metal embedment in the stud zone.

In order to define the effect of the maximal horizontal movement of a compensator (60 mm) the experiment described in the publication [Zverinski, P. et al., 2013] was performed. According to the tests (table 1) the load while performing 60 mm movement made up 53.96 kN. Accordingly one stud experiences the force of 53.96 kN :5= 10.8 kN.

Table 1. Force occurring during expansion joint movement.

No. of a tested module of an expansion joint	Actual dimensions of an expansion joint module rubber compensator -120 L × b × h, mm	Force F, kN	Movement, mm
1	100 × 40 × 80	53.96	60

Based on the calculations stated above horizontal force for one stud makes up:

$$F_{stud} = (F_{br} + F_{compr})\ /\ 5 - F_{shear} = 56 + 53.96)\ /\ 5 - 15 = 6.99kN \tag{6}$$

Moreover while calculating the concrete basement stress we should take into account that when installing rubber compensator -120 module the stud nut is tightened with the F $_{tight.}$ which according to the table 2 creates the stress transmitted through the metal plate to the concrete base. While using studs with the thread M16 and the pitch 1.5 and characterized by the rotational force 180 N×m the force makes up 60kN. This force is transmitted to the part of metal embedment, that’s why it makes up 60 kN×5=300kN. The stress under the metal plate makes up $\sigma_1 = F_{tight.} \div S$ = 300 : 0,15 = 2 MPa.

Table 2. Guide values of tightening torques and pre-tightening forces for the screws made of stainless steel and acid-resistant steel A2/A4.

	Strength class 70		Strength class 80	
Thread	Pre-tightening force, N	Tightening torque, N m	Pre-tightening force, N	Tightening torque, N m
M12	24200	56	32000	75
M16	45000	135	60000	180
M20	71000	455	140000	605

Materials: steel A2/A4.
Yield point when there is stretching Rstr: for the strength class 70 – 450 N/mm; for the strength class 80 – 600 N/mm

Minimal tightening force that prevents rubber slippage is defined according to the following equation:

$$F_{friction} \geq F_{shear} \times k_{safety} \tag{7}$$

where we take k_{safety} equal to 1.5

$$F_{friction} = F_{tightening} \times \mu \tag{8}$$

where µ - friction factor that we take equal to 0.8. Whence it follows that $F_{tightening}$ = 22.5 : 0, 8 = 28.125 kN. According to interpolation method (table 2) we define the necessary tightening torque, which will be equal to 84.4 N×m. Thus due to the tightening force of the fastened nut and the pressure generated by the wheel combined compression pressure appears σ_1

$$\sigma_1 = F_{tightening}\ /\ S + P \tag{9}$$

where $F_{tightening.}$ is a force of a nut pre-tightening (60 kN) with the thread diameter M16 (according to design documents) (table 1);
S – area of a metal embedment (30 000 mm^2 – according to Figure 3);
P – tyre pressure equal to 1 MPa.
As a result of the calculation σ_1 = 3 MPa. Due to the car’s braking $F_{br.}$ and the movement of a compensator $F_{squeeze}$ total pressure σ_2 is calculated as follows

$$\sigma_2 = F_{br} + F_{compr}\ /\ 5)\ /\ S \tag{10}$$

where $F_{br.}$ – according to the equation (2) – 56 kN;
F_{compr} is compression of an expansion joint module according to table 1 – 53.96 kN;
5 – number of studs; S – according to Figure 3 – 30 000mm^2.
Area of the wheel's contact with the coating equals to 3.14×(0.47÷2)^2= 0.1734 m^2.

As a result, σ_2 = 56:0.1734+ (53.96 : 5):(0.15 m ×0.2 m) = 0.683 MPa. We calculate combined pressure using vector addition of σ_1 and σ_2:

$$\sigma = (\sigma_2^2 + \sigma_1^2)^{0.5} = 3.08 MPa \qquad (11)$$

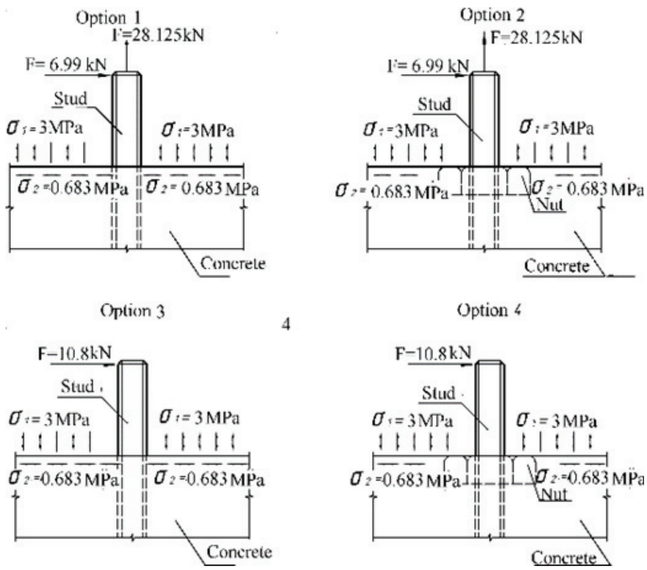

Fig. 5. The scheme to calculate the stresses in the zone where a stud contacts concrete.

To check the calculations we modeled mathematically the ends of the expansion joints attachment and subsequently analyzed von Mises contour plots. The modulus of steel elasticity is 210GPa, Poisson's ratio is 0.29, and for concrete E = 47GPa and Poisson's ratio is 0.2. To reduce the stresses in the zone where the stud contacts the concrete the M16 nut was modeled at the level of concrete grouting. The maximum values of the stresses at joints attachment are shown in the Figures 6 and 7. Taking into account the requirements of GOST R ISO 3506-1 [Mechanical properties] in the Table 2, we need for the M16 stud with a 1.5 thread pitch the steel A2 (with a strength class equaling to 80) to provide corrosion resistance and strength.

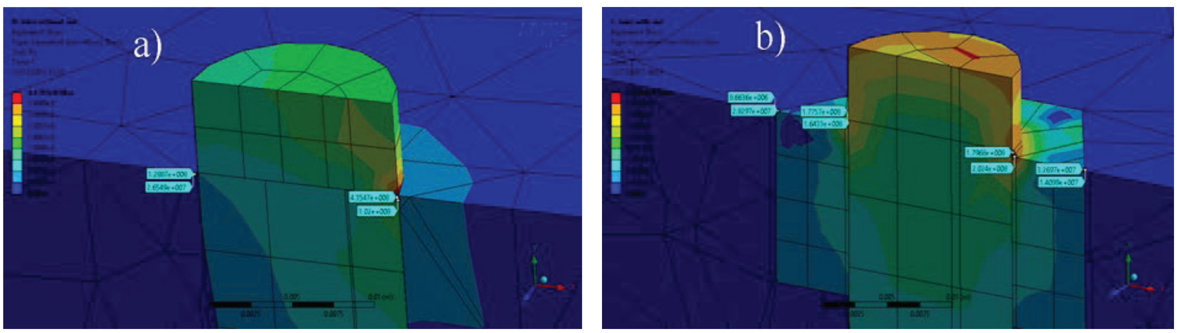

Fig. 6. Stress contour plots in the elements of expansion joint attachment considering the shear of the rubber plate: a) for option 1(Fig. 5), b) for option 2 (Fig.5).

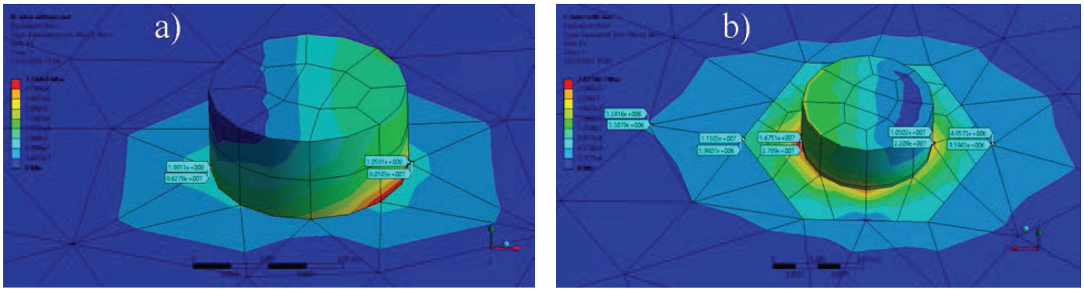

Fig. 7. Stress contour plots in the elements of expansion joint attachment considering the shear of the rubber plate: a) for option 3 (Fig. 5), b) for option 4 (Fig.5).

Having analyzed the obtained stresses in the zone where a stud contacts concrete (option 2, fig 5 – 14.099 MPa) we have come to conclusion that to resist horizontal and vertical loads it is necessary to use high-strength concrete with the compressive strength of at least 70-80 MPa [Mikulski, V.G. (2004)].

2.1. Conclusions on the stresses assessment in the rubber compensator-120 attachment.

The above mentioned analysis of the forces and stresses proves the need for a stud and M16 nut from A2 stainless steel at the attachment place of the rubber and steel compensator as well as for employing concrete joint grouting with a compressive strength of at least 70-80 MPa and frost and salt resistance at least 300*. The most important factor determining the attachment performance of the rubber and steel compensator is the availability of the required forces in the stud to provide the necessary friction between concrete and rubber to prevent additional forces applied on the stud under constant and live load. The existing force effort in the attachment is necessary to ensure throughout the entire life cycle of the expansion joint.

3. Materials for high-strength concrete and the ways to produce it

For high-strength concrete it is necessary to ensure on the concreting site the normal flow of complex colloidal and chemical and physical processes [Urkhanova, L.A. (2012)], which are influenced by numerous technological, weather and climatic factors, the quality of the materials used, etc.

It is known that the mechanical properties of the coarse aggregate, its shape and grain size, as well as a chemical interaction between the aggregate and the cement matrix significantly affect the strength of the high-strength concrete [Shevchenko, V.A. (2015)]. The upper and lower limit of the grain size of the aggregate shall be defined so that to achieve the maximum density of the concrete filling volume and thus to reduce the internal stresses caused by the heterogeneity of the structure. It is recommended to use for high-strength concrete basalt, gabbro or granite crushed stone. [Meshcherin, B. (2008)]

Natural large and medium sands are used in the high-strength concrete as fine aggregate. The proportion of sand in the mixture of fillers should range from 0.32 to 0.25 and decrease with an increase of the cement quantity and the required concrete strength. To bind the high-strength concrete the cement activity is not less than 50 MPa and with a density of more normal 25%. The most important characteristics of the cement used in the high-strength concrete are clinker mineralogical composition as well as the grain size and the ratio of cement.

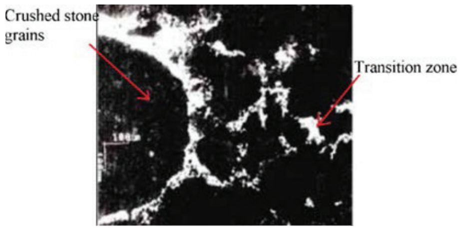

Fig. 8. Concrete composition.

The strength of the cement stone depends on the water and cement ratio. To ensure stable strength of the concrete the value of the water amd cement ratio must be constant and not exceed 0.4, thereby reducing the porosity and increasing the strength of the cement stone matrix [Guzeev, E.A. (1999)

According to [Guzeev, E.A. (1999)] the physical model of concrete suggested by Guzeev E.A., Piradov K.A. and Leonovich S. N. appears to be a system of different scale grains (clinker, sand and crushed stone) characterized by the interaction links in the form of active forces created by physical, chemical and adhesive processes as a result of cement hydration. This structure of high-strength concrete is heterogeneous. At the cement-aggregate interface there are contacts cavities [Leonovich, (1999)], which are the stress raisers causing concrete strength reduction (Figure 8).

It is possible to counter these negative phenomena by strengthening the links among concrete constituents. For this purpose different types of dispersed reinforcement are employed in the contact area, as well as activation and modification of mating surfaces of mineral materials, clinker constituents and new growths.

Reference [Busel, A.V. (2009)] suggests that coarse aggregate should be treated with inorganic activator in the form of polyvalent metals' salts (Me^{+n}). The study of crushed granite electrokinetic features showed that the treatment of its surface with aqueous solution of salts of the said metals leads to the change in ξ-potential of a mineral surface as well as to the change of a negatively charged surface into a positively charged one. It significantly changes its physical and chemical parameters while interacting with hardened cement paste and provides for the gain in concrete strength and moreover at its earlier age [Busel, A.V. (2009)]. The building of a solid crystalhydrate tobermorite structure of hardened cement paste is facilitated by the formation of the compounds $2CaSiO_2 \cdot mMe\ nH_2O$. If the activated crushed stone is used the strength of concrete gains by 30-35%.

Fine aggregate is introduced in order to eliminate micro-defects in the structure of cement hardened paste. Microsilica in the form of powder or aqueous suspension, fly-ash and metakaolin are used as aggregates for high strength concrete [Zaitsev, I. (2007)]. Thanks to their microsizes aggregate grains interacting with cement densify the structure of concrete. The use of both microsilica and fly ash as aggregates leads to good results. Due to the difference in the size of grains of these aggregates matrix structure becomes denser which is especially beneficial for the resistance of concrete to aggressive environment. It is determined that the amount of microsilica shouldn't exceed 10% of the overall cement amount. Even if microsilica makes up 2% of the concrete amount it is enough to significantly strengthen the concrete and facilitate its properties [Shevchenko, V.A (2015)].

It should be noted that the greater the strength of concrete the greater its brittleness and the lower its plastic-deformation properties which leads to the immediate material destruction when it reaches its limit state. The dynamic impact of transport on expansion joints elements leads to stress causing a concrete base destruction. This phenomenon can be prevented by introducing dispersed reinforcement (fiber) into high-strength concrete [Golubev, (2009)].

Complex multi-component additives combining individual ones used for various applications is a relevant trend in producing high-quality cement concrete distinguished by its wide functionality.

Thus the studies contained in the thesis [Simakina, G.N. (2006)] suggest the following fine additives: aggregates characterized by high pozzolanic properties based on milled technogenic waste obtained from natural materials stones breaking combined with super- and hypersuperplasticizers and reinforcing fiber to be used as complex modificators components for high strength fiber-reinforced concrete. Dispersed reinforcement provides for the modification of concrete at two levels: micro-level being the level of cement matrix and macro-level being the level of cement concrete. Two-level dispersed reinforcement is considered to be the effective means to increase compressive and tensile strength, cracking resistance and impact toughness.

Based on everything stated above the promising way of producing high-strength concrete which provides for the strength needed to accommodate dynamic loads is to introduce catalyzed aggregates, active fine aggregates and reinforcing fibers allowing to elastically perceive the efforts transmitted from expansion joints to mounting studs.

4. Experimental research and its results approbation

Based on theoretical assumptions it was offered a new technical solution[Krotov, Rubtsova, 2014)] including the fastening of an expansion to span beams using studs embedded into the base made of fiber concrete filling the cavities of mating areas. This technical solution was approbated while constructing the Minsk ring road (Figure 4). Reinforcement cage is installed into the cavity. Studs are welded to the cage and then the cavity is filled with concrete mixture of the following composition: kg/m3

Portland cement M 500D0 – 550

Water 135.2;

Activated crushed stone fraction 10-16 – 800.0;

	6.3-10	– 350.0;
	4 – 6.3	– 150.0;
	2-4	– 50.0;
Natural sand	– 500.0;	
Microsilica	– 10% of the total cement mass;	
Fiber	– 2% of the total cement mass;	
Plasticizers	– 1.3% of the total cement mass.	

Fig. 9. Expansion joint structure with a rubber compensator with traffic preserved next to it. High-strength concrete was used.

The mixture had the following properties:

Water/cement proportion 0.246

Cone slump 16-20cm

Compression test of high-strength concrete resulted in it actively gaining strength proved by the theoretical background concerning the effectiveness of fine aggregates, activated crushed stone and reinforcing fiber (Figure 10).

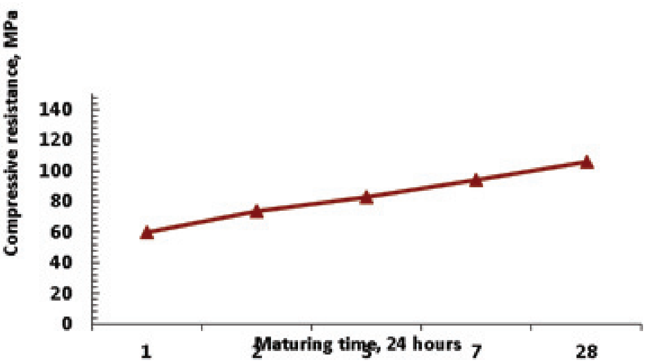

Fig. 10. Concrete strength changes based on the types of additives.

As a result we achieved the required strength of high-strength concrete which made up 106 MPa being 28 days old. Experimental expansion joint proved to be successful after 7 years of operation (Figure 11, 12) experiencing heavy traffic load (Traffic flow up to 100 thousand motor vehicles per 24 hours).

During the operation period this joint was subject to the following if necessary: dirt and dust were removed, nuts tightened according to the efforts and joint fixation sockets sealed.

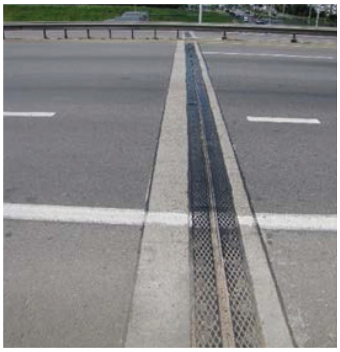

Fig. 11. Minsk ring road, the 8th km (the joint is installed in 2008).

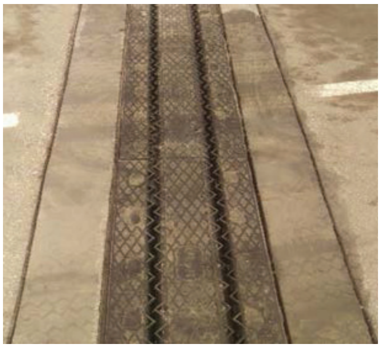

Fig. 12. Nezavisimosti Av. crosses Filimonova str. (expansion joint installed in 2015).

5. Conclusion

- The use of an expansion joint with rubber compensators provides for the stability of a span deformation and wheel load perception provided it is appropriately fastened to the concrete base.
- The formation of the joint on the basis of high-strength concrete provides for its elastic operation.
- Joint use of activated aggregate, active finely grained additives and fiber helps produce the high-strength concrete production characterized by the perception of dynamic traffic load. High-strength concrete characterized by this composition provides for intensive strength development during the first 72 hours (strength reaches 80 MPa). Thus it is possible to dismantle the forms and open the road for the traffic in a short time. The use of expansion joints safely embedded into the concrete base doesn't lead to great expenses concerning their maintenance and repair because of the simultaneous operation of all the elements of an expansion joint and its fastening mechanism.

References

Busel, A.V., V. Kiselev, Chistova, 2009. Activation of coarse aggregate is cement reserve saving and strength increase of the heavy concrete. Teknnologii betonov. Materialy (Technologies of concrete. Materials), № 7-8, 28-30.

Department "Belavtodor", 2011. Expansion joints in the bridges. Design rules. ТКП 318-2011.

Ephanov A.V., Ovchinnikov I.G., Shesterikov, V.I. Makarov V.I., 2005.Expansion joints of highway bridges. Design and operation features. Textbook. Textbook for students of the specialties 291000, 291100.

Golubev, V.Y., 2009. High-strength concrete with a high viscosity. Thesis abstract. PhD, technical sciences: 05.23.05.

Guidelines to design and install polymeric bridge bearings: BCH 86-83.

Guzeev, E.A., 1999. Concrete fracture mechanics: questions, theories and practices.

Krotov R.G., T.A. Rubtsova, submit. 07.10.2013, publ. 10.30.2014. Expansion joint of the bridge span. Pat BY 10378 E 02 B 3/16 / appl. BeldorNII Belarusian Road Research Institute, Republican Unitary Enterprise, № 20130787.

Leonovich I.I., S.V. Bogdanovich, 2012. Diagnostics of roads: a tutorial, BNTU.

Leonovich S.N., 1999. Crack resistance and durability of concrete and reinforced concrete elements..

Mechanical properties of fasteners made of corrosion-resistant stainless steel. Part 1: Bolts, screws and studs: GOST R ISO 3506-1-2009.

Meshcherin, B., 2008. High strength, and heavy-duty concrete: production technologies and application. Magazine: StroyPROFIl. Category: concrete products: technologies and equipment. № 8, 32-35.

Mikulski, V.G., 2004. Construction Materials. Materials Science. Educational edition.

Shevchenko, V.A., 2012. The technology of special concrete. Textbook. Siberian Federal University.

Simakina, G.N., 2006. High-strength fiber-reinforced concrete. Thesis abstract. PhD, technical sciences: 05.23.05.

Transtekhnika.,BelNII, 2006. Road vehicles. The requirements for the technical condition to provide traffic safety. Test methods: STB 1641-

Uglova E.et al., 2014.Design of road constructions taking into account the dynamic effects of modern traffic. Roads and people, № 3 , 22-26.

Urkhanova, L.A. A.S. Efremenko, 2012. Application of spoil tip ash as an active mineral additive to a lightweight high-strength concrete. Scientific and technical and industrial magazine: Stroitelnye materialy/Building Materials, № 1, 31-33.

Verenko V.A., Mytko L.R., 2010. The project of the non-rigid type of the pavement, the Belarusian National Technical University, Moscow.

Zaitsev, I., 2007. High-strength concrete. StroyPROFIl. Category: Concrete and concrete products: technologies and equipment, № 8.

Zverinski, P. G., et al, 2013.The design of the expansion joint with a rubber compensator 120 providing movement up to 120 mm. Roads and Bridges, No. 1 (11), 90 - 95.