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USE OF THE FOAMED CONCRETE IN THE STRUCTURE OF PASSIVE HOUSE FOUNDATION SLAB

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Abstract

The use of cellular concrete in civil engineering has a long history. It is very popular as a thermal and sound insulation layer of ceiling and roof systems. Structural use is still limited to geotechnical solutions where strength parameters of foamed concrete are comparable to well compacted sand. Thanks to other benefits like self-levelling, self-compaction, high freeze/thaw resistance and biological resistance, foamed concrete gains popularity in such applications as excavation infill, soil stabilisation and lightweight foundations. A foundation slab made of foamed concrete has also another advantage. Very promising thermal insulation makes that solution ideal for thermal saving applications, especially when floor heating is applied.

This paper presents the concept of a dwelling-house sandwich foundation slab partly made of foamed concrete. The idea emerged after critical review of existing methods of founding of passive houses with use of structural layer made of non-structural materials (usually foamed polystyrene). In the proposed solution, foamed concrete creates an insulated base slab for a house structure. High drying shrinkage and relatively low tensile strength makes the total substitution of reinforced concrete impossible, but significantly reduces its depth to a thin floor layer. In addition to thermal insulation, the base layer of foamed concrete distributes the wall reactions which makes the proposed solution excellent for weak soils. The described concept is exemplified with realised foundations. Some developed design procedures and recommendations are presented.

Keywords: Foamed concrete, foundation slab, energy saving

1. Introduction

Cellular concrete was introduced into the construction industry in the middle of the last century. First applications were limited to non-structural applications like void fillings, roof thermal insulations and ceiling acoustic damping.

Foamed concrete is one type of cellular concrete, produced in a process of foaming of cement slurry. This is the most popular, economical and controllable pore-forming process, which results in creation of the material lighter than conventional concrete. Cement & Concrete Institute defines foamed concrete as a cementitious material with a minimum of 20% of foam entrained into the cement mortar [1]. Adequately to the volume of the foam agent, foamed concrete may be produced in densities between $300\,kg/m^3$ to $1600\,kg/m^3$ and compressive strengths $0.5 \div 15\,MPa$.

2. Potentials of foamed concrete for a structural use

In structural engineering there arises a necessity of application of structural materials which are light, durable, simple in use, versatile, economic and environmentally sustainable. Foamed concrete, which was initially used as an insulating material, satisfies all of these requirements thus has a great potential for structural use, although it may not be a direct substitution for normal weight concrete.

The properties of foamed concrete depend on its composition (type of binder, proportions of ingredients) and methods of formation and curing (resulting microstructrure). The pore structure has major influence on such parameters as strength, permeability, diffusivity, shrinkage and creep, hence its characterisation is highly important.

2.1 Strength parameters

Compressive strength is a common performance measure for concretes. A hypothetical compressive behavior (stress–strain relationship) of a cellular material is presented in Figure 1 [2].

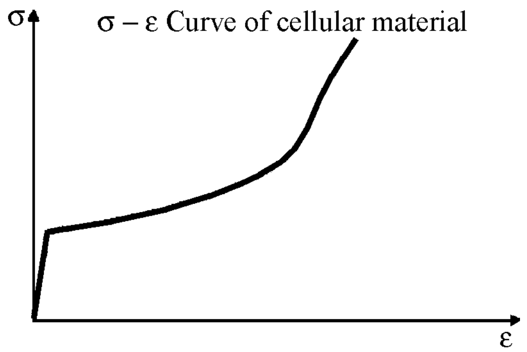

Figure 1: Stress–strain curve of a cellular material [2]

In conventional applications of foamed concrete as a filling material there is no need of high strengths. Therefore it is believed that foamed concrete, which typically consists of cement, filler, water and foam, is a low-strength non-durable material with no possibility of structural applications where high strengths are desired.

Nevertheless, the use of fine fillers, such as simply fine sand [3] or pozzolanic materials such as pulverized fuel ash, slate waste or silica fume instead of or in addition to cement/sand [4, 5, 6] provides promising increase in strength (up to 25 MPa and above). Obviously, higher strength corresponds to higher density: compressive strength increases linearly with density [5]. Cement & Concrete Institute in [1] states that $1600\,kg/m^3$ is the minimum density at which typical foamed concrete could be used in structural elements while Jones & McCarthy in [4] suggest that the value can be lowered to $1400\,kg/m^3$ for the foamed concrete with pozzolanas.

A brittle mode of failure is observed in compressed foamed concrete samples. Coupled with relatively low values of compressive strength, it is believed to be the result of unconfined conditions of tests leading to early crack initiation [2]. Confined conditions reduce the occurrence and propagation of cracks. It was not possible in practice, however, to achieve the stress-strain relationship as presented in Figure 1. The elements usually fail in elastic stage, not exhibiting plastic properties due to expected microstructure damage and consequent densification.

In comparison to aggregate concretes, in which there is a slight increase in strength after 28 days, a further gain in strength is observed in fly-ash concrete after 56 days [4] or even 91 days [3]. Therefore, foamed concrete elements require comparatively much longer period of curing.

The value of tensile strength of foamed concrete is typically $10 \div 15\%$ of the compressive strength while the flexural strength is about 25% [5]. Application of pozzolanic materials decreases the values of tensile strength and elastic modulus [4]. This is worrisome because these parameters are low enough in typical foamed concrete itself. Therefore, foamed concrete of a given grade exhibits worse characteristics for flexural applications than normal weight concrete of the same grade, particularly in case of deflections.

However, low tensile strength and elastic modulus are inherent properties of concrete dealt with application of reinforcement. The use of polypropylene fibres is a very popular reinforcement method [4], but it was also proposed to reinforce foamed concrete elements with vinyl fibres [6] or with more sophisticated nanodispersive reinforcement in a form of carbon nanotubes [7].

Moreover, a further improvement of strength parameters can be achieved by lowering the water/cement ratio of fresh foamed concrete mix. To sustain its beneficial workability, some foam-compatible plasticizers need to be applied [4].

To increase the strength properties of foamed concrete along with improvement of its weight and workability, the foam can be modified by introduction of specially designed types of foam agents or addition of styrofoam [6, 8]. The choice of admixtures must assure stability of the foam and proper formation of the bubbles in the final material.

2.2 Early-age properties

The thermal–moisture effects of hardening process must be considered as one of the most important problems of all cement-based materials, including foamed concrete. The process is similar as in typical concrete, in which the hydration heat and drying shrinkage lead to cracking of the element.

Nevertheless, in foamed concrete, characterised with significant level of porosity, the rate of water migration from hardening concrete is faster than in conventional concrete. Therefore, drying shrinkage in foamed concrete poses much greater risk. A change of foamed concrete composition may be considered to reduce the threat of negative thermal–moisture effects which are the greatest when only cement is used as a binder [5]. Application of pozzolanic admixtures allows to decrease the hydration heat, thus lowers the potential thermal shock, and retards water desorption which results in decreased shrinkage [4]. The use of fine aggregate (sand) also gives promising results in this matter.

2.3 Physical, chemical and biological resistance

Foamed concrete, being a porous material, exhibits significant sorption characteristics [5]. Water vapour diffusion can be observed even in a dry state. While in a direct contact with water, moisture transfer occurs by absorption of water and transmission by capillarity (sorptivity). The sorption characteristics are the best in cement–sand foamed concretes with a large foam content and get worse when density increases or when pozzolanic materials are added [9].

The material has excellent frost resistance in a dry state [3]. Nevertheless, increased amount of water in pores is reported to intensify freeze/thaw reactions. At very high degrees of saturation the material becomes brittle and undergoes complete failure [5].

Foamed concrete, especially with a pozzolanic admixture, possesses poor carbonation resistance with high rates of carbonation [4], so it must be carefully protected in the environments where carbonation-induced corrosion may occur. Application of carbon steel for reinforcement should be avoided. On the other hand, foamed concrete – as a cementitious material – has very good biological resistance.

Foamed concrete exhibits good fire-resistance properties and is an incombustible material [5]. In comparison to normal weight concrete, foamed concrete has better fire-proof properties and is less prone to strength loss in fire, especially at lower densities. This is because it is a relatively homogeneous material with low thermal conductivity and diffusivity.

2.4 Thermal and acoustic insulation

Foamed concrete provides a high level of sound and thermal insulation, mainly thanks to its density and high porosity [1, 2, 4, 5, 8, 10]. The amount, size and distribution of pores has a crucial meaning.

Nevertheless, the side effect of its high porosity are corresponding sorption characteristics, which have negative influence on the thermal resistance [9]. Thus, it is essential to minimise the contact of a foamed-concrete element with water.

2.5 Transportation and installation

Foamed concrete has high workability. It is a free-flowing and self-compacting material, so it does not require compacting, vibrating or levelling [1, 8]. Therefore, application of foamed concrete is beneficial for productivity and comfort at erection stage.

Thanks to the production technology of foamed concrete, i.e. in-situ foam entrainment, the volume of the material is limited, so it is efficient in transportation and placement [3, 8].

3. Application in foundation slabs

The main advantage of foamed concrete is its light weight which ensures economy in the design and execution of supporting structures, including foundations. Additionally, it provides a high degree of thermal insulation, making foamed concrete a perfect material for use in a passive houses design.

Introduction of foamed concrete as a replacement of compacted soil in a base layer for a foundation has a series of advantages. The material has the strength properties at least as good as well-compacted soil. It can be easily placed (poured) and does not settle, so no compaction is required. Its light weight ensures limitation of loads imposed to the subsoil along with providing uniform distribution of reactions from the supported structure. No lateral pressure is exerted.

Foamed concrete is currently used for light weight foundations in densities below $800\,\mathrm{kg/m^3}$. However, there are applications of higher-density foamed concretes where there is higher demand on strength, such as in road works as a compensation bed or under flooring in industrial buildings [8]. Promising results of these applications may be a good basis for use of foamed concrete as a support for heavier building structures.

The proposed foundation slab is a sandwich solution with a foamed concrete base layer and a reinforced concrete structural layer. In a standard solution, as presented in Figure 2, under the load-bearing walls the continuous 40 cm x 20 cm wall sleeper ribs of reinforced concrete are applied in a form similar to conventional strip foundations. The grid is joint with a diaphragm in a form of a 10-cm thick reinforced concrete slab into a monolithic structure. The voids are filled with hard extruded-polystyrene panels.

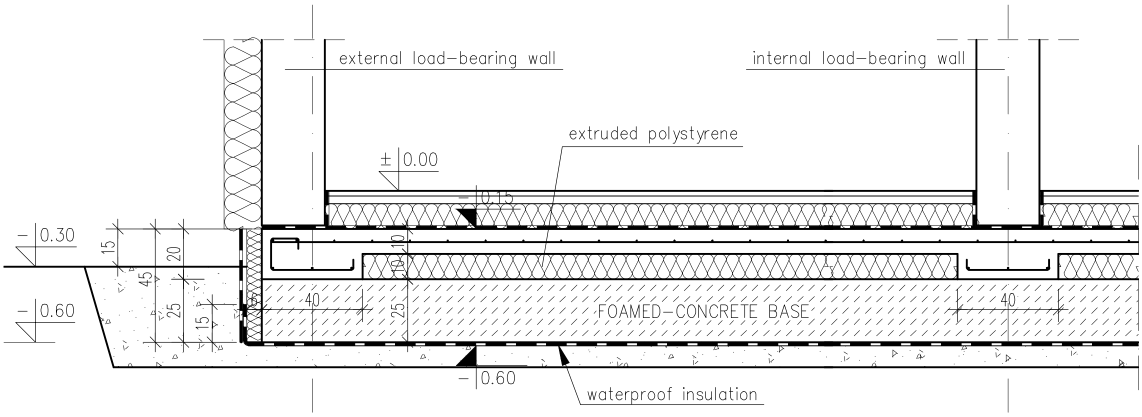

Figure 2: Foundation slab for good geotechnical conditions

The dimensions of the reinforced concrete ribs are designed in a way that assures a desired load-bearing capacity of the element itself and limitation of stresses exerted by the supported structure on the foamed concrete bed and then on the subsoil.

If hydro–geological conditions on a site are poor, modification of the slab can be applied with a plain concrete ring continuous foundation at the outer perimeter of the foundation slab. Figure 3 shows the ring foundation when the minimum foundation depth (0.5 m below terrain level) is satisfactory. Figure 4 presents the ring foundation for a slab on heaving soils, where the foundation base has to be located below the freezing depth (min. 0.8 m below terrain level).

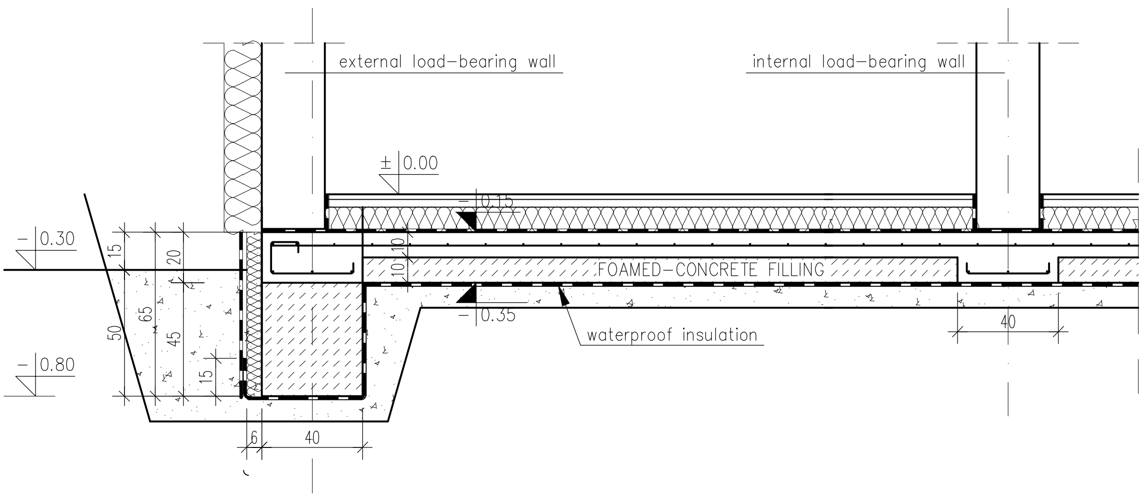

Figure 3: Foundation slab for poor geotechnical conditions. Standard version

A further distinction has to be made between the standard version (Figure 4) and the so-called “thermo” version (Figure 3). The main differences are the thermal insulation properties of the two solutions. It must be noted that application of the standard version requires relatively good

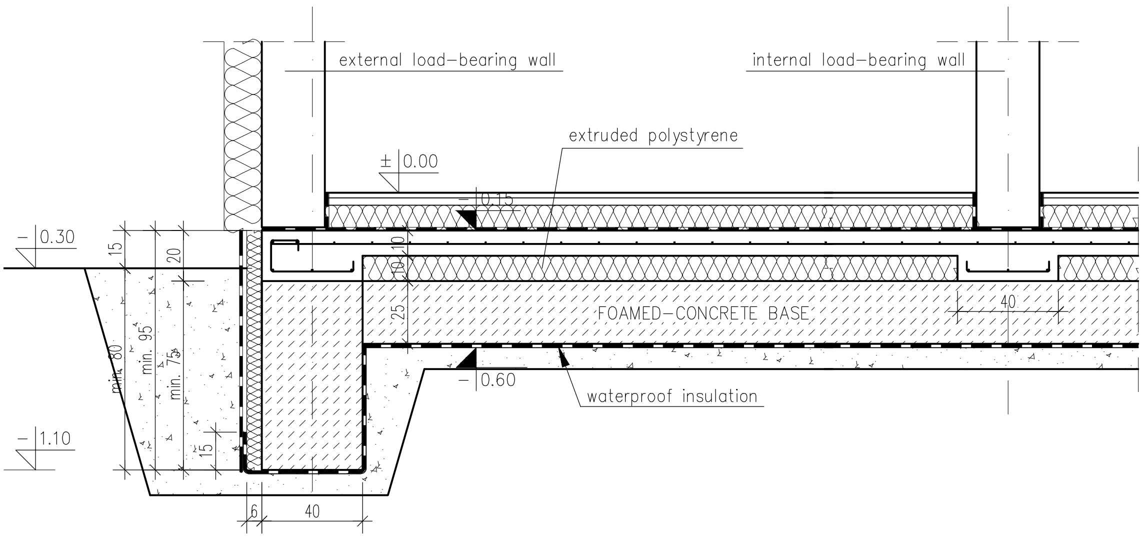

Figure 4: Foundation slab for poor geotechnical conditions. Thermo version

geotechnical parameters of the subsoil as the loads from the foundation are transmitted directly onto the subsoil; foamed concrete plays only the insulating role.

4. Numerical model

Behaviour of a foundation slab depends mainly on its deformability and stiffness of the subsoil. These two parameters were chosen as variables in the FEM analysis.

A scheme of the modelled structure with a detailed arrangement of the FEM mesh is shown in Figure 5. The model was created using cuboidal finite elements. As a support the Winkler subsoil with linear elements was used. Possibility of ground separation under the foundation was ensured by excluding supporting bars after the occurrence of tensile stresses during calculation process.

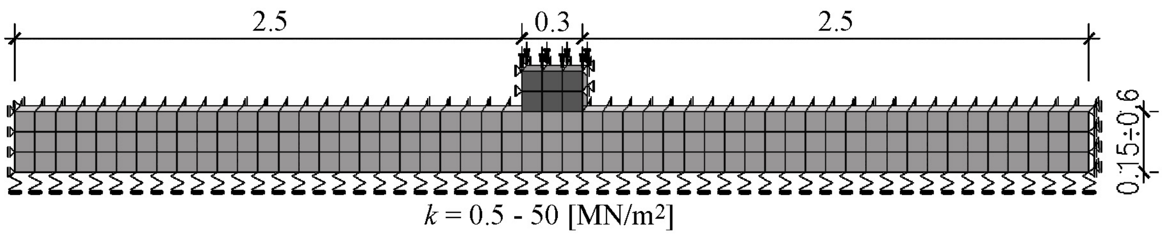

Figure 5: Scheme of the finite element model

All analyses were performed with use of the MAFEM 3D program created and developed in the Department of Structural Engineering of the Silesian University of Technology. The program, based on the Willam Warnke material model modified by Majewski [11], allows of the elasto–plastic analysis of cohesive–frictional materials.

A large group of models with different depths of the foamed concrete layer and elasticity of the subsoil Winkler bars was analysed. Concrete and steel material characteristics as well as geometry were constant for all models. The assumed values for normal weight concrete were taken as: uniaxial compressive strength 30 MPa, uniaxial tensile strength 2.7 MPa, initial modulus of elasticity 22 GPa, Poisson's ratio 0.166, ultimate strain at uniaxial compression 0.0022.

Foamed concrete parameters were taken on the basis of the data disclosed by the producer: compressive strength was taken as 0.8 MPa, tensile strength 0.21 MPa, initial modulus of elasticity 1.0 GPa, Poisson's ratio 0.166 and ultimate strain at compression 0.02.

Stiffness parameter of the subsoil, defined by the k coefficient, varied between 0.5 and 50 MN/m^2.

4.1 Results of the analysis

The aim of the analyses was to find the conditions of the work of the foamed concrete slabs loaded with the reaction of the sleeper ribs. Possible failure models were defined.

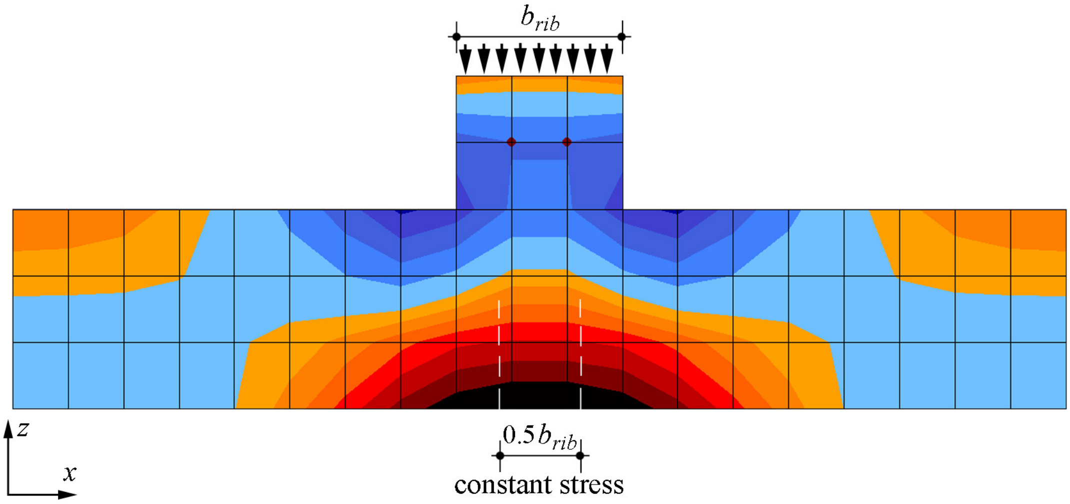

Figure 6: Distribution of σ_x stresses characteristic for bending of the foamed concrete layer

Figure 6 presents an exemplary σ_x stress distribution diagram characteristic for bending of the foamed concrete layer. Dashed lines represent the boundaries of the zone where the stresses are almost constant. The lines can be simultaneously considered as the sections where bending condition should be controlled.

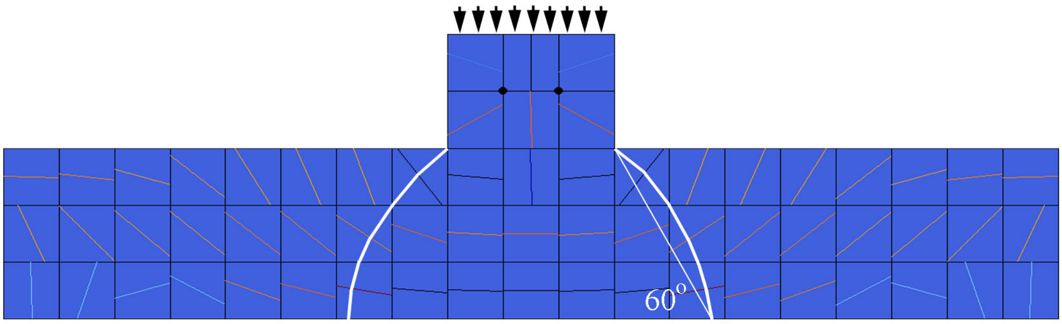

Figure 7: Punching surface in the foamed concrete slab

Figure 7 presents the direction vectors of the main tensile stresses. The line perpendicular to these vectors (denoted with a white line) defines the punching surface. As it is shown, the inclination angle of this surface is equal to approximately 60°. Such a result complies with the results obtained in [10].

Figure 8 and Figure 9 show the passive earth pressure distributions for various subsoil stiffness parameters and various depths of the foamed concrete slab. It can be noticed that the range of the pressure zone widens and becomes more uniform along with the weakening of the subsoil (Figure 8). A similar effect can be observed as the depth of the slab increases (Figure 9). The maximum pressure occurs under the rib and reaches the greatest values for the stiffest subsoil and the thinnest slab.

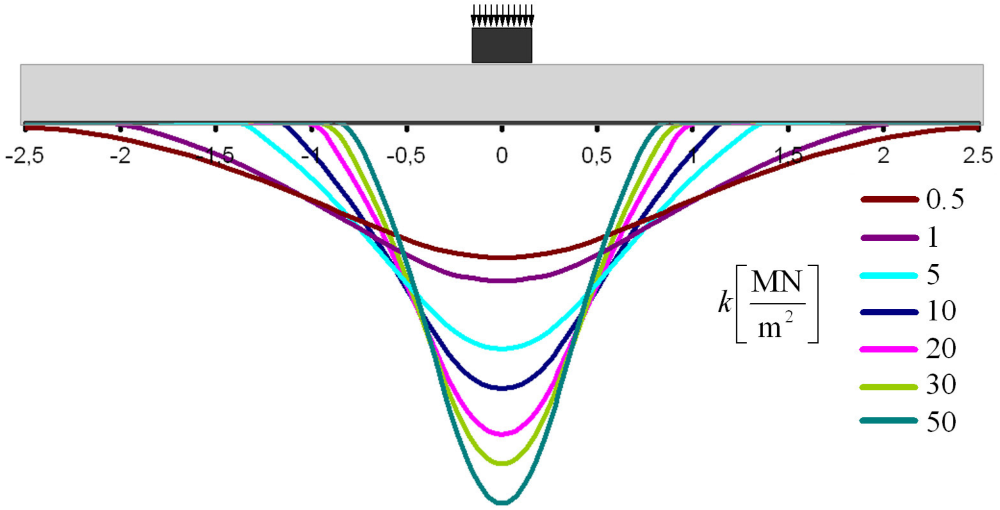

Figure 8: Passive earth pressure distribution depending on the subsoil stiffness

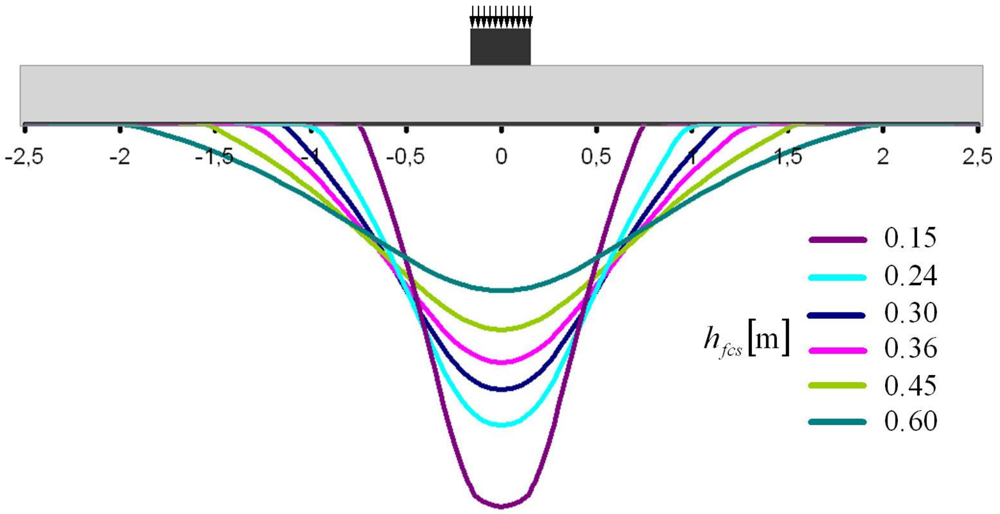

Figure 9: Passive earth pressure distribution depending on the foamed concrete slab thickness

5. Design model

Wide applications need simple solutions. This is the reason why a simple design model was created on the basis of the achieved FEM results. The model is presented in this section.

There are five possible failure situations:

1. compressive failure of foamed concrete under the rib of the RC foundation slab,
2. flexural failure in the bottom zone of the foamed concrete layer,

3. punching shear failure of the foamed concrete layer,
4. separation of the edge of the foamed concrete layer due to combined flexural and punching effects,
5. depletion of bearing capacity of the subsoil with no damages in the foundation sandwich.

The last failure situation is a geotechnical problem and will not be discussed in the paper.

5.1 Compressive failure of foamed concrete

This failure situation is possible for extremely advantageous geotechnical conditions when the foamed concrete layer is founded in hard soils, like rocks or well-graded sands. The local compressive pressure caused by the rib of the foundation slab should be checked according to the condition:

$$\frac{Q_r}{b_{rib}} \leq f_{fcd}, \tag{1}$$

where:

Q_r	–	continuous load transferred from the sleeper rib of the RC slab (per meter of the rib's length),
b_{rib}	–	width of the sleeper rib,
f_{fcd}	–	compressive strength of foamed concrete.

5.2 Flexural failure of foamed concrete

This failure may appear as a consequence of typical bending of the foundation slab caused by the passive ground pressure. The impact width (the area where the passive earth pressure will appear) depends on the thickness of the FC layer, the angle of the load transfer and soil deformability. On the basis of the FEM analyses described in section 4., the following expression to calculate the impact width may be proposed:

$$r_{imp} = \frac{4.7 \cdot h_{fcs}^{0.8}}{\sqrt[4]{k}}, \tag{2}$$

where:

h_{fcs}	–	depth of the foamed concrete slab (given in [m]),
k	–	stiffness parameter of the subsoil (given in [MN/m]).

The original curvilinear shape of the subsoil stress block may be substituted by a bilinear (trapezoid) one shown in Figure 10. A fold point is situated under the fourth part of the rib's width. Such an assumption results from the considerations presented in subsection 4.1 where it was proved that the stress change attenuates at this point. Considering vertical force equilibrium, the maximum value of the passive earth pressure could be found as:

$$\sigma_{max} = \frac{Q_r}{r_{imp} + 0.75 b_{rib}}. \tag{3}$$

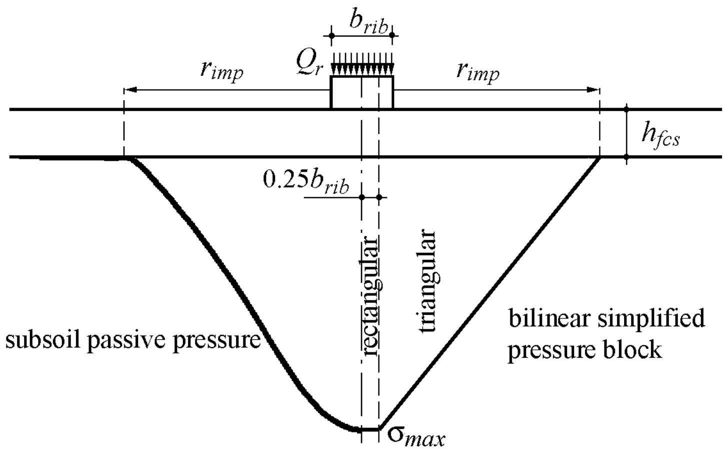

Figure 10: Substitute passive earth pressure block

The maximum bending moment can be determined with the cantilever model presented in Figure 11, in which a substitute bilinear passive earth pressure block is assumed. The value of the maximum bending moment at the section of the fold point is equal to:

$$M_{max} = \frac{\sigma_{max} \cdot (r_{imp} + 0.25b_{rib})^2}{6}. \tag{4}$$

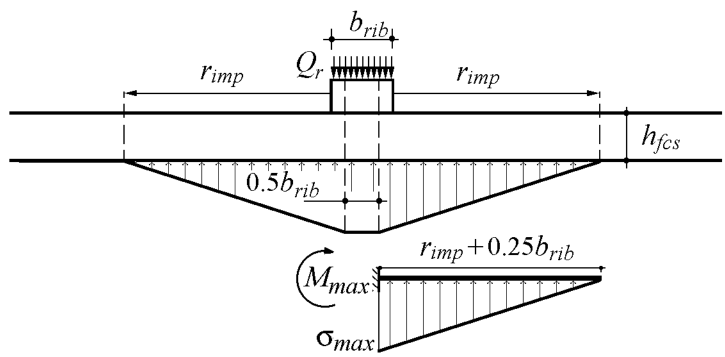

Figure 11: Cantilever model for bending of the foamed concrete slab

The load-bearing condition requires that the stress resulting from the bending moment exerted on the slab of given geometry cannot exceed in any cross-section the material's tensile strength:

$$\frac{M_{max}}{W} \leq f_{fctd}, \tag{5}$$

where:

f_{fctd} – tensile strength at flexure of foamed concrete.

The comparison was made between the results obtained in the FEM analysis and with the proposed design model. The results are presented in a form of diagrams in Figure 12 and Figure 13. The line in the diagrams represents the ideal correlation. It can be noticed that the results are close to the line; this proves that the proposed design model is precise to a satisfactory extent.

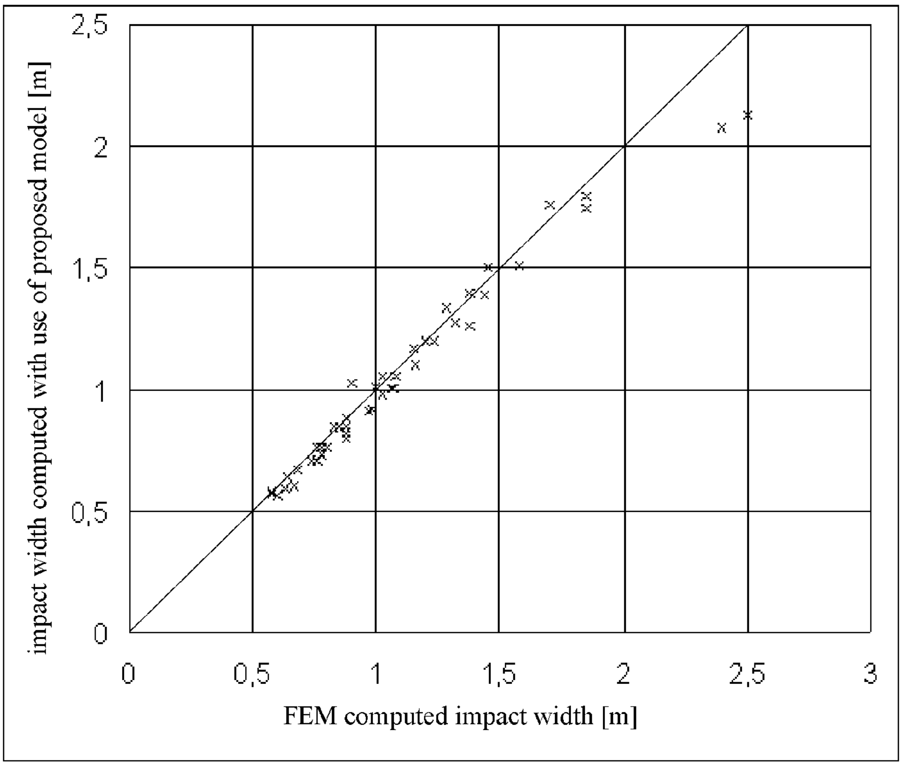

Figure 12: Comparison of results of FE analysis and proposed model. Impact width

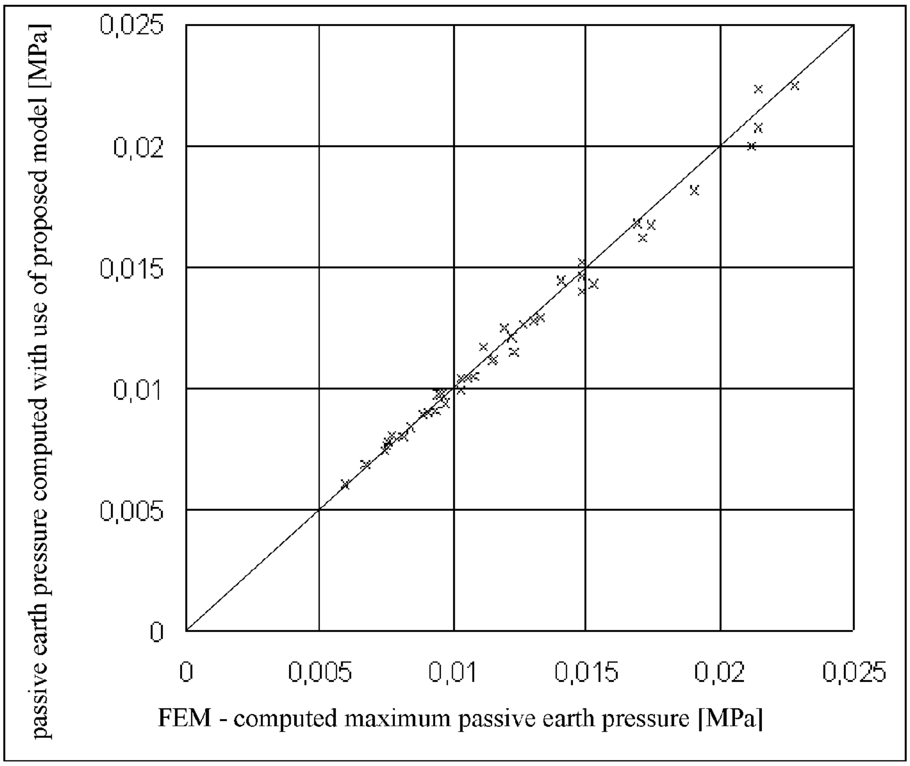

Figure 13: Comparison of results of FE analysis and proposed model. Passive earth pressure

5.3 Punching shear failure of foamed concrete layer

The FEM analysis has shown that the angle of stress distribution is close to 60° (Figure 7). The design model for punching is presented in Figure 14. As it is shown, reduced punching force neglecting passive earth pressure within the zone of a direct load transfer must be introduced.

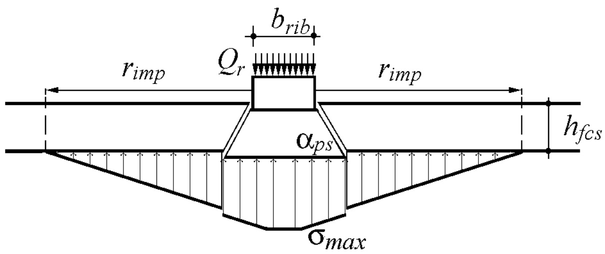

Figure 14: Design model for punching shear in the foamed concrete slab

5.4 Edge separation of the rib with the end of the foamed concrete layer

Effective protection for that failure situation is provided by proper joining of the sleeper rib to the top floor. It may be realised by anchoring the floor reinforcing bars inside the rib. Due to that requirement it is also recommended to cast the end rib together with the floor.

6. Summary

The presented model was developed to meet the satisfy of the building market for insulated sandwich foundation slabs design instruments. By now, on the basis of the resented technology, a group of single-storey houses has been erected in the southern Poland and Slovakia. This is the experimental polygon for evolution of the concept of the foamed concrete sandwich slab to more demanding structural solutions. Additionally, in the nearest future, a full scale tests of a sleeper rib on the foamed concrete slab are planned to confirm correctness of the presented FEM and design model.

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