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POLYURETHANE FOAM AS AGGREGATE FOR THERMAL INSULATING MORTARS AND LIGHTWEIGHT CONCRETE

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Preliminary notes
The contribution describes the use of polyurethane foam after the end of its life cycle as an aggregate both for thermal insulating mortars for various wall surfaces and for lightweight concrete. The structure and the physical and mechanical properties of thermal insulating mortar are described here. The verification of application of thermal insulating polyurethane mortar in the thickness of 50 ÷ 70 mm to a reference building, where external walls were insulated, is provided further. The second important area dealt with in this contribution is that of lightweight concrete, for which polyurethane foam of grain size of 0,125 ÷ 6 mm is used as an aggregate. The physical and mechanical properties of polyurethane concrete of various densities and an example of its prefabrication are presented.

Keywords: *aggregate, lightweight concrete, mechanical properties, physical properties, polyurethane foam, thermal insulating mortar*

Poliuretanska pjena kao agregat za toplinske izolacijske žbuke i laki beton

Prethodno priopćenje
Prilog opisuje uporabu poliuretanske pjene nakon završetka njezinog životnog ciklusa kao agregata i za toplinske izolacije žbuke za različite zidne površine i za laki beton. Ovdje su opisane struktura i fizikalno-mehanička svojstva toplinske izolacijske žbuke. Nadalje se daje provjera primjene toplinske izolacijske poliuretanske žbuke u debljini 50 do 70 mm na referentnoj zgradi, kod koje su vanjski zidovi izolirani. Drugo važno područje kojim se bavi ovaj prilog je da se poliuretanska pjena veličine zrna od 0,125 do 6 mm koristi kao agregat kod lakog betona. Prikazana su fizikalna i mehanička svojstava betona od poliuretana različitih gustoća i primjer njegove prerade.

Ključne riječi: *agregat, fizikalna svojstva, laki beton, mehanička svojstva, poliuretanska pjena, toplinsko izolacijska žbuka*

1 Introduction

At present, lightweight aggregate building materials are applied increasingly to construction practice in association with thermal and acoustic requirements and simultaneous reduction in building construction weight.

As aggregates for lightweight aggregate concrete, crushed or crumbled polystyrene, expanded clay and expanded volcanic glass, e.g. perlite are used most commonly [1, 2, 3]. A new aggregate being increasingly applied to the lightening of concrete mixes is crushed polyurethane foam of density less than 60 kg/m^3, which can be added to the mix both individually and in combination with other lightweight aggregates or fine-grained aggregates [4, 5]. A similar situation is in the area of mortars for rendering and plastering, where besides classical thermal insulating aggregates, i.e. perlite and polystyrene, crushed polyurethane foams of the same densities as with lightweight concrete mixes can be used as well.

An important parameter, on which the service life and the functionality of the above-mentioned types of renders and plasters depend, is a masonry surface treatment before application.

2 Polyurethane foam – description and properties

Polyurethane foam is a macromolecular structural material (thermoset), prevailingly on an organic basis. It is produced by an exothermic reaction – polyaddition of diphenyl diisocyanate with mixes of polyhydric polyethers and polyester alcohols, activators, accelerators, stabilizers, flame retardants, water and auxiliary blowing agents [6]. Due to the temperature of the chemical reaction and due to the carbon dioxide CO_2 produced, the polyurethane substance being formed is foamed and creates a microscopic closed cell structure (see Fig. 1), thanks to which final polyurethane foam has excellent thermal and water insulating properties. The physical and mechanical properties and the use of polyurethane foam in the area of construction depend on its density. For instance, the polyurethane foam having a density of 30 kg/m^3 can be used by spraying in the interiors for ceiling and wall insulation. The polyurethane foam of a density of 40 kg/m^3 can be applied in the exterior by spraying onto vertical surfaces for the purpose of insulation, and the polyurethane foam of a density of 60 kg/m^3 is used for spray roof insulation. In Tab. 1 the mechanical and thermo-technical properties of polyurethane foam depending on density are presented.

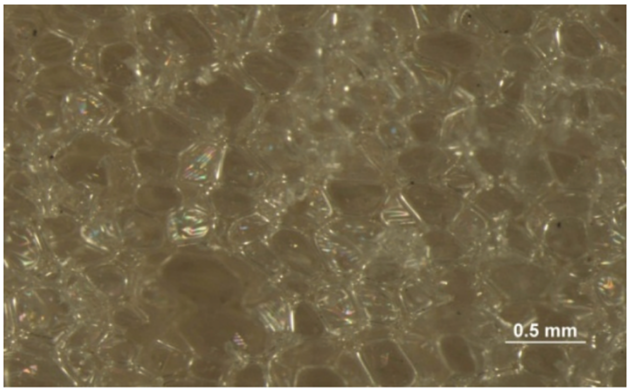

Figure 1 Cell structure of polyurethane foam at 25× magnification

3 Polyurethane foam after the end of life cycle

As aggregates for insulating mortars and lightweight concrete, crumbs of hard polyurethane foam with a maximum grain size of 6 mm are used. The proper process of treatment of polyurethane foam for its utilization as aggregate for thermal insulating renders and plasters and lightweight concrete can be described in the following three points:

– Disintegration of polyurethane using a hammer crusher to a grain size of 12 mm as a maximum.
– Grain size reduction using high-speed knife mills to a polyurethane grain size of 6 mm as a maximum. Knife adjustment, position, grinding and knife mill screen shape must be adjusted specifically for polyurethane crushing.
– To avoid the crushing of the treated hard polyurethane foam after the end of its life cycle, with regard to its susceptibility to breaking, to a powder with a grain size < 1 mm. Sorting of the polyurethane crumb using vibrating or rotary screens, and storage of the crumb in large capacity textile bags – so-called big bags.

Table 1 Mechanical and thermo-technical properties of polyurethane foam

Property	Unit			
Density	kg/m^3	30	40	60
MECHANICAL PROPERTIES				
Compressive strength	MPa	0,20	0,25	0,40
Tensile strength	MPa	0,35	0,60	0,8
Bending strength	MPa	0,30	0,45	0,7
Shear strength	MPa	0,15	0,20	0,30
Young's modulus	MPa	5	7	12
THERMO-TECHNICAL PROPERTIES				
Thermal conductivity λ				
W/(m·K)			0,025	
Linear expansion coefficient (for density of 30 to 100 kg/m^3)				
1/K			$(5 \div 8)\times10^{-5}$	
Water vapour diffusion resistance factor (for density of 30 to 100 kg/m^3)				
μ			30 to 100	
ABSORPTION CAPACITY (at 20 °C)				
After 24 hours	% by volume		to 2 max 5	
After 28 days	% by volume		to 2 max 5	
CONTOUR STABILITY (at 30 °C)				
% by volume			0 ÷ 0,2	
Temperature range	°C		–200 to +140	
For a short time	°C		+250	
FLAMMABILITY GRADE			B2 DIN 4102	
By the amount of flame retardant, the flammability grade and properties, i.e. self-extinguishability, resistance to flying flames and resistance to radiant heat, can be influenced.				
Specific heat capacity	kJ/(kg·K)		1,382	

4 Structure of materials containing polyurethane aggregates

Structure as well as texture describe and quantify the character of individual material particles, their arrangement and relations at various scales of observation. As far as polyurethane mixes are concerned, they have very non-ordered structures, and thus the use of devices with different levels of magnification is necessary for studying their modes of arrangement. The study of microstructure of these polyurethane materials provides a possibility of explaining the principle of process of structure formation, hardening and bonding between the binder and the aggregate and their interaction, which may help in foreseeing the long-term behaviour of the mix.

4.1 Characteristics of feed materials classified as grains

A polyurethane aggregate for insulating mortars and lightweight concrete was observed using both a stereo magnifier and a microscope (observations in VIS/UV mode). As the feed material, the 0/1 mm and 0/4 mm polyurethane fractions were used (see Figs. 2 and 3). For the better imaging of polyurethane crumb, observation of UV radiation inducing fluorescence in certain substances, such as organic resins, was used. The fluorescent light generated like that can be then observed. Images obtained are, in comparison with observation in normal light, with more contrast, and thanks to brilliant colours of fluorescent light, polyurethane grains are unambiguously differentiable from the surrounding material.

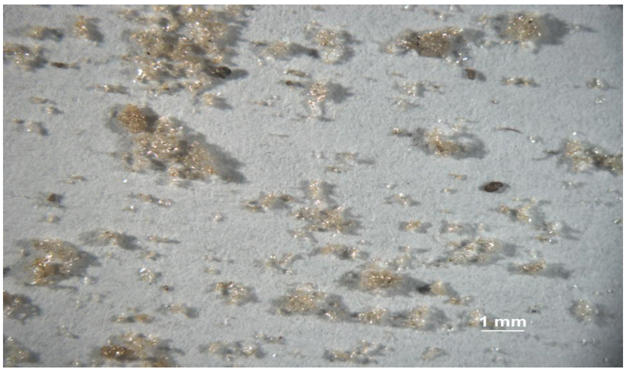

Figure 2 Photograph of polyurethane crumb, 0/1 mm fraction, magnification 7×

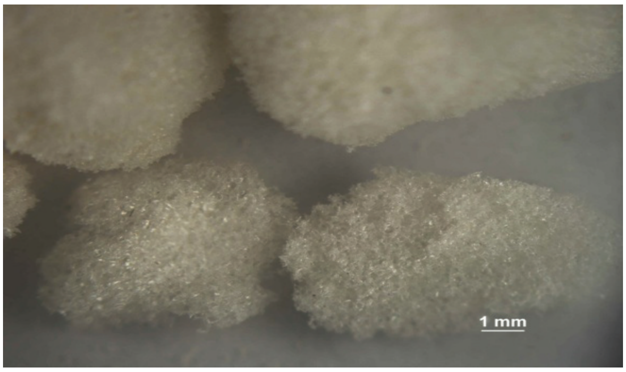

Figure 3 Photograph of polyurethane crumb, 1/4 mm fraction, magnification 7×

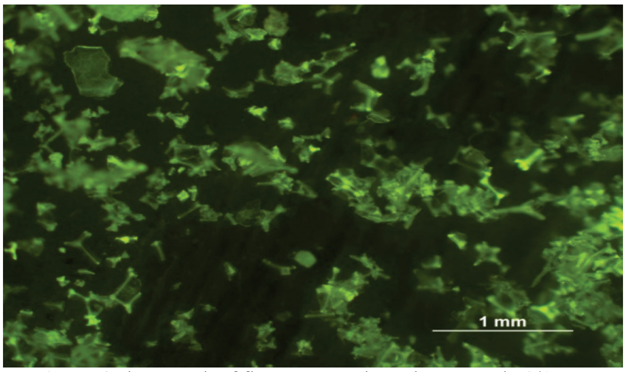

Figure 4 Photograph of fluorescent polyurethane crumb, 0/1 mm fraction, WB filter, magnified 40×

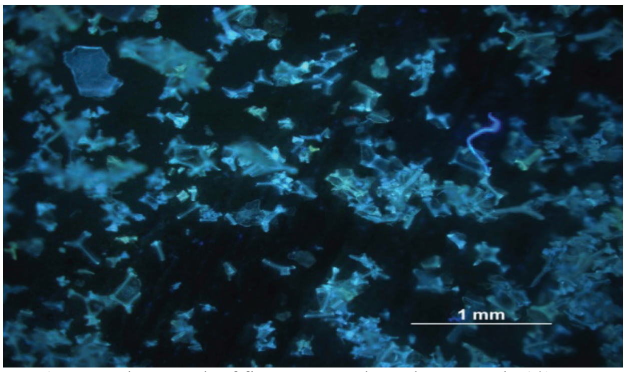

Figure 5 Photograph of fluorescent polyurethane crumb, 0/1 mm fraction, WU filter, magnified 40×

Depending on the used filter, polyurethane materials are yellow-green (WU filter) or have various shades of blue according to composition (WB filter). In Figs. 4 and 5 there is the 0/1 mm fraction of polyurethane foam after crushing with the WU and the WB filter, respectively. In fluorescent light, it is evident that not only polyurethanes but also other organic materials, such as fibres, fragments of polyethylene and other materials occurring in the crumb, have fluorescent properties.

In a mix, these fluorescent grains can be thus differentiated well from the inorganic binder that has not the ability to fluoresce.

4.2 Characteristics of prepared mixes

Two mixes differing in the granularity of used polyurethane crumb were observed, namely the mix 1 having the maximum polyurethane grain size of 1 mm and the mix 2 having the maximum polyurethane grain size of 4 mm. To represent clearly the distribution of pores and particles in the hardened mix and the relation between the binder and the polyurethane grains, observation using the stereo magnifier was carried out, see Fig. 6 and 7. However, in this manner of imaging, polyurethane grains are not sufficiently clearly distinguishable from the surrounding binder that has almost the same colour in white reflected light. For this reason, observation in incident white light using the microscope BX 60 with significant colour correction in image analysis and further observation in fluorescent light using two filters (WB and WU) were performed.

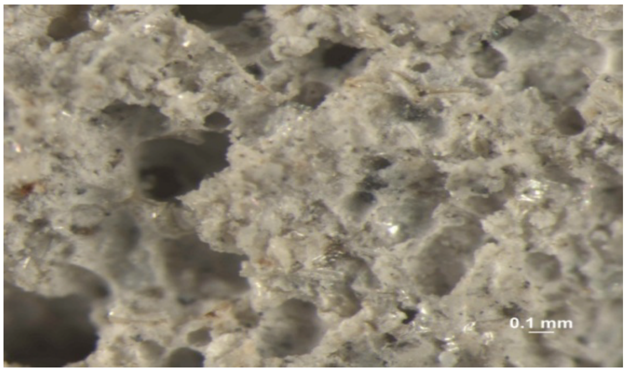

Figure 6 Photograph of building mixes containing polyurethane crumb – mix containing the 0/1 mm polyurethane fraction, magnification 40×

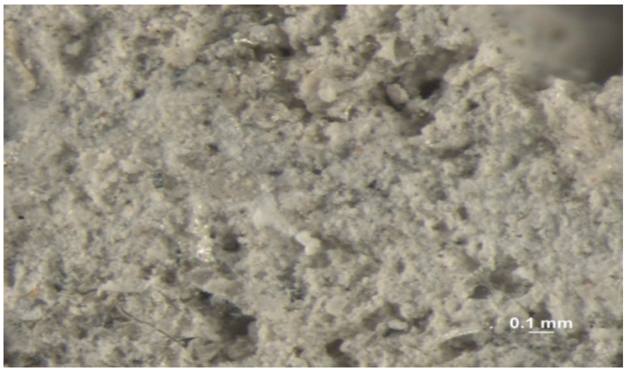

Figure 7 Photograph of building mixes containing polyurethane crumb – mix containing the 1/4 mm polyurethane fraction, magnification 40×

Microphotographs given in Figs. 8 ÷ 13 document well the fact that each of individual types of imaging has relatively little explanatory power, and required information about the type of material, arrangement and surface of voids will be obtained only by combining all the types. The microphotographs taken in UV light and with the WB filter show very well polyurethane grains without making difference in composition; in those taken in UV light and with the WU filter, various types of fluorescent materials can be distinguished. To be comparable, microphotographs are always taken at the same magnification and place. Photographs taken by the stereo magnifier cover the larger fields of view and are not wholly compatible with the microphotographs. By simple comparison of the photographs taken by the stereo magnifier on the same scale, it is apparent at first glance that the mix containing the coarser crumb is characterised, in contrary to the other mix, by the presence of pores in the larger size range, in which in addition to pores of size of the order of tenths of millimetres, pores of size of millimetres are also included. The shape of pores is prevailingly spherical, only exceptionally pores are slightly elongated. In the material, they are distributed evenly. To determine the quantitative and qualitative properties of pores more accurately, an image analysis will be used in the following stage.

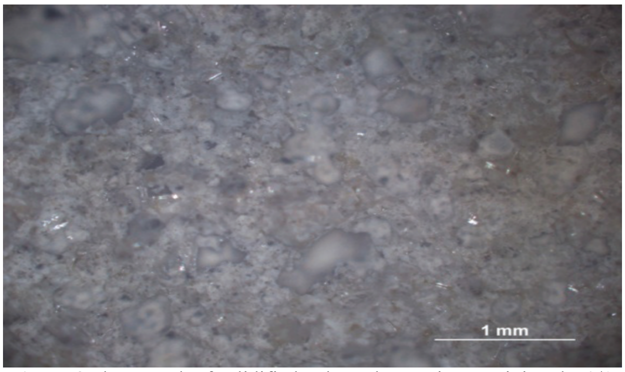

Figure 8 Photograph of solidified polyurethane mix containing the 0/1 mm fraction, incident white light, magnified 40×

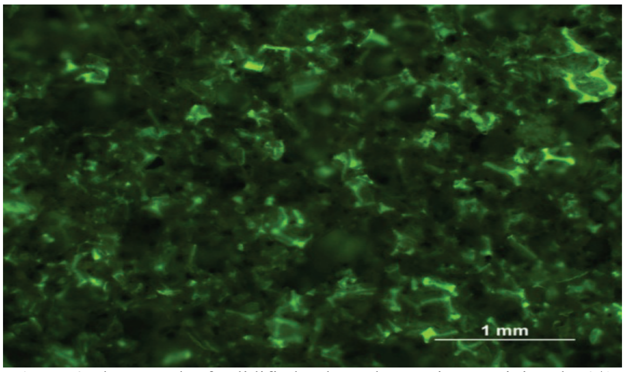

Figure 9 Photograph of solidified polyurethane mix containing the 0/1 mm fraction, UV light with WB filter, magnified 40×

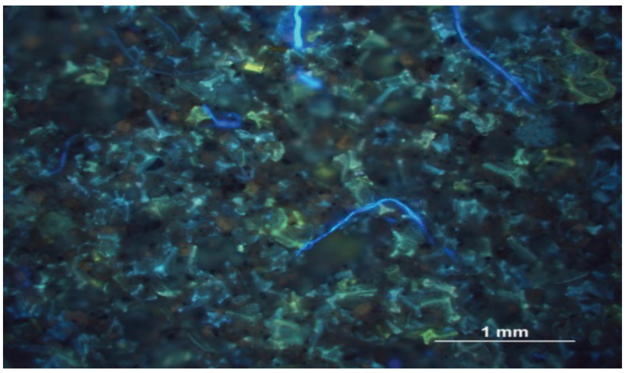

Figure 10 Photograph of solidified polyurethane mix containing the 0/1 mm fraction, UV light with WU filter, magnified 40×

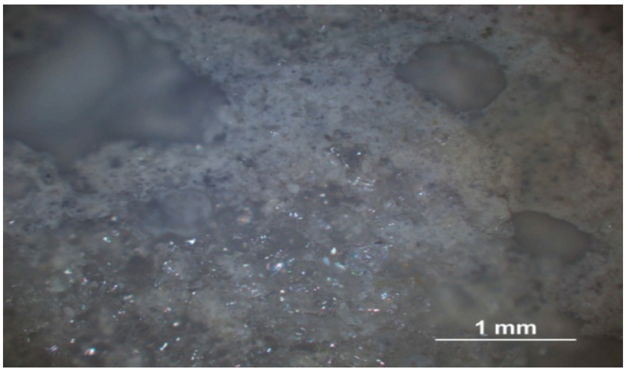

Figure 11 Photograph of solidified polyurethane mix containing the 1/4 mm fraction, incident white light, magnified 40×

On the basis of observation in UV light, it can be stated that polyurethane crumbs are distributed more or less evenly in the solidified mix, any clusters occur neither in mixes containing fine-grained crumb, nor in mixes with coarse-grained crumb.

5 Insulating mortars

Insulating mortars based on polyurethane foam were developed thanks to subsidies from the state budget in a form of research and development project in the programme IMPULS, reg. number FI-IM5/015. Polyurethane (polyurethane foam) as an aggregate for thermal insulating mortars for rendering and plastering is a secondary raw material, i.e. recycled product. It has the suitable density, excellent thermal insulating properties, and is chemically and volumetrically stable. After polyurethane waste disintegration and subsequent sorting, thermal insulating mortars for rendering and plastering could be or were designed with reference to the optimum grain size of thermal insulating renders and plasters. With regard to the fact that individual polyurethane grains are open, in thermal insulating mortars the grains are incorporated optimally from the point of view of segregation of ingredients differing in volume in render and plaster mixes. Furthermore, the open grain of polyurethane is partially water absorbing, so that thermal insulating mortars when being applied do not require using the exact amount of mixing water. Why choose thermal insulating mortars based on polyurethane for application?

- They enable moisture to be drained naturally away from the interior of buildings; implementation of thermal insulation is less labour intensive;
- Renders and plasters can be applied manually or mechanically;
- In the case of refurbishment and additional thermal insulation, a polyurethane render can be applied directly to coarse-grained renders of the type of Brizolit (Czech patented artificial stone exterior finish with sparkling flecks of mica);
- They increase the total thermal resistance of the building while allowing water vapour to pass freely through the wall.
- The physical and mechanical properties of thermal insulating mortar stated in Tab. 2 were tested according to the requirements of Czech standard ČSN EN 998-1 [7].

Table 2 Physical and mechanical properties of thermal insulating mortar on the basis of polyurethane, 1/4 mm fraction

Parameter	Measured value
Density of hardened mortar	350 kg/m^3
Grain size	1÷4 mm
Compressive strength of thermal insulating mortar	1 MPa
Mortar cohesion	0,05 MPa
Mortar adhesive strength	0,05 MPa
Water vapour diffusion coefficient μ	5,5
Mixing water consumption	0,5÷0,8 l/kg of dry mix
Thermal conductivity coefficient λ	0,06 W/(m·K)
Spreading rate of thermal insulating mortar	5 kg/m^2 at 10 mm thickness
Pot life	120 min
Max. thickness of one layer applied	40 mm
Determined maximum thickness of render/plaster	80 mm
Reaction to fire	class B, s2, d0
Porosity	65÷70 %
Capillary water absorption in non-hydrophobized mortar	1,5 kg/m^2· $\sqrt{\text{min}}$
Capillary water absorption in hydrophobized mortar	0,40 kg/m^2· $\sqrt{\text{min}}$

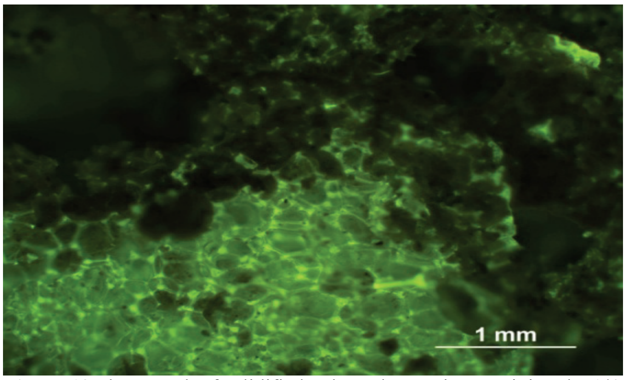

Figure 12 Photograph of solidified polyurethane mix containing the 1/4 mm fraction, UV light with WB filter, magnified 40×

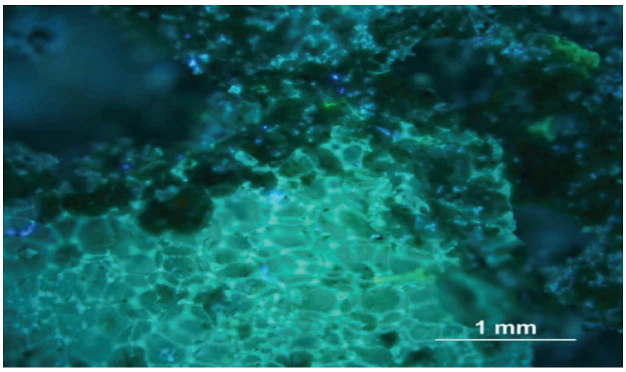

Figure 13 Photograph of solidified polyurethane mix containing the 1/4 mm fraction, UV light with WU filter, magnified 40×

5.1 An example of application of polyurethane-based insulating mortar

Polyurethane-based insulating mortar was applied for thermal insulating the external walls of a selected building. The thickness of external masonry walls of the given building is 600 ÷ 900 mm, and the composition of the external wall masonry is heterogeneous. It includes above all stonework, laid in lime plaster; this is interlaid diversely and irregularly with burnt and in places with unburnt bricks. An extension to the north side of the given building, which was implemented in the year 1990, is constructed on a concrete foundation and is built of gas-silicate blocks stuck together with lime mortar. The whole building is basementless.

Figure 14 A view of reference building from the west before insulation by means of thermal insulating polyurethane mortar for rendering

Figure 15 A view of final façade from the west, insulated by means of thermal insulating polyurethane mortar for rendering

Figure 16 A view of interior arch and masonry without original plaster inside the building

In Fig. 14, there is a view of the building before thermal insulating the external walls using thermal insulating mortar for rendering; in Fig. 15, the same building after thermal insulating can be seen. In Fig. 16 there is a view of interior thermal insulation before the application of thermal insulating mortar for plastering; in Fig. 17 there is a view of the same interior after the application.

Figure 17 A view of interior arch after application of thermal insulating polyurethane mortar for plastering and after finishing (pargeting and painting)

6
Lightweight concrete based on polyurethane foam

It is the concrete containing the crushed polyurethane foam of the density of 30 ÷ 60 kg/m^3 that can occupy a very special position among the types of lightweight concrete. This entirely new material fulfils all requirements put on modern building materials. The physical and mechanical properties of concrete containing a polyurethane foam-based aggregate are provided in Tab. 3.

Table 3 Physical and mechanical properties of lightweight concrete based on polyurethane foam

Lightweight concrete 400	
Density	400 ÷ 600 kg/m^3
Compressive strength min	0,6 MPa
Thermal conductivity coefficient λ	0,10 W/(m·K)
Application	ceilings, roofs
Lightweight concrete 600	
Density	600 ÷ 800 kg/m^3
Compressive strength min	0,9 MPa
Thermal conductivity coefficient λ	0,12 W/(m·K)
Application	ceilings, roofs, floors
Lightweight concrete 800	
Density	800 ÷ 1000 kg/m^3
Compressive strength min	1,5 ÷ 1,9 MPa
Thermal conductivity coefficient λ	0,15 ÷ 0,18 W/(m·K)
Application	floors
Lightweight concrete 1000	
Density	1000 ÷ 1200 kg/m^3
Compressive strength min	3,5 ÷ 5,1 MPa
Thermal conductivity coefficient λ	0,18 ÷ 0,20 W/(m·K)
Application	floors, terraces, sound insulation panels, prefabricated products

Polyurethane foam-based lightweight concrete is a new building material that is able to replace the present-day lightweight concrete. It is characterised especially as follows:

- In crushed polyurethane in concrete, air is entrained. Air entrained like that keeps a rather large amount of heat in the material and thus decreases thermal conductivity of the material and also causes a low density. By coating the polyurethane grains with the binder, this material, which is otherwise flammable, becomes flame resistant in this combination.
- It is possible to dose polyurethane of various grain size compositions, through which the structure of concrete can be determined in advance and the concrete mix can be mixed with reproducible values in any ratio. A range of possibilities, interesting from the point of view of construction, moves from extremely lightweight (floating) concrete to structural lightweight concrete.
- Any segregation of individual ingredients in the mix does not occur up to the cement-water ratio of 1,2.
- To achieve suitable strength parameters of concrete mix based on this material, a corresponding grain size curve of polyurethane should be determined, because it holds true that, at a certain density of polyurethane-based lightweight concrete, the higher the number of fractions of polyurethane as an aggregate, the higher the strength.

6.1
Concrete mix composition

In the course of the preparation of a polyurethane concrete mix, it is necessary to realize that lightweight concrete the density of which ranges from 400 to 1200 kg/m^3 is to be produced, individual ingredients being markedly different either in density or in character. To get a homogeneous mix in this case, particles of polyurethane are to be covered with an adhesive layer acting as a binder between individual particles of polyurethane and the other hydraulic mineral binders.

6.2
Examples of applications of concrete with waste polyurethane foam
6.2.1
Prefabrication

Prefabricated construction represents an important segment of building industry [8, 9].

In cooperation with Prefa Brno, j.s.c., plant Kuřim, the application of prefabrication to concrete with waste polyurethane foam of the density of fresh concrete mix of 1100 kg/m^3 was tested. The mixed concrete mix having slump consistency S3 (100 ÷ 150 mm) was transported to a mould of size 3000×2000×150 mm by means of an overhead monorail distribution system. In the prepared mould, reinforcement was placed earlier; cover to the reinforcement being 30 mm, see Figs. 18 and 19.

After filling the mould with concrete with waste polyurethane foam, compaction by an immersion vibrator was performed, see Fig. 20, and the top layer of the mould was smoothed with a bar.

After 24 hours, a panel was lifted from the mould for verification of manipulability, see Fig. 21. The 24-hour compressive strength of concrete with waste polyurethane foam amounted to 2,9 MPa and after 28 days, in which the test specimens were stored in the aquatic environment, the compressive strength was 5,1 MPa.

Figure 18 A view into the mould with reinforcement

Figure 19 A detail of consistency and deposition of concrete with waste polyurethane foam with reinforcement in the mould

Figure 20 Compaction of concrete with waste polyurethane foam in the mould by an immersion vibrator

Figure 21 Remoulding a precast concrete with waste polyurethane foam unit after 24 hours

6.2.2 Concrete with waste polyurethane foam preparation, transport

Prepared concrete with waste polyurethane foam, which has a density of 500 ÷ 600 kg/m^3, can be supplied to customers to form a thermal and sound insulating layer below anhydrite, i.e. self-levelling poured floors. A typical design of construction is given in Fig. 22.

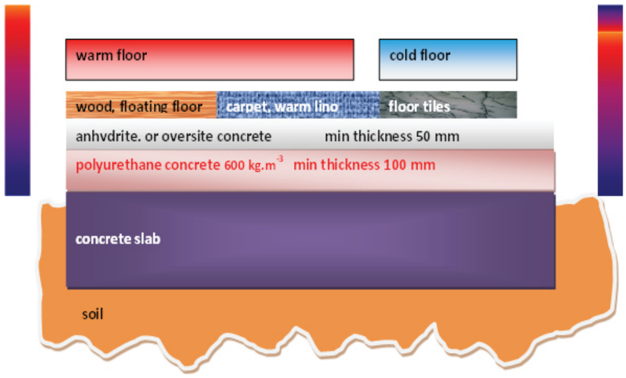

Figure 4 Diagram of application of transport concrete with waste polyurethane foam below anhydrite, i.e. self-levelling poured floors

The proper mix of concrete with waste polyurethane foam is carried out in a classical manner in a concrete mixing plant; the mix is subsequently transported to the place of delivery by a lorry-mounted mixer.

The consistency of concrete with waste polyurethane foam, from the point of view of deposition by simple discharging, falls within the slump classes S1 to S2. For pumping-grade concrete with waste polyurethane foam, the consistency falls within the slump class S3 (100 ÷ 150 mm).

The rheology of concrete with waste polyurethane foam mix can be controlled by a specially developed powdered plasticiser DAXNER®.

6.2.3 Concrete with waste polyurethane foam supplied as dry ready mix

Concrete with waste polyurethane foam can be supplied as a dry ready mix in bags, intended for blending in a classical free-fall concrete mixer.

With reference to the properties of polyurethane aggregate, in the concrete with waste polyurethane foam neither shaking off nor fragmentation of individual ingredients of dry concrete mix occurs.

Concrete with waste polyurethane foam designed for application using standard rendering and plastering machines, where a dry concrete mix is supplied in bags and dosed into the rendering or plastering machine with an integrated mixing zone, is gradually introduced on the market.

7 Conclusion

It follows from the above-presented results of applied research that polyurethane foam after the end of its life cycle is a full-value alternative to expanded volcanic glass and polystyrene crumb used at present as aggregates in thermal insulating renders and plasters. In the area of lightweight concrete mix technologies, it is a case of replacement of polystyrene concrete and foam light concrete. As follows from physical and mechanical testing, it is not the case of structural concrete, but it is the case of concrete filling.

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