On Innovative Concrete-Rubber Composite Blocks Reducing Effects of Dynamic Mechanical Impact: The Review of Structural Solutions

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Abstract. In this paper structural solutions concerning innovative precast concrete hollow blocks with rubber injects are discussed. Knowing that the concrete material has relatively low damping factor, injecting in blocks additional rubber layers improves the overall damping coefficient against propagation of mechanical waves. In order to prepare in the concrete block required hollows under the rubber injects, special form made of plastic or steel is required. Discussed solution is very cheap to achieve. Prepared form could be placed into the cuboid form, where concrete mix has already been poured. After the congeal process both forms could be removed and in the premade hollows, rubber material could be injected. According to that, production process is changed in only a small manner in comparison to the original concrete blocks production. Moreover, as an inject, recycled rubber material may be used. Research conducted by other researchers mainly concerns case, where crumbed rubber is added to the concrete mix in order to obtain desired composite parameters. In this paper different approach is discussed, where rubber is injected into hollow concrete blocks. There were and are performed dynamic and thermal numerical analyses with different shapes or rubber injects. One of the main aims of performed studies is to estimate the damping factor against propagation of mechanical wave in blocks. On the other hand, heat transfer of proposed blocks is also very important from the economical point of view. Despite of analysing single precast concrete-rubber hollow blocks, analyses concerning utilization of that blocks in three-layered wall have also been performed. ADINA code has been used, which is fully based on finite element method. As a concrete material describing hollow blocks C16/20 and C20/25 concrete strength classes have been adopted, which are the most popularly used in Poland. Rubber has been represented via Mooney-Rivlin and/or Zahorski material model. In order to use Zahorski model, special modification of ADINA material library has been introduced. Through the analyses, it has been shown that shape of rubber injects have significant influence on mechanical waves refraction and their dissipation. Moreover, due to relatively small volume of rubber injects in comparison to the whole concrete block, the reduction of block compressive strength would be insignificant. Presented in this paper prototype solutions may be treated as innovative because of rarely met combination of concrete with rubber as well as relatively easy and cheap implementation in the production process.
1. Introduction

Rubber materials due to their relatively high possibility of damping vibrations are frequently used in civil engineering. These materials may be found in special bases under bridge constructions, railroad structures, machinery etc. Depending on physical properties, soft and hard rubbers are distinguished. The softer the rubber, the greater the mechanical wave damping properties and the higher tensile strength. On the other hand, soft rubbers have relatively small compressive strength. Hence, in civil engineering structures, hard rubbers are frequently used, which are mainly subjected to compression.

Nowadays, all over the world a significant emphasis is placed on waste recycling process. In case of rubber materials there are various recycling methods. One of the most popular way of rubber recycling is shredding/crumbing. The other way is to fuse the rubber granulate and prepare desired element via injection in special forms. In Poland, recycled rubber is used in many ways i.e. as an admixture of asphalt layers, as an underlay of playing fields and playgrounds, as a merge with steel in bridge bearings etc. It should be noted, that besides the recycling process, eco-innovative solutions are continuously sought to widen the range of recycled materials utilization.

The history of elasticity theory is very old, however the first professional review of that history has been presented by de Saint-Venant in 1864. Over twenty years later, a very thorough review has been presented by Isaac Todhunter and Karl Pearson. It is believed that the first experimental tests concerning large deformations of rubber materials has been started at the end of the first half of the twentieth century. In 1940 Mooney [1] performed experimental test on rubber materials and determined the constitutive equations describing the rubber behaviour under applied external loading. In proposed mathematical model concerning rubber material tension and compression, three different assumptions have been taken into considerations i.e. material isotropy, neglected change of volume and hysteresis, shear proportional to the traction. On the basis of above strain-energy function was derived, which reflected the rubber behaviour up to 400% of elongation and 50% of compression. From 1948 Rivlin et al. [2-6] furtherly developed mathematical model proposed by Mooney and performed many experimental tests, concerning different rubber materials, applied load types and observed deformations. On the basis of performed by Mooney and Rivlin et al. studies, the Mooney-Rivlin mathematical model describing rubber materials behaviour has been successfully established, which is frequently used till today. In the 50’s and 60’s of twentieth century, Zahorski [7, 8] on the basis of Mooney-Rivlin material model and his experimental studies, proposed his energy-strain formula describing significantly more accurately rubber material under large deformations. Author shown that Mooney-Rivlin model well describes rubber behaviour up to 200% of elongation, whereas his model accurately describes up to 300% of elongation, respectively. It should be noted that over the years, there has been proposed many derivatives of Mooney-Rivlin and Zahorski model to describe rubber and foams behaviour i.e. Ogden [9], Arruda-Boyce [10], Susman-Bathe [11] etc.

In the civil engineering structures, the main goal is to partially or nearly completely reduce the vibrations resulting from ground motions, working machines, transportation etc. Many special studies are conducted allowing observation how mechanical waves propagate through different types of materials. Major and Major [12] studied the propagation of acceleration wave in three segmental, homogeneous and isotropic hyperelastic rod with slowly changing cross-section area. Steel and aluminium segments were analysed in different configurations. Both materials were described with Murnaghan’s nonlinear elastic model. One-plane stress as an approximate form of analysis was used to derive the equation of energy transport for incident, reflected and refracted acceleration wave. Through the analysis, due to different material densities, jumps in the wave acceleration at the connection of segments were shown. On the basis of analysed aluminium/steel/aluminium rod it was shown that the transmitted wave intensity was lower than incident when the wave passed from the first to the second analysed rod segment. Opposite phenomenon was observed on passing from the second to the third segment. In different paper Major et al. [13] studied the propagation of a shock wave in the isotropic materials with the Blatz-Ko hyperelastic potential. In case of nations laying near the contact of tectonic plates or in areas exceed to the mining rockbursts, studies of ground motions on waves
propagation in actual structures are performed. The leading research centre is Japan, where significant emphasis is placed on ground motion vibrations transferred on civil engineering constructions i.e. [14-17].

Nowadays, due to the growing awareness of caring about the environment, solutions allowing the use of waste subjected to the recycling process are being sought. It is clearly visible in many areas of life i.e. repeat use of glass bottles, biodegrade car parts produced in automotive industry, utilization of recycled concrete as an aggregate in new civil engineering construction etc. Knowing that the rubber material is characterized with significant damping properties, studies concerning utilization of that material in civil engineering are conducted. Numerical studies concerning wave propagation in different rubber models described via Mooney-Rivlin and Zahorski material models were discussed in [18]. It was shown that in Zahorski material model, obtained stresses resulted from applied impact loading were slightly higher than these obtained in Mooney-Rivlin, what was the effect of different stress-strain relation. On the basis of [18], Major and Major [19] analysed numerically cubic sandstone block with bored holes under the steel rods, where between the steel rod and sandstone material, rubber was injected. It was shown, that with rubber material, propagating wave from steel anchor connecting other structure element may be significantly damped. According to that, sandstone material would be significantly more protected against cracking through transmitted vibrations from steel rod. It should be noted that there are many papers discussing connection of concrete mix with rubber granulate to improve bending and dynamic resistance of structures. Gerges et al. [20] performed experimental studies of mechanical and dynamical rubber-concrete material properties by partial sand replacing with rubber granulate. Four different specimens were taken into considerations, where sand was replaced in the range of 5-20% with 5% step. It was shown, that despite the compressive strength was limited, density was lowered, and higher impact resistance was achieved. Replacement of aggregate via recycled rubber in geopolymer concrete was the subject of interest by Aly et al. [21]. Through the experimental tests it was shown that compressive strength of geopolymer concrete can be slightly enhanced, if the level of rubber granulate is lower than 10% of total element volume. Moreover, it was stated that the more the rubber granulate the higher improvement of dynamic resistance. The influence of crumbled rubber on different mechanical properties in concrete slabs, beams etc. was discussed in [22-27].

In this paper an innovative way of concrete-rubber connection to improve structural elements damping properties is discussed. Despite well-known concrete mix with rubber granulate connection, there is proposed a new method of injecting rubber material into specially prepared hollows in concrete elements. That method significantly lowers the undesirable reduction of compressive element strength at approximately the same level of obtained damping in comparison to the traditional method of connecting the concrete mix with rubber granulate.

2. Incompressible rubber materials behaviour

Each of the known materials depending on the influence of applied external forces or due to forced displacements sustain small or large deformations. On the basis of experimental tests, the material behaviour subjected to various external factors is described via constitutive equations. It should be noted that general model describing the influence of any factor on deformation of any material does not exist. For a one chosen material there are plenty of different descriptive models. Each model describes well material behaviour under some external factors, whereas other parameters are slightly worse reflected or are even neglected. General constitutive equation describing the elastic isotropic material may be presented as:

\[ W = W(I_1, I_2, I_3) \]  

where: \( I_1, I_2, I_3 \) are deformation tensor invariants.

Eq. (1) corresponds to the case, where elastic body does not have imposed internal bonds. According to that by imposing the internal bonds, one obtains an incompressible body and the
deformations cannot change that body’s volume. That leads to $I_3 = 1$. By substituting that invariant into Eq. (1) one obtains that for the incompressible elastic body, function of deformation energy depends only on $I_1, I_2$ invariants. On the basis of non-linear theory of elasticity rubber is treated as an incompressible material, thus it may be described via two invariants $I_1, I_2$ with the third $I_3 = 1$. In case of rubber material constitutive equations are derived from mechanical energy balance equations. Hence, stress-strain or strain-energy relation is mainly described. It is worth noting that one generalized constitutive equations describing rubber cannot be found in the literature, due to specific rubber and rubber-like materials behavior under large deformations. Hence, in each studied case, the constitutive equations have to be determined anew via the experimental tests.

On the basis of Eq. (1) and [8], one obtains a constitutive relationship describing hyperelastic Zahorski material in the following form:

$$W(I_1, I_2) = C_1(I_1 - 3) + C_2(I_2 - 3) + C_3(I_3^2 - 9)$$

(2)

where $C_i (i = 1, 2, 3)$ denotes the material constants.

Similar constitutive equation is derived for Mooney-Rivlin material, for which only two material constants are used $C_1$ and $C_2$. According to that, one obtains:

$$W(I_1, I_2) = C_1(I_1 - 3) + C_2(I_2 - 3)$$

(3)

By comparing (2) and (3) one may notice, that in Eq. (2) describing Zahorski material behavior there is one more equation member in regard to the Eq. (3). This small difference in material behavior description shows, that Zahorski material would have slightly different stress-strain relation in comparison to the Mooney-Rivlin. Moreover, consideration of more material constants in the constitutive equation increases the complexity of the problem. On the other hand, material characterized with greater number of constants better describes its behavior under applied external factors. The differences in stress-strain relation in Mooney-Rivlin and Zahorski material model for rubber “A” with following material constants: $C_1 = 62780$ Pa, $C_2 = 8829$ Pa and $C_3 = 6867$ Pa on the basis of [7] is presented in figure 1.

![Figure 1](image_url)

**Figure 1.** The difference in stress-strain relation between Mooney-Rivlin (a) and Zahorski (b) material model.

One may notice, that the third material constant $C_3$ in Eq. (2) results in higher stresses obtained in Zahorski material, both under rubber compression and tension at the same level of analyzed strain. Moreover, when rubber is stretched (Engineering strain > 0) the curve concerning Zahorski material has slightly different course than that presented for Mooney-Rivlin.
3. Numerical solutions and results discussion
In this section proposed till now numerical solutions of innovative concrete hollow blocks with injected rubber are presented and discussed. Presented solutions concerns different shapes of rubber injects and their influence on dynamical effects damping. Each prototype solution was defined and calculated with the use of ADINA code, based on finite element method. Depending on the solution Mooney-Rivlin or Zahorski material model was used to describe injected rubber.

3.1. First prototype solution of concrete hollow block with inserted rubber pad
The first prototype solution of concrete hollow block with inserted rubber pad was presented by Major et al. in [27]. The model consisted of a solid block made of C20/25 concrete grade with rubber inserted in a specially prepared tunnels made between the top and bottom block surface. Following block dimensions were adopted: 0.50 m (length), 0.22 m (width) and 0.25 m (height). The tunnels were made in the shape of I letter with two colocaally connected T letter shapes. For the rubber material Mooney-Rivlin material model has been used. Presented solution was subjected to four independent dynamic loads. Concentrated force acting perpendicularly at the midpoint of front vertical surface, vertical/horizontal line load passing through the front surface midpoint and uniform pressure applied to the vertical front surface was studied, respectively. The acting load was assumed to be applied within a very small amount of time equal $1 \times 10^{-5}$ s. According to that load raised its value from 0 up to desired level at $1 \times 10^{-5}$ s, then it has been completely removed till the end of the analysis. Application of load in that manner allowed to observe clear mechanical wave propagation in the form of stress plots. In order to check how the inserted rubber pad raised the mechanical wave damping, an analysis concerning identical solid concrete block without rubber pads and prepared tunnels was performed.

Presented results showed that the rubber pads significantly damped the mechanical wave resulted from applied dynamic load. Through the studied sensor points located on the rear composite block wall it was shown that depending on the sensor point location (the volume of rubber that mechanical wave had to pass through and the distance between measurement point and applied loading point/line) one could observe 73% up to 94% damping of the mechanical wave. In case of applied pressure dynamic load damping of mechanical wave propagation in measured points varied from 53% up to 78%. It was stated that in block subjected to dynamic pressure load, some part of the mechanical wave could pass from the front to the rear surface only through the concrete material. It was connected with block outline made of concrete and one of the measurement points located on that outline. It should be noted, that rubber pad is inserted into the concrete block, thus it does not provide cover near the hollow block edges, which have to be made of concrete.

Similar analysis was shown in [28] where section of a wall made of concrete hollow blocks with rubber pads subjected to the dynamic concentrated load was studied. The wall section was made of exactly the same concrete hollow blocks as in previous study, however, mortars between blocks were added. It was proved, that loading applied directly to the composite hollow block allow to significantly reduce the mechanical wave intensity on the rear wall side. Despite that, some of the mechanical wave could freely propagate through the blocks concrete outline as well as through the mortars. In case of load applied exactly to the mortar it was stated that the mechanical wave intensity in the line of applied load is only slightly reduced due to reflection and refraction of wave at the connection of concrete and rubber materials. Despite that, the larger the distance of sensor point in perpendicular direction to the acting load line on the rear wall surface, the greater mechanical wave reduction was observed in comparison to the same wall made of solid concrete blocks. It is worth noting that proposed rubber element shape significantly reduces bending strength of the hollow block in the direction of applied load, thus further modifications were required.

3.2. Modification of rubber inserts shape
The next step in the study concerned modification of rubber inserts shape in the single concrete hollow block [29, 30]. Nearly the same dimensions of block were adopted, however block’s connection edges complexity was simplified and adopted as a planar plane. Dynamic analysis was limited to the
pressure load applied, which gave the lowest mechanical wave damping results in the first prototype model. In [30] rubber material has been replaced with polyurethane foam and one layer of mortar on front and rear block surface were added as in actual structures. In that model both dynamic and thermal analysis were performed. Once again in both papers, hollows under rubber inserts were prepared from the top to the bottom surface of the block. The shape of analyzed hollows in concrete block is presented in figure 2, whereas Mises-Hencky stress (MHS) plot presenting wave propagation in both solid and composite block are presented in figure 3.

![Figure 2. Concrete hollow block with rubber crosses](image)

![Figure 3. Wave propagation in the form of MHS plot in the solid concrete block (a), concrete hollow block with rubber inserts described with Mooney-Rivlin material (b). Time 4·10⁻⁵ s.](image)

On the basis of figure 3 one may notice, that rubber inserts in the concrete hollow block, significantly change mechanical wave propagation (figure 3b) in comparison to the solid concrete block (figure 3a). Through the numerical calculations it was observed, that the mechanical wave damping fit in range of 47-80% for rubber material inserts and 14-76% in hollow block with polyurethane foam injects. In case of rubber elements [29] it was 6 percentage points lower than for the prototype model lowest obtained value of mechanical wave reduction and 2 percentage points higher for the highest percentage damping, respectively. In the second case of polyurethane foam elements [30], damping near the YZ external surfaces was significantly lower than for rubber, whereas in the points located in line passing through two foam elements, mechanical wave damping was nearly
same damped. Once more, significant difference in damping was connected with different localization of sensor points on the rear surface of hollow block. The lowest percentage damping was obtained on measurement points where mechanical wave propagated through the concrete material only (near the external YZ block surfaces). Despite that wave propagated through the concrete material, however complex shape of rubber/polyurethane foam elements located near the external edges resulted in slight mechanical wave refraction. It is worth noting that some of the energy transferred was reflected via rubber elements and wave interference could be observed near the edge, where loading was applied.

In case of hollow concrete block with polyurethane foam inject, thermal analysis was also performed [30]. Following temperatures has been assumed: 20°C subjected to the “inner” block side and -20°C to the exterior side, respectively. Temperature distribution along the Y-axis was studied after 12, 24, 36 and 48 hours. It was proved, that in the composite block temperatures after each studied time step were approximately 1.5 – 2.0°C higher than in typical solid concrete block. After obtained promising results, thermal analysis was performed [31] concerning the concrete/concrete-polyurethane block located behind bricks and insulation layer. For single composite, thermal conductivity parameter $\lambda$ was derived, which was equal $1.686 \text{ W/m·K}$. That parameter was approximately 15.7% better, than for identical solid concrete block. In case of composite located behind bricks and insulation layers, heat transfer coefficient was only slightly improved i.e. from $U = 0.344 \text{ W/m²K}$ when solid concrete blocks were used to $U = 0.341 \text{ W/m²K}$, when composites were studied. In case of single block layer analyzed, the difference between obtained heat transfer coefficients was equal 0.248 W/m²K. It should be noted, that in analyzed blocks with separate insulation layer, a utilization of polyurethane foam injects does not give measurable benefits of temperature distribution in comparison to the solid concrete blocks used. Despite that, acoustic wave reduction would be significantly enhanced.

3.3. Further project development

All performed analyses of concrete hollow block with crossed shape of rubber/polyurethane injects concerned cases, where only single block with some added different layers was studied. According to the [28] it was wise, to check how that concrete blocks with crossed shape rubber injects behaves as a wall, subjected to dynamic impact. In [32] single layer wall made of composites connected with mortars, subjected to the concentrated force impact was taken into considerations. Three vertical layers of concrete blocks were assumed, with two blocks placed horizontally separated via air space gap. Two different types of dynamic loading were taken into considerations i.e. pressure applied to the whole front surface of a wall and concentrated force applied exactly in the center of that front wall surface.

Through the numerical analysis it was shown that mechanical wave damping in case of concentrated force applied to the wall made of composites fit in range of 55-97% in comparison to the wall made of solid concrete blocks. Of course, the 97% of mechanical wave damping was observed in the measurement point located on the rear wall, in quite far perpendicular distance to the line of applied load line of action. Mechanical wave, had to pass through many rubber injects, which absorbed some of the transferred energy and significantly refracted the wave. In the second case, where pressure dynamic load was applied, range of mechanical wave damping was significantly lower i.e. 37-65%. That decrease in the mechanical wave damping was once again connected with wave propagation through the mortars and concrete material located on the outline of analyzed blocks.

One of the latest analysis [33] concerned case of three layered wall subjected to dynamic load, where first layer consisted of small concrete hollow blocks with rubber inject shape identical to the prototype model (see [28]), air space gap, and normal concrete hollow blocks with cross shape of rubber injects. In figure 4 composites shape and layers/injects dimensions are presented, whereas in figure 5 mechanical wave propagation in a wall made of solid concrete blocks and made of composites is demonstrated.
Figure 4. Wave propagation in the form of MHS plot in the solid concrete block (a), concrete hollow block with rubber inserts described with Mooney-Rivlin material (b). Time $4 \times 10^{-5}$ s.

Figure 5. Wave propagation in the form of MHS plot in the wall made of solid concrete block (a), concrete hollow block with rubber inserts described with Mooney-Rivlin material (b). Time $6.842 \times 10^{-5}$ s.

Through the analysis, where the most unfavorable case of dynamic load application was investigated i.e. on the mortar at the connection of blocks, it was shown that mechanical wave propagation may be furtherly significantly damped. White strips in the middle of the presented models in figure 5 reflects the air space. As shown in figure 5a, one may notice that the mechanical wave propagation in the wall made of solid concrete block propagates in circular shape and the energy transferred is only slightly reduced along with the distance covered. In case of wall made of composites figure 5b, it is clearly visible, that the energy is transferred mainly through the mortar and blocks’ concrete material outlines, whereas the greater the distance from the mortar along X-axis the lower the energy transferred. In that particular case, significantly greater load was investigated. Two forces with 1000 N were applied, instead of one. Even though, depending on the location of sensor point, mechanical wave energy on the rear wall surface was approximately 21-61% lower than energy obtained in the wall made of solid concrete blocks.
Conclusions

In this paper a short review of proposed structural solutions concerning concrete hollow blocks with rubber inserts/injects was presented. Discussed solutions are a fresh look onto the connection of concrete with rubber, which may be easily and cheaply implemented in the production process. It should be noted that performed by other researchers experimental and numerical studies concern cases, where crumbed rubber is added to the concrete mix in respective proportions. Rubber insertion/injection into the completed product or addition of crumbed rubber to a concrete mix allow to achieve a composite with significant mechanical/ acoustic wave damping properties. It should be noted that in case of crumbed rubber added to concrete mix, at the end of congeal process one obtains composite element with significantly greater bending strength in regard to the concrete hollow blocks with inserted/injected rubber. Depending on the hollows made under the rubber inserts/injects and their volume compared to the solid concrete block, bending strength of that composite may remain same as in solid block or would be reduced/slightly enhanced. Compressive blocks strength remains same as in solid concrete, if only small rubber elements with appropriate arrangement is used. After some critical point of rubber volume, the greater the rubber volume the lower the compressive strength. Same phenomenon is observed in case of elements made by adding crumbed rubber to concrete mix, however, limit point of rubber volume is significantly lower than in presented solutions. It is worth noting that promising results of mechanical wave reduction in composites with kept nearly the same compressive and bending strength as solid concrete blocks should be validated with experimental tests which will be held in the near future.

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