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Dry mixes on gypsum and mixed bases in the construction of low-rise residential buildings using 3D printing technology

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Abstract: 3D-printed building construction technology is developing in most countries, such as France, China, Russia and others, and the dry mixes and equipment used are being improved. The development of 3D-printing construction technology is dictated by its many advantages: architectural diversity, speed and automation of the technological process of construction of buildings and structures with a noticeable reduction in the cost of production. However, there are a number of problems of this technology that are waiting for optimal solutions. The paper proposes solutions to two such problems: firstly, the choice of mixture with gypsum and gypsum-cement binders, ensuring the continuity of the 3D printing process of the building and allowing the construction of buildings up to three floors with sufficient safety margin, high seismic stability, as well as with good heat and noise insulation; secondly, the design of buildings with a rational structural and technological solution of the roof and floor, allowing the interface of these structures with load-bearing printed walls.
Different compositions of dry mixes were tested in a series of field tests of large-sized wall blocks made with the use of a construction 3D-printer and filled with especially light porous expanded claydite, expanded clay concrete or heat-insulating foam gypsum with subsequent testing on press equipment of increased load-carrying capacity (with determination of bearing capacity and deformability of the large-sized block).
When designing low-rise buildings, erected by additive technology, as an optimal design of floors, it is proposed to use frame-monolithic beam structures made of metal thin-walled steel galvanized profiles, filled with foam gypsum mix, providing heat and noise insulation and covered with a thin layer of high-strength self-leveling gypsum mix, providing the necessary structural strength of the floor and, accordingly, the minimum load on the foundation.
Keywords: construction 3D printing, monolithic foam gypsum, attic and interfloor slabs, dry mixes, light steel galvanized thin-walled profiles

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1. INTRODUCTION

One of the modern trends in the automation of construction of buildings and structures is the use of a construction robot or construction 3D-printer controlled by an appropriate computer program, which are currently mass-produced by many domestic and foreign enterprises, for example, GC "AMT-SPECAVIA", Yaroslavl, Russia. Undeniable advantages of additive or construction 3D printing technology: 1) the speed and continuity of the construction process, 2) the possibility of giving graceful architectural forms to erected buildings, 3) the exclusion of a large amount of manual labor, 4) the possibility of laying inside the walls, floors and slabs of electrical cables, water pipes, pipes for heating and ventilation of buildings in the process of its printing, 5) waste-free construction itself - serve as driving forces for the rapid introduction of 3D printing technology in construction [1-3]. Recently, not only individual houses, but also residential areas have been built. Figure 1 shows the construction of a settlement using 3D printing technology in the village of Aisha in the Republic of Tatarstan [4].

Fig. 1. Construction of a settlement using 3D printing technology in the village of Aisha, Republic of Tatarstan.

Automated building printing places special requirements on raw materials, in particular dry mixes and the resulting composition to match fully their performance with the continuous operation of mixing and printing equipment, the construction of walls and slabs, meeting the requirements of building regulations and sanitary standards. The viscous mass or mortar mixture fed by the extruder of a 3D construction printer for printing a wall must harden during one pass along the contour of the layer so that when applying subsequent layers, the previous layer must not give sagging from the weight of the layers above it, the mass must have sufficient viscosity and must not allow thickening or setting in the extruder and, accordingly, in the hoses or conveyors feeding the mixture [5-10]. At the same time, the layer of the laid mixture should not spread out and lose the height of the seal, and the hardening of the mortar mix of load-bearing printed walls in time should comply with the known laws of concrete science [11-15]. The authors of the article analyzed the use of individual varieties of dry mixes on gypsum and gypsum-cement bases.

2. METHODS AND MATERIALS

For manufacturing large-sized fragments of load-bearing walls made in the natural thickness of walls (400 and 500 mm) (Fig... wall fragments with expanded clay concrete, foam gypsum, window, etc.) 3D-printer S-6045M of portal type of the Russian production of GC "AMT-SPECAVIA" was used. Technical characteristics of the construction 3D-printer are given in Table 1. The general view of the printer is shown in Fig. 2.

Table 1. Specifications of the printer for 3D printing of construction products and structures.

№	Name	Description
1	Manufacturer country	Russia; The equipment is certified in the territory of the Customs Union and in the European Union (CE). Registration number of the TC Declaration of Conformity N RU D- RU.AL92.V.17528 HS code CU 8479100000, Serial production.
2	Type of drive	Stepper motors with spur gearboxes
3	Performance	0.7 cubic meters of mortar per hour
4	Working area, mm	3500x3100x1000
5	Positioning speed / Positioning accuracy	12 m/min/ 2 mm
6	Printed layer size, mm (height, width)	from 5 to 20 / from 20 to 50
7	Concrete consumption, m^3 per 1 sq.m of wall for 4-layer printing	0.12
8	Printer size: - length, mm; - width, mm; - height, mm; - weight, kg	 4000 4000 3600 870
9	Printer type	Regulatory documentation for production of products TU 4833-001-21740072-2016

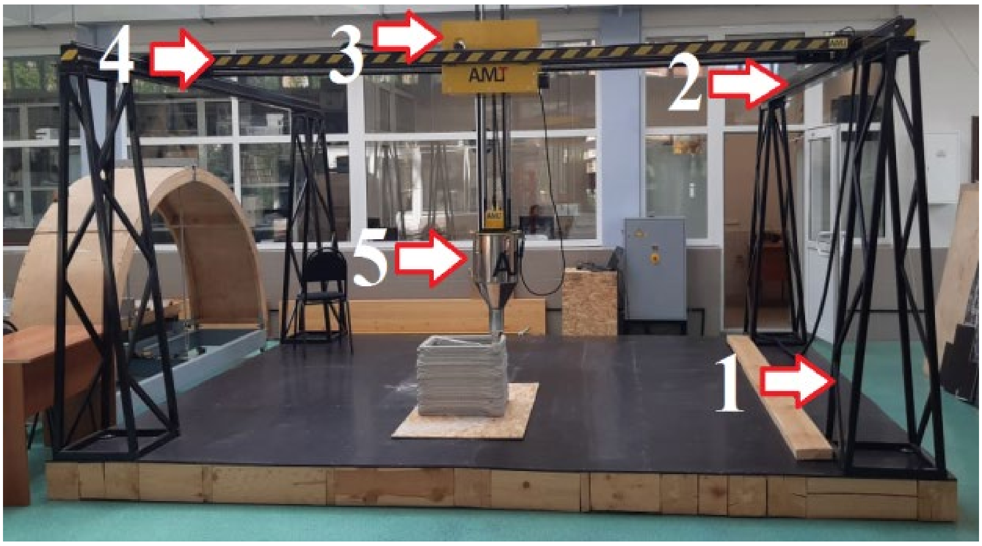

Fig. 2. Construction 3D printer S-6045M in the laboratory of the Scientific and Educational Center of Innovative Technologies of USPTU *1 – support column; 2 – guiding beams; 3 – gantry beam slide for raising and lowering the print head; 4 – gantry beam; 5 – print head with screw extruder.*

A mixer (similar to a plastering station) M-TEC M280 was used to prepare and feed the mortar mixture into the printer. The process of preparing mortar for 3D printing using this mixer is as follows: dry mix is loaded into the mixer hopper, then it is mixed in the screw mixer with simultaneous dosing of water and pumped through the supply rubber pipeline into the consumption hopper of the 3D printer.

Fig. 3. Plastering station M-TEC M280.

For experiments we used dry mix for construction 3D-printing on gypsum-cement base (Fig. 4) of Barcraft brand (production of LLC "Ufa Gypsum Company", TU 5745-001-52983495-2015), mix composition: gypsum binder G5 - 70%, Portland cement CEM525 - 18%, trepel - 12%. Quartz sand with a maximum particle size of 0.63 m was used as an aggregate in the dry mix for 3D printing. The ratio of sand and gypsum-cement-puzzolan binder is 2:1. The rheological characteristics of the 3D printing mix were evaluated by a standard cone immersion (SCI) in the mortar mixture, this characteristic was within 8-10 cm.

Fig. 4. Loading hopper of the M-TEC M280 plastering station.

The strength properties of the solidified mortar were evaluated by testing cubes, beams and prisms (Fig. 5) on a WDW-100E universal testing machine (Fig. 6), which allowed plotting stress – relative strain diagrams of solidifying mortars at different ages (Fig. 7). Fragments of bearing walls (Fig. 8) were tested on presses of increased load capacity of 500 tons (Fig. 9-12). The bearing capacity (in terms of breaking forces), deformability and crack resistance were evaluated.

Fig. 5. Testing of prism specimens.

Fig. 6. WDW-100E universal testing machine.

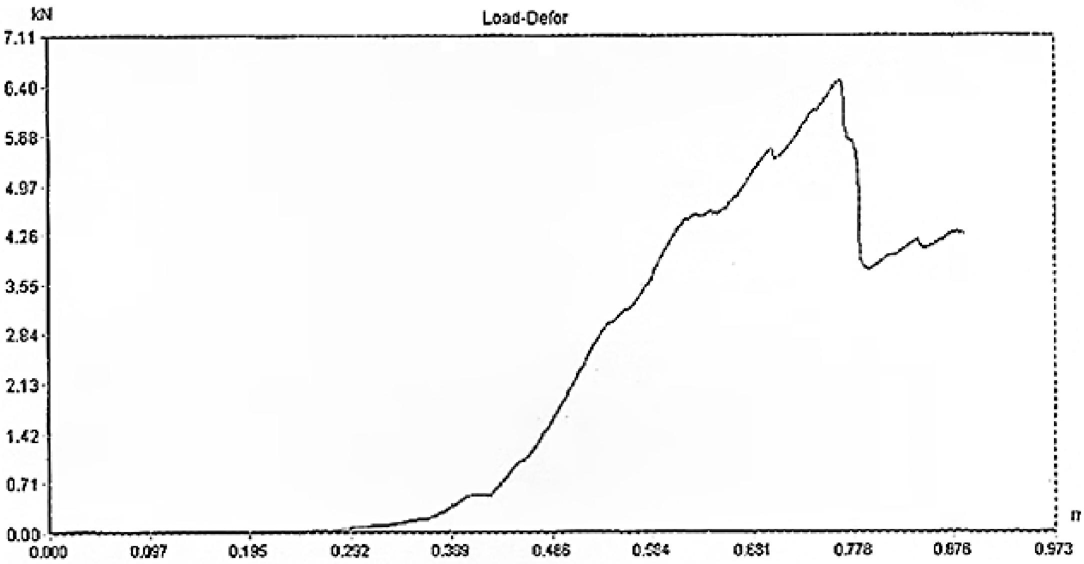

Fig. 7. Stress – relative strain diagram of solidifying solutions.

Fig. 8. Pouring of 3D printed vertical envelope structures with foamed gypsum nanocomposite.

Fig. 9-12. Testing process of 3D-printed wall blocks on the P-500 press.

3. RESULTS AND DISCUSSION

Let us briefly analyze both the positive experience and the inevitable associated problems accumulated over the past decade by foreign and domestic pioneering enterprises to introduce 3D printing of buildings into the production process.

The accumulated experience allows to print various structural elements of buildings and structures of vertical orientation quickly enough, such as partitions of external and internal walls, partitions of different thickness depending on their type (external, internal) and functional (load-bearing, self-supporting) purpose. However, unfortunately, there is no successful experience in the construction of horizontal building structures (in particular, slabs between technical and residential floors) using 3D printing technology, and the construction of these structures using traditional materials, products and technological processes (monolithic concrete, precast reinforced concrete slabs, concrete mixers, concrete pumps, mobile cranes, etc.) makes the entire process of building construction very expensive and, consequently, reduces the overall efficiency of additive construction. Therefore, in the structural solution of a hollow wall printed on a construction printer shown in Fig. 13, the outer and inner shells play either the role of fixed formwork for filling vertical cavities with monolithic concrete (to create a so-called “hidden” frame), or the role of a structural self-supporting framework for filling the interior space with thermal insulation material (foam concrete, foam gypsum) in order to increase the thermal resistance of external walls. These factors, in our opinion, are the main reasons that significantly reduce the efficiency and cost-effectiveness of additive method of construction and prevent its large-scale implementation, primarily in housing and civil construction.

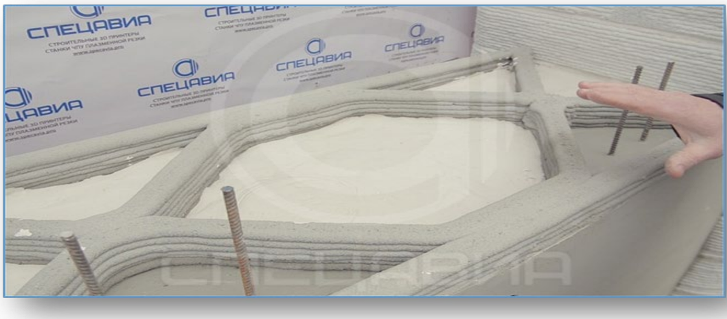

Fig. 13. A variant of the structural solution of a 3D-printed exterior wall with filling of internal voids with heat-insulating foam gypsum and monolithic concrete (to create an internal load-bearing frame).

Another practically unsolvable problem at present is the lack of approved calculation methods for determining the strength, deformability and crack resistance of printed structures, including walls, pylons, pillars with a hollow (well) configuration in plan (with various methods of internal filling with monolithic concrete and heat-insulating materials). To assess the load-bearing capacity of such structures, pilot tests were conducted on 3D-printed large-format (500×400×500 mm) fragments of pillars and pylons with different filling of their interior space (using heat-insulating materials (foam gypsum, expanded perlite) and structural and heat-insulating large-porous expanded clay concrete). The tests were carried out in the laboratory diagnostic complex for testing of construction materials and structures of the Architectural and Construction Institute of USPTU.

The tests showed that the averaged values of compressive stresses leading to local and large-scale failures of the printed wall fragments during long-term loading varied from 16 kgf/cm^2 to 22 kgf/cm^2, (1.56 MPa – 2.15 MPa). The tests revealed an interesting feature: the load-bearing capacity of the printed structures with and without filling the internal cavities with various heat-insulating and even structural-insulating materials is practically unchanged. This can be explained by the fact that the bearing capacity of the printed shell (from the mortar mix on gypsum-cement base M250) is significantly higher than the strength of the inner layers, so they practically do not contribute to the increase of bearing capacity [4].

When comparing the results of the conducted tests with the requirements of the current domestic regulations SP 15.13330.2020 “Stone and reinforced stone structures”; SP 63.13330. 2018 “Concrete and reinforced concrete structures”, then taking the printed pillars and partitions of external walls as concrete structural elements, we can conclude that the minimum design resistance to compression of these pillars on average will be 16/1.6 = 10 kgf/cm^2, and if we consider the 3D-printed pillar structure as an analogy of masonry (similar to well masonry or masonry of hollow porous ceramics), then the average design compression resistance of this structure will be about 16/2.0 = 8 kgf/cm^2 (where 1.6 and 2.0 are the transition coefficients from destructive stresses to design resistance (or “reserve coefficients”) for concrete structures and masonry, respectively). Due to the fact that the design resistance of the material samples of printed wall structures significantly exceeds the similar design resistance for masonry of brick, concrete, aerated concrete and hollow porous blocks (5-7 kgf/cm^2 - for masonry of brick and concrete stones, 4-6 kgf/cm^2 – for masonry of cellular concrete (foam concrete, aerated concrete), tables 6.1 and 6.3 of SP 15.13330. 2020 “Stone and reinforced stone structures”), then the existing 3D printing technology (in terms of load-bearing capacity of external and internal walls) allows to erect all types of low-rise buildings (up to 3 floors inclusive) without restrictions, even taking into account higher (compared to wooden beam slabs and slabs using light steel thin-walled structures) loads from the weight of prefabricated or monolithic reinforced concrete slabs and cement-sand floor blinding coat.

When choosing a rational planning and structural solution of low-rise residential building, erected by additive technology with the use of gypsum-based dry mixes, it would be desirable to take into account more than a century of positive foreign and domestic experience of operation of residential buildings, built entirely (exterior and interior walls, partitions) of gypsum-concrete blocks (and made on the basis of conventional construction gypsum, not only composite gypsum-cement binder of increased water resistance (gypsum-cement-puzzolan, gypsum-lime-slag, etc.) [9]. To ensure increased operational reliability of these buildings, three mandatory requirements were met: a pitched rafter roof must be installed; the basement part of the building must be made of water-resistant building materials (ceramic brick, concrete, masonry of concrete stones, etc.) to a height from the planning level of at least 40 cm; it is desirable to build interstorey and attic floors without the use of monolithic concrete or prefabricated reinforced concrete slabs, and on a lighter scheme based on wooden or poured concrete beams. If these requirements are met, these buildings will successfully serve for many decades, which is confirmed by the positive experience of operation of tens of thousands of two-storey buildings with load-bearing walls made of gypsum concrete, built in the USSR in the 40-60s (Fig. 14).

Fig. 14. Residential building with load-bearing walls made of gypsum concrete in Ufa on Kalinina St. after 80 years of operation.

Fig. 15 shows the project of a residential house (a house of high comfort, erected using 3D printing technology), made almost entirely of gypsum materials: walls, partitions are printed from gypsum-based mortar compositions (the voids of external walls are filled with foam gypsum or backfill of reduced density expanded claydite (with volume weight $\gamma \leq 250$ kg/m^3) or expanded perlite ($\gamma \leq 150$ kg/m^3), the interstorey and attic floor are made on the frame scheme with the use of thin-walled light steel structures made of galvanized steel, monolithic foam gypsum ($\gamma \leq 400$ kg/m^3), which also serves as a soundproofing layer of gypsum board and the upper gypsum layer of increased strength (made of poured self-leveling gypsum mixture). The test results have shown that the load-bearing capacity and stiffness of such slabs are more than sufficient to support the existing loads (it is significantly higher than the load-bearing capacity of slabs using wooden beams and comparable to the load-bearing capacity and deformability of reinforced concrete slabs at a much lower weight) [4, 16]. The roof of this building is pitched using rafter systems based on thin-walled galvanized profiles (bent channels two millimeters thick galvanized steel), instead of wooden purlins used flat fiber-cement or asbestos-cement sheets, roofing is made of colored flexible (soft) asphalt shingles Shinglas (production TechnoNIKOL). Figures 15-20 show the results of determining the stress-strain state of bearing printed exterior and interior walls of this two-storey building, performed (based on real tests of gypsum-cement mixture (Fig. 7)) in the program complex LIRA-SAD and ANSYS. It is shown that the maximum stress level even in the most loaded inner wall does not exceed 10-20 % of the maximum allowable values. An additional advantage of the given constructive solution of this building is its increased fire safety, as all its bearing and enclosing structures are made of non-combustible materials, which is especially important in conditions of dense construction of the territory.

Fig. 15. Visualization of an individual residential building made of gypsum-based mixes using 3D printing technology.

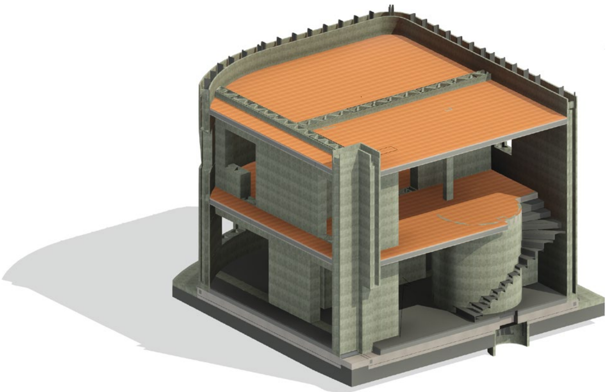

Fig. 16. Longitudinal cross section of the building (rafter roof structures are not shown).

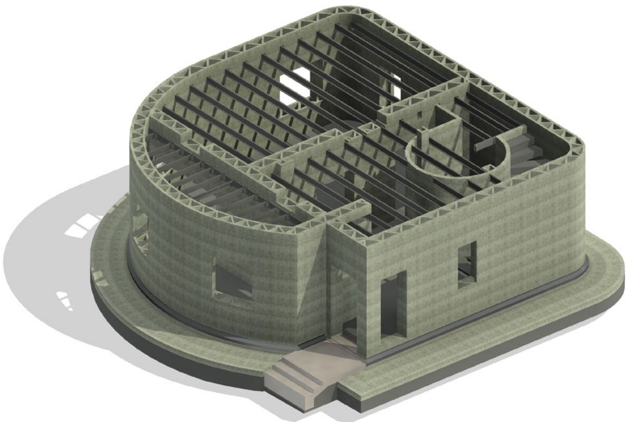

Fig. 17. Layout of transoms (made of LTWSS) on walls for floor slab construction.

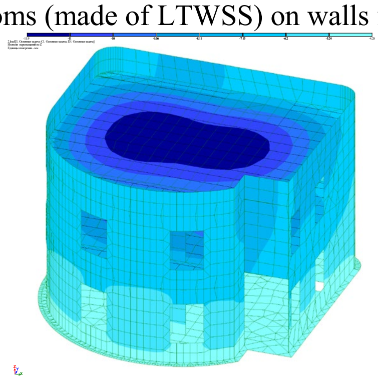

Fig. 18. Maximum deformations of walls and slabs in nonlinear formulation (LIRA-SAD program).

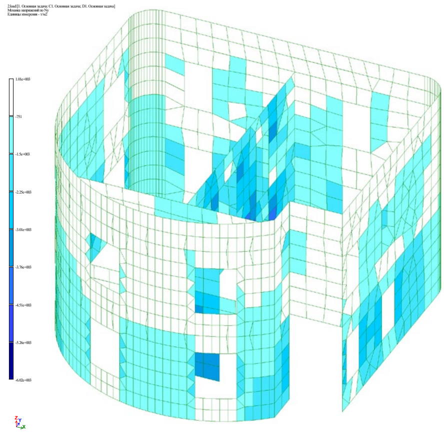

Fig. 19. Longitudinal forces in exterior and interior walls (LIRA-SAD program).

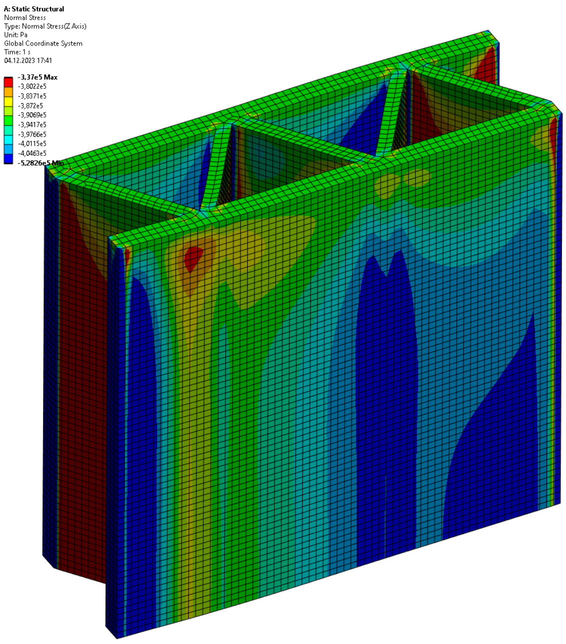

Fig. 20. Normal stresses in the most loaded section of the inner printed wall (along the Z direction along the vertical axis of the wall), calculated in the ANSYS program complex.

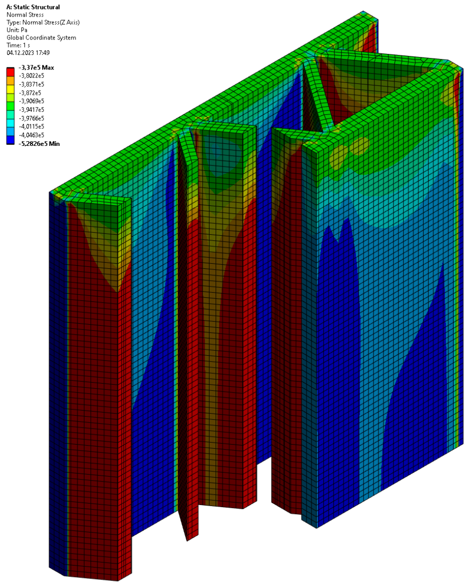

Fig. 21. Normal stresses in the most loaded section of the inner printed wall (along the Z direction along the vertical axis of the wall, longitudinal-transverse section), calculated in the ANSYS program complex.

Currently, the design work has been completed, the specialists of Ufa Gypsum Company LLC have started installation of a high-performance portal 3D printer capable of printing buildings with the size of 12×12m and height up to 7m inclusive, at the construction site, and the authors of this article hope that the research results presented in the article will allow them and other construction companies to increase the efficiency and cost-effectiveness of the construction of residential areas using 3D printing technology in the conditions of real construction production [16-18].

4. CONCLUSIONS

1. Analyzing the accumulated experience in the use of wall materials for low-rise construction on gypsum and cement bases it can be concluded that for additive construction the most rational will be the use of mortar compositions on gypsum or mixed binders (gypsum, gypsum-cement-puzzolan, gypsum-lime-slag, etc.). The use of dry mortar mixtures based on gypsum binders allows (compared to similar cement-based mixes) to accelerate significantly the entire technological process of 3D printing in the construction of buildings, primarily due to their faster setting and hardening.

2. Tests of 3D-printed large-format fragments (500×400×500 mm) of exterior walls with filling the interior space with various types of thermal insulation materials on loose (lightweight expanded claydite, expanded perlite) or monolithic (porous gypsum concrete or foam gypsum) bases have shown, that their load-bearing capacity corresponds to the indicators of brickwork (made of brick or small concrete blocks of M75 grade on M35 mortar) and significantly (almost twice) exceeds the load-bearing capacity of the outer wall made of aerated concrete blocks (density 400-500 kg/m^3). This allows 3D printing technology to erect load-bearing walls of low-rise buildings (up to two floors inclusive) without internal reinforced concrete framework, which significantly facilitates and speeds up the process of erecting exterior and interior walls.

3. A constructive solution of a two-storey residential building erected by industrial 3D-printing technology exclusively with load-bearing walls of increased hollowness (with filling of internal voids with heat-insulating backfills made of especially light expanded claydite, expanded perlite or foam gypsum) and ceilings made by monolithic frame technology (made of light steel thin-walled foam gypsum profiles and gypsum walling), foam perlite or foam gypsum) floors made of monolithic frame technology (light steel thin-walled foam gypsum profiles and gypsum blinding coat) and pitched truss roofing (made of LTWSS profiles and fiber cement sheets). This building is completely made of non-combustible materials, characterized by increased energy efficiency and high fire resistance.

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