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Energy Efficient Polystyrene Aerated Concrete Composite Products and Condition Monitoring for Building Structures and Facilities in the Arctic Regions

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Abstract. The harsh climatic conditions of the Arctic zone of the Russian Federation in combination with the current requirements for ensuring comfortable accommodation conditions in buildings and structures lead to strengthening of respective thermal protection regulations. The article outlines the basics for the multi-layer composite material technology based on the use of aerated concrete and polystyrene foam. The novelty of the technology, as confirmed by respective patents of the Russian Federation, consists in layering of aerated concrete and non-foamed or partially foamed polystyrene into a mold, followed by its closing with a lid and subsequent heat and moisture treatment by steaming. The steaming process triggers spontaneous expansion of the aerated concrete mixture and polystyrene, compaction of their structural layers, and acceleration of concrete curing. The result is a composite product with improved performance, complying with the current regulatory requirements for the thermal protection of buildings.

In order to ensure the reliability and durability of construction projects, systematic quality control is required for all raw materials used in manufacturing of building structures, as well as proper condition monitoring for all operated buildings and structures. The Kola Testing Centre for Building Materials and Articles (KTCBMA), established 20 years ago, conducts certification and definitive testing of building materials for compliance with the current standards, as well as non-destructive testing of concrete and reinforced concrete structures.

1. Introduction

The Arctic zone of the Russian Federation (AZRF) is the largest in the world. It is actively used to cover the domestic demand in various types of mineral resources [0]. One of the most developed Russian and global Arctic Regions is the Murmansk region, the richest region in raw materials reserves not only in the AZRF, but throughout the entire country. Its severe climatic conditions require special performance of building products and structures to ensure durability and comfortable indoor accommodation conditions. However, possessing extensive natural and energy resources, the Russian Federation applies extremely unsustainable consumption strategies. Until recently, insufficient attention has been paid to the unproductive heat losses both during construction and operation of buildings and structures. While Western countries use no more than 20–22% of all thermal energy produced on heating, the Russian value is nearly 34% [1]. This energy consumption situation and the huge heat loss into environment are caused by the insufficient thermal insulation properties of the insulation materials used and low thermal resistance of the enclosures. In addition, reliability, safety



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and durability of building products, buildings, structures and facilities require regular monitoring of their performance and compliance with the applicable regulatory requirements. On October 1, 2003, the State Committee for Construction of the Russian Federation approved SNiP 23-02-2003 “Thermal Protection of Buildings”, increasing the rated heat transfer resistance values of the enclosures by a factor of 3–3.5 as compared to the values applied previously. Compliance with these tighter regulations, for example, in the climatic conditions of the Murmansk region (for the estimated heat transfer resistance value of at least $3.5 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$), would require significantly increasing the thickness of all outer walls, in particular: to 1.9 m for single ceramic brick; to 2.8 m for silicate brick; to 1.2 m for 1000 kg/m^3 lightweight concrete; and even to 0.7–0.8 m for the most heat-effective $600\text{--}700 \text{ kg/m}^3$ cellular concrete [2]. Obviously, such wall thicknesses are both structurally and economically unfeasible. Therefore, enclosing structures made of currently known single-layer walling materials are not capable of ensuring the required heat-protective performance.

2. Main Body

The previous experience of civil and residential construction indicates that the required thermal performance may be achieved through the creation of composite materials consisting of load-bearing (structural) and non-load-bearing (thermal insulation) layers [3,4]. In the paper [5], it is noted that materials “formed by a volumetric combination of chemically diverse components with a clear interface between them are referred to as composite materials. Composite materials are characterized by properties that are not typical for any of components when taken individually.” Various multi-layer composite materials consisting of load-bearing and insulating layers are widely used [3]. Most frequently, vibration-compacted heavy or lightweight concrete is used for the load-bearing structural layer. The heat-insulating layer is created with the use of heat-efficient fibrous or foam materials (mineral wool, polyurethane foam, polystyrene foam, etc.), most often in the form of prefabricated plates or mats. This design has many deficiencies typical for all multi-layered products and caused by the structural and thermal engineering heterogeneity of their structural layers in terms of density leading to the inevitable formation of gaps between the layers, where moisture can accumulate and produce a thermal bypass during wall freezing. At the same time, it is necessary to ensure reliable adhesion of the structural layers to each other, for which special expansion inserts or various flexible connections are used, enhancing the design and contributing to the engineering heterogeneity of the structures. In order to eliminate the above deficiencies of composite walling and heat-insulating materials, ensure monolithic adhesion between their structural layers and significantly reduce their thermal conductivity, we have developed a new technology based on the following assumptions:

1. The load-bearing structural layers in a multi-layer product shall be created using structural heat-insulating aerated concrete rather than vibration-compacted heavy-weight or light-weight concrete. The porous structure of aerated concrete formed by swelling (volume boosting) of a fine-grained concrete mix as a result of gas formation in the process of chemical reaction between aluminum powder and calcium hydroxide is much closer in its structure to the porous heat-insulation material than vibration-compacted concrete. The best temperature for gas formation and swelling of the concrete mix is in the range of $35\text{--}45\text{ }^\circ\text{C}$.

2. The heat-insulation layer shall be created by using one of the most common and effective modern insulation thermal material, foam polystyrene, which has such unique properties as the thermal conductivity of $0.029\text{--}0.044 \text{ W}/(\text{m} \cdot ^\circ\text{K})$ with the density of $15\text{ to }85 \text{ kg/m}^3$ (i.e. close to the thermal conductivity of air), hygroscopicity not exceeding 0.4% (wt.), and water absorption of 0.5% to 1% (wt.). Polystyrene doesn’t decay (even when used in soil), has high biostability, low corrosion activity, and high resistance to weak and strong acids. However, polystyrene is fire hazardous, with low fire resistance (heat resistance of $65\text{--}70\text{ }^\circ\text{C}$), and emits poisonous substances during combustion. The PSB-S grade polystyrene foam currently produced in the Russian Federation contains fire retardant additives that impede burning and ensure self-extinguishing after the fire source is removed. Polystyrene granules are capable of generating static electricity, which enables their small polymer particles to form explosive mixtures [6, 7]. The strengthening of requirements for reduced heat losses

to the environment has led to the widespread use of various insulating materials. Polystyrene foam (PF) has the major share of up to 80%, being one of the most effective, cheap and technologically advanced insulating materials in terms of its manufacture and use. Under normal conditions, its sustainability, hygienic rating and safety are beyond doubt (for example, it is used to produce disposable tableware and as a packaging material). At temperatures up to 85 °C, it produces no harmful effects on the indoor atmosphere and does not support the growth of bacteria and fungi. A distinctive feature of suspension bead polystyrene is its ability to foam (expand) up to 30–50 times within 3–5 minutes at temperatures of 90–100 °C. Most often, polystyrene foaming is conducted with the use of water steam in special prefoaming cells.

3. One of the most common methods for accelerating concrete curing on a mineral binder is its heat-moisture treatment by steaming at isothermal temperature of the vapor-air medium of 85–100 °C and relative humidity of 90–100%. Steaming of molded articles begins 3–5 hours after the concrete has gained initial strength to ensure that the thermal strain is perceived without destroying the structure. During concrete steaming, the temperature in the steaming cell is gradually increased for three to four hours from the initial level to the maximum isothermal temperature and maintained for six to eight hours, followed by the temperature reduction to 30–35 °C and unloading of the cell. During 12–16 hours of steaming, the concrete acquires 65–70% of its grade strength.

As can be seen, the concrete steaming process uses the same temperature ranges as required for gas formation and expansion of the gas-concrete mixture and for polystyrene foaming. The specific feature of the technology proposed, the novelty of which has been confirmed by invention patents of the Russian Federation Nos. 2259272 and 2286249, consists in the layering of the aerated concrete mix and non-foamed or partially foamed suspension polystyrene into a mold (without filling its entire height). After the layering of all structural layers, the mold is closed with a lid, rigidly secured to the sides of the mold. In order to avoid premature swelling, the aerated concrete mixture is sealed with cold (unheated) water. When closed, the mold is put (without prior exposure) into the steaming cell and the steaming process begins. During the steaming, the following four processes occur spontaneously, without external impacts, in different sequences:

1. At temperatures of 35–45 °C, due to gas formation, the gas-concrete mixture is expanded, increasing in volume 1.3 to 1.7. times
2. At temperatures of 85–100 °C, polystyrene starts foaming, expanding in volume 30 to 50 times.
3. Expansion of the swelling materials, limited by the rigid mold that is closed on all sides, results in the formation of a product with a seamless adhesion between its structural layers.
4. Curing of the aerated concrete mix is accelerated.

Due to the volumetric expansion of materials in the structural layers (aerated concrete and polystyrene), limited by the rigid walls of the closed mold, the self-pressing effect develops in the body of the product, as well as mutual pressing of its structural layers, thereby eliminating the need for any special expansion inserts or flexible connections and preventing the emergence of gaps and thermal bypasses between the structural layers. By the number of structural layers, the new composite material, referred to as polystyrene aerated concrete (PAC), can be two- and three-layered. Experiments have shown that, depending on the thickness of the aerated concrete layer, PAC of various densities can be obtained: from extremely light grades with the density of 200–300 kg/m³ to structural heat insulating grades of 500–1000 kg/m³.

In order to increase the adhesion of aerated concrete to polystyrene and create a steam barrier layer, a waterproofing material strip based on an organic binder (roofing felt, glassine, etc.) can be laid between the structural layers. The seamless adhesion of structural layers with a clear functional purpose creates products with improved performance, with the strength-density ratio of $A_{\text{compr}} = 120\text{--}160$, thermal conductivity of 0.06–0.08 W/m·°C, and frost resistance of up to 100 cycles [8]. Table 1 shows the averaged and adjusted indicators of physical and mechanical properties of polystyrene aerated concrete as compared with traditional aerated concrete.

Table 1. Results of Comparative Tests of Physical and Mechanical Properties of PAC and Conventional Aerated Concrete

Property	Polystyrene aerated concrete design density, kg/m ³				Aerated concrete density, kg/m ³		
	300	400	500	600	400	500	600
Average concrete density, kg/m ³	302	426	491	636	384	504	607
Compression strength, MPa	1.5	1.8	2.6	4.7	1.0	2.0	4.2
Strength after alternate wetting and drying, MPa:							
- before test	1.0	2.1	3.4	4.0	0.6	-	3.0
- after 10 cycles	1.0	1.8	3.6	4.3	0.6	-	3.4
- after 20 cycles	1.0	1.6	3.4	4.3	0.7	-	3.9
- after 50 cycles	1.1	2.0	3.8	3.8	0.6	-	3.3
Water absorption, %							
– by weight	48.7	31.9	28.3	25.0	92.8	72.6	40.4
– by volume	11.9	12.1	12.8	15.6	40.1	35.3	31.5
Capillary leak, %	19.8	13.8	14.2	8.9	25.3	19.6	18.1
Frost resistance, cycles	35–50	50–75	50–75	75–100	5	25	50
Thermal conductivity, W/m·°C	0.058	0.060	0.063	0.072	0.088	0.100	0.148

As seen from Table 1, PAC exceeds conventional aerated concrete 1.5–2.0 times in terms of its strength characteristics and capillary leak, while water absorption is three to four times lower. The high frost resistance of PAC is also notable. Even at densities of 300–400 kg/m³, the samples withstand 25–50 cycles of alternate freezing and thawing. This is explained by the use of the 700–1000 kg/m³ gas concrete mix in the manufacture of PAC, regardless of its required resulting density. Frost resistance of composite PAC depends on the frost resistance of the aerated concrete used, and not on that of polystyrene foam having water absorption of less than 1%. The significant decrease in the thermal conductivity of PAC (by 1.5–1.7 times as compared with cellular concrete) should also be noted. Tests have shown that in multi-layer PAC, strong adhesion of structural layers is achieved. When a sample cube is crushed in determining the compressive strength, the destruction occurs in the body of the aerated concrete and not along the interface with polystyrene (see Figure 1) [9].





Figure 1. Destruction of Two- and Three-Layer Samples of Polystyrene Aerated Concrete

The laboratory results have been subsequently confirmed by pilot production of small wall blocks of 195x198x398 mm (as per nominal sizes under GOST 21520-89 “Small-sized wall blocks of cellular concrete”). The weight of a single PAC block was around 11–12 kg. In terms of the size, one PAC block substitutes eight single ceramic bricks weighing around 21.6 kg (with the average brick weight of 2.7 kg). Therefore, PAC walls are almost twice as light as ceramic walls, which reduces the load on foundation and increases bricklaying productivity. Moreover, due to their improved thermal characteristics, PAC block walls can have smaller thicknesses, thus providing additional technical and economic advantages.

The harsh climatic conditions of the Arctic zone of the Russian Federation impose higher requirements not only on the rational use of fuel and energy resources and heat loss reduction, but also on ensuring the quality, reliability and durability of building structures and systematic monitoring of the physical condition of facilities under construction and in operation. Regular quality monitoring is required at all stages of construction, from the examination of raw materials of natural and man-made origin to inspections of the physical condition of constructed and reconstructed buildings and structures. Material quality control and on-site inspections of structures and facilities shall be carried out by specialized accredited or certified testing centers (laboratories).

One of such centers, the Kola Testing Center for Building Materials and Articles (KTCBMA), was established at the I. V. Tananaev Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials of the Kola Scientific Center of the Russian Academy of Sciences. It was established in 1997 and certified by the state regional center for standardization, metrology and testing of Rosstandart in the Murmansk region. The center has the necessary equipment and highly qualified personnel for testing building materials and products for compliance with relevant standards. Below are the main types of work performed by the KTCBMA for construction companies and industrial enterprises of the Murmansk region and other regions:

- assays of mineral and chemical composition, physical and chemical studies, physical, mechanical and thermophysical tests of natural and man-made raw materials for the manufacture of building materials;
- quality assessments of building materials (rock, inorganic binders, heavy, light and cellular concrete, thermal insulation, ceramic and refractory materials);
- development of compositions and technology for building materials based on local raw materials and industrial waste;
- inspections of the technical condition of buildings and structures (concrete, reinforced concrete and brick structures) for compliance with the current standards;
- radiation quality control of raw materials, building materials and facilities;
- scientific, technical and advisory support in the practical implementation of projects.

Over 20 years of its existence, the KTCBMA has performed hundreds of certification and definitive tests of building materials and products for compliance with the effective standards,

establishing concrete and building brick grades in terms of their compressive strength, frost resistance, thermal conductivity, and water resistance. The Center has conducted numerous on-site inspections of concrete and reinforced concrete structures with the use of non-destructive testing methods.

3. Conclusion

1. Based on the laboratory and pilot production results, a technology for energy-efficient composite products has been developed based on aerated concrete and polystyrene foam, which correspond to the regulatory requirements in terms of their physical and mechanical properties.

2. The successfully operating Kola Testing Center for Building Materials and Articles regularly monitors the quality of building materials and products and inspects constructed and reconstructed buildings and structures, which ensures their reliability, safety and durability for use under Arctic conditions.

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