Possibilities and limitations of high-strength lightweight fiber-reinforced concrete structures

T Q Duong¹, N T Vu², A S Inozemtcev¹ and E V Korolev¹

¹Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia
²Southwest State University,50 let Oktyabrya str., 94, Kursk, Kurskaya Oblast, Russia

Abstract. The paper shows the study of the possibilities, limitations in the design of structures made of high-strength lightweight fiber-reinforced concrete and its use in the construction of a high-rise building using the LIRA SAPR software package. The calculations of the finite-element spatial model show that compared to heavy concrete, using high-strength lightweight fiber-reinforced concrete in the multi-storey buildings construction provides a large number of advantages, such as: reducing deflection of the building from its own weight up to 44.0%, from effect to wind loads - by 2.4 ... 2.6% with a decrease in the period of the first 3 vibrations of the building structure by 11.3%; an increase in the number of storeys to 7 floors without changing foundation bearing capacity; increasing specific usable area per 1 m² of building land by 26.6%; reducing consumption of materials for the foundation while maintaining the number of storeys of the building or the possibility of construction in weak soils. At the same time, the technology of high-strength lightweight fiber-reinforced concrete, combining low average density and high strength, is associated with an increase in the cost of the material, therefore, the existing limitations can be identified: the dependence of economic efficiency on the structural features of a particular building, construction conditions and local resources used for concrete production.

1. Introduction

Nowadays, the actual direction of research is developing building materials with complex set of operational properties. One of these materials is high-strength or structural lightweight concrete, combining low average density and high strength [1]. Common experience in using this material in the design and construction of multi-storey buildings has been known since the mid-20th century. Structural lightweight concrete with a compressive strength from 35 to 41 MPa has been successfully used for nearly four decades by manufacturers of precast and prestressed concrete in North America [2]. Moreover, this concrete is increasingly used in long-span structures. For example, concrete with a density of 1,850 kg/m³ was used for the manufacture of load-bearing elements for the floors of a Parking complex in Chicago with 20-meter spans [3].

The 18th-storey Dallas Statler-Hilton building in the USA, which was built in 1955, is considered to be the first skyscraper, in which structural lightweight concrete was fully used in the above-ground structures
Later, there are many structures, in which all bearing elements of floors are fully applied structural lightweight concrete, such as: 180-meters towers of the 60-storey Marina City in Chicago in 1962; 184-meters tower Park Regis Tower Australia Square (1967) 196-meters tower Lake Point Tower in Chicago.

In 1997, the tower of the American financial center Bank of America was built using lightweight concrete with an average density from 1880 to 1890 kg/m$^3$ with a compressive strength from 43.2 to 51.1 MPa.

During the construction of the Gaya Hospital in London, lightweight concrete with expanded ash aggregate “Lytag” was used to reduce load on the foundation in structural and envelope elements. For the construction of User Tower (122-meter) and Communication Tower (145-meter) lightweight concrete with strength of 31.3 MPa at a consumption of Portland cement 390 kg/m$^3$ was used [3]. In this case, the first five floors were built using solid-body slabs made of structural lightweight concrete, and the subsequent floors were arranged from special ribbed-slab floor.

Brazilian scientists [4] in 2003 proposed formulations of high-strength lightweight concrete on local aggregates. The compressive strength of this concrete ranged from 39.5 to 53.6 MPa after 28 days of natural hardening and the average density was from 1460 to 1605 kg/m$^3$ at a consumption of Portland cement from 440 to 710 kg/m$^3$. The specific strength was from 24.6 to 30.7 MPa, respectively. This indicators were bigger the values of domestic developments. [4–6].

In Europe, the USA and other countries, the use of structural lightweight concrete has a very wide practice [7]. For example, from 1989 to 1997, only in Norway approximately 200 thousand m$^3$ of lightweight concrete were laid. Among the unique structures built using reinforced concrete on expanded clay is the building at the New York International Airport, in which four sections overlap a room with sides 90 and 60 meters and using expanded clay concrete with a compressive strength of 41 MPa, an average density of 1850 kg/m$^3$. As well as the dome of the Assembly hall of the University of Illinois, the replacement of heavy concrete by lightweight concrete allowed to reduce the building mass by 6.8 thousand tons.

In addition, advances in structural lightweight concrete were not limited to multi-story residential and office buildings. The appearance of structures with a smaller cross-section made of such concrete made it possible to expand architectural capabilities in the construction of public buildings [3]. Despite the growing values of physical, mechanical properties [8, 9], technical and economic efficiency [10, 11], the use of structural lightweight concrete is an example of unique solutions, which is not used in ordinary construction.

A possible limitation for the development of high-strength lightweight concrete technology in industry is the lack of typical structural analysis using structural lightweight concrete. Therefore, it is important to study the possibilities and limitations in the calculation of structures made of high-strength lightweight concrete and modeling its use in the construction of buildings and structures for various purposes.

2. Object and research methods

The frame of a 26-storey (24 aboveground, 1 basement and 1 technical) residential building made of monolithic reinforced concrete is considered as the object of research. The height of the floor is 3 m, the area of the standard floor is 1080 m$^2$, the area of the basement (2 floors) is 2142 m$^2$. The calculation is carried out with the following characteristics of structures: columns of square section with side of 550 mm, thickness of vertical diaphragms – 200 mm, thickness of floor – 200 mm and reinforced with a cross system of stiffeners along the bottom of the slab with section dimensions 200×400 mm. External walls and internal partitions are made of light materials and supported on floor slabs. To ensure rigidity and stability of the frame elements in the building structure, the joint work of the elevator stiffness core, columns, slabs and floor beams, foundation slab with hanging piles, combined into a spatial system are provided.
Heavy concrete (HC) and high-strength lightweight fiber-reinforced concrete (HLWFC) with average density of 2400 and 1400 kg/m$^3$, respectively, and strength class B60, longitudinal and transverse reinforcement class A500, were selected as the material for the supporting structures.

Ho Chi Minh City (Vietnam), characterized by the 1 wind region (wind load is 0.23 kPa), was chosen as a conditional construction site.

Calculation of the finite-element spatial model of the building was carried out in the LIRA SAPR software package (Figure 1). For the simulation of columns and stiffeners, 10-type rod finite elements with 6 degrees of freedom in the nodes were used. With the help of universal rectangular finite elements of the 41st type shell, the work of floor slabs and vertical stiffening diaphragms was simulated. To approach the real conditions of frame work, we perform displacement axes of beams until compressed face of plate coincides with compressed face of beam.

![Figure 1. Design scheme of the building](image)

3. Research results

The building frame is designed for the following loads: constant loads (own weight of load-bearing structures, bulkhead weight, ground pressure on retaining walls) and short-term (snow load, payload and wind load) in accordance with [12]. Since the city of Ho Chi Minh is not in the zone of constant seismic activity, the seismic load for the construction object is not provided.

Based on the accepted initial conditions, design of the building was calculated. The result of calculating the stress-strain state of 26-floor-building structures is presented in Figure 2 and Table 1.
Table 1. The stress-strain state of a 26-storied building structure

| № | Characteristic                                      | HC     | HLVFC  | Reduction, % |
|---|-----------------------------------------------------|--------|--------|--------------|
| 1 | Own weight of building, $10^3$ kN                   | 226.7  | 126.9  | 44.0         |
| 2 | Total wind load along the X-axis, kN                | 780.5  | 760.9  | 2.6          |
| 3 | Total wind load along the Y-axis, kN                | 1099   | 1071   | 2.6          |
| 4 | Deflection from the building's own weight, mm       | 19.3   | 10.8   | 44.0         |
| 5 | Displacement from the wind along X (taking into account ripple), mm | 12.9 | 12.6 | 2.4 |
| 6 | Displacement from the wind along Y (taking into account ripple), mm | 21.7 | 21.1 | 2.8 |
| 7 | The first period of oscillation, s                  | 4.15   | 3.68   | 11.3         |
| 8 | The second period of oscillation, s                 | 3.77   | 3.34   | 11.3         |
| 9 | The third period of oscillation, s                  | 3.43   | 3.04   | 11.3         |

Note. The magnitude of the wind load is presented taking into account the ripple.

The presented calculation results show that the maximum nodal displacements along the Z axis arising under the action of its own weight are 19.3 and 10.8 mm, respectively, for structures made of heavy concrete and high-strength lightweight fiber-reinforced concrete and do not exceed permissible values according to Appendix E of SP 20.13330.2011. A natural significant decrease in the building's own weight when using concrete of lower average density leads to a proportional decrease in the deflection value by 44.0% (Figure 2, a). Analysis of the results of dynamic calculation of wind loads, taking into account the pulsation component, shows that the total load along the X and Y axis also decreases from 780.5 kN to 760.9 kN and from 1099 kN to 1071 kN, respectively. In this case, maximum horizontal displacements for the structure of HLVFC along the X axis decrease from 2.4 to 2.8%.
Based on the results of modal analysis, the parameters of the building’s natural oscillations and their shape were obtained (Figure 3). It can be concluded that the translational and torsional forms of natural oscillations are characterized by a lower value of the oscillation period of the building structure. The structure made of lightweight concrete is lighter by 11.3% than that of heavy concrete. It is obviously that a moment of inertia reduced due to a decrease in the mass of the structure.

Figure 3. Forms of building’s oscillation:
   a – the first period of oscillation; b – the second period of oscillation; c – the third period of oscillation

Thus, the decrease in the mass of structures leads to a decrease in dynamic loads. The calculation of reinforcement for manufacture of above-ground part (excluding the foundation) provided the total concrete consumption.

The calculation of metal reinforcement according to two limit states with a maximum crack width of continuous opening – 0.3 mm, short opening – 0.4 mm, relative humidity – 80% and the reliability coefficient under operating conditions $\gamma_b = 0.9$ is presented in table 2.

Table 2. Consumption of materials for manufacturing structures

| №  | Material constructions | HC  | HLCWFC | Reduction, % |
|----|------------------------|-----|--------|--------------|
| 1  | Concrete, m$^3$        | 9174| 9174   | 0.0          |
| 2  | Reinforcement, t        | 247 | 199    | 13.1         |

As can be concluded from the table 2, the use of HLCWFC allows to reduce the amount of reinforcement by 13.1%. At the same time, reducing the consumption of used materials could save total cost and duration of the work.

Taking into account the features of soils (table 3) in the selected area of construction (Ho Chi Minh city), the calculation of the foundation was performed. At the base of the structure, fluid-plastic clays (layer 1) located at a depth of 25.4 m above the ground and layers of refractory clay loams, clays (layers 2 and 7), plastic sandy loams (layers 4, 6, 8) and semi-solid clays (layer 5) become ingrained below them. The groundwater level is fixed at a depth of 15.2 m from the earth's surface.
Table 3. Initial soil conditions for the selected construction site

| №   | Soil description   | h, m | \(I_P\), % | \(I_L\) | \(e\) | \(\rho, 10^3 \text{ kg/m}^3\) | \(\rho_s, 10^3 \text{ kg/m}^3\) |
|-----|--------------------|------|-------------|---------|------|------------------------------|-------------------------------|
| 1   | Fluid clay        | 25.40| 36          | 1.00    | 2.31 | 0.49                         | 0.79                          |
| 2   | Refractory loam   | 1.60 | 14          | 0.41    | 0.72 | 0.99                         | 2.71                          |
| 3   | Refractory clay   | 6.00 | 23          | 0.27    | 0.92 | 0.90                         | 2.74                          |
| 4   | Plastic sandy loam| 6.40 | 7           | 0.40    | 0.57 | 1.06                         | 2.70                          |
| 5   | Semisolid clay    | 3.10 | 21          | 0.11    | 0.71 | 1.01                         | 2.74                          |
| 6   | Plastic sandy loam| 8.50 | 6           | 0.48    | 0.69 | 0.99                         | 2.70                          |
| 7   | Semi-solid loam   | 7.50 | 16          | 0.11    | 0.72 | 1.00                         | 2.71                          |
| 8   | Plastic sandy loam| –    | 6           | 0.40    | 0.59 | 1.05                         | 2.70                          |

Notes: \(h\) – thickness of soil layer, \(I_P\) – plasticity number, \(I_L\) – yield index, \(e\) – porosity coefficient, \(\rho\) – soil density, \(\rho_s\) – density of soil particles.

To select the required working length of the pile, a calculation is made on the assumption that soil is a linearly deformable medium and formation of a plastic zone in the soil is not allowed. Figure 4 shows the design scheme of the pile in the ground, showing that the length of piles according to the calculations of the foundation device in the selected soil conditions should exceed 58.85 m.

Figure 4. Design scheme of the pile in the ground

Thus, as a pile, a round product (60-meter-length and 1-meter-diameter) made of heavy concrete B30 and reinforced with a frame of 16 rods of reinforcement A400 20-mm-diameter can be selected. In this case, material consumption for one pile is 47.12 m³ and 2367.4 kg of concrete and reinforcement, respectively. The bearing capacity of the pile section is \(F = 6404\) kN.

In order to calculate the number of piles, we take into account that the total load acting on the foundation consists of the building's own weight (3.02 kN/m² for the variant with HLWFC and 5.39 kN/m² for the variant with YC) and the payload on the overlap, which is 8.0 kN/m².

Taking into account the own weight of building and payload, the number of piles required for the foundation in accordance with the load-bearing capacity is 56 (table 4). As can be seen from the table below, material consumption for manufacturing foundation is reduced by 28.6%.
Table 4. Material consumption for piles

| №  | Indicator                  | HC   | HLWFC | Reduction, % |
|----|----------------------------|------|-------|--------------|
| 1  | Number of piles, piece     | 72   | 56    | 28.6         |
| 2  | Concrete consumption, m³   | 3393 | 2639  | 28.6         |
| 3  | Reinforcement consumption, thousand tons | 170.5 | 132.6 | 28.6         |

This is one of the most important advantages of using high-strength lightweight fiber-reinforce concrete in construction of high-rise buildings, allowing construction in more difficult ground conditions or to increase the payload by increasing the number of storeys. So, when using the same number of piles for the foundation and its load-bearing capacity, the number of building storeys made of HLWFC can be increased to 7 floors (Fig.5).

Figure 5. The increase in the number of building storeys using HLWFC

A comparative analysis of the stress-strain state of the structures of buildings of the initial (26 floors) and increased number of storeys (33 floors) is performed. Figures 6 and 7 shows the change in displacement from the own weight of building and in the horizontal plane from the wind load.

Figure 6. Deflection from the own weight of the 26-and 33-storey building of HC and HLWFC
From Figure 6 it can be seen that an increase in the number of building storeys leads to an increase in displacement on each floor of the building, but the maximum value of this parameter for building structures made from HLWFC is less than that from HC. In addition, it can be seen that the difference in displacement increases together with an increase in the number of building storeys. Displacement from wind loads varies in a similar way, but with a smaller difference for structures made of different materials.

Thus, calculations of the structural characteristics of buildings from HLWFC show conspicuous advantages that can provide economic efficiency of construction by reducing material consumption for equal-storey buildings or increasing the number of storeys of buildings (table 5).

**Table 5. Calculation of the maximum efficiency using HLWFC in structures**

| №  | Indicator                              | Value when changing the number of storeys |
|----|----------------------------------------|------------------------------------------|
|    |                                        | HC / 26 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |      |
| 1  | Concrete consumption, thousand m³      |         | 9.18 | 9.18 | 9.50 | 9.82 | 10.14 | 10.47 | 10.79 | 11.11 | 11.44 |
| 2  | Reinforcement consumption, ton.        |         | 247 | 199 | 209 | 219 | 230 | 241 | 252 | 264 | 275 |
| 3  | Number of piles, piece                |         | 72 | 56 | 59 | 61 | 62 | 65 | 67 | 69 | 72 |
| 4  | Specific usable area of buildings per 1 m² of land, m²/m² |         | 13.1 | 13.1 | 13.6 | 14.1 | 14.6 | 15.1 | 15.6 | 16.1 | 16.6 |

Table 5 shows that the construction of a building from HLWFC with an increase in the number of floors (an increase in height by 5 floors from the initial one) provides an increase in the available specific area. When using the same bearing capacity of the foundations, the value of this indicator increases by 26.6 %: from 13.1 to 16.6 m² per 1 m² of building area. At the same time, economic effectiveness of this solutions consists of many factors, so the rationale for implementation should be based on calculations of each project, taking into account features of development and functional purpose of the object.
4. Conclusions

The calculations performed in this work demonstrate that using high-strength lightweight fiber-reinforced concrete in the construction of multi-storey buildings provides a number of advantages compared to heavy concrete:

– reducing the displacement of the building from the action of its own weight to 44.0%, when wind loads is 2.4…2.6% while reducing in the period of the first 3 oscillation of the building structure by 11.3%;
– increasing to 7-storeys-building without changing the bearing capacity of foundation, which provides an increase in the specific usable area per 1 m² of land for construction by 26.6 %;
– reducing the consumption of materials for the foundation while maintaining the number of building storeys or the possibility of construction in difficult soils.

At the same time, the technology of high-strength lightweight fiber-reinforced concrete, combining low average density and high strength, is associated with an increase in cost of material, therefore, as an existing limitation, we can conclude the dependence of economic efficiency on the structural features of a particular building, construction conditions and local resources used for concrete production.

Acknowledgments

The work was carried out within the framework of agreement No. 14.583.21.0072 on the provision of subsidies for the implementation of the Federal target program "Research and development in priority areas of development of the scientific and technological complex of Russia for 2014-2020" (project ID- RFMEFI58318X0072) with the financial support of the Ministry of education and science of the Russian Federation.

References

[1] Inozemtsev A.S., Korolev E.V. 2014 High-strength lightweight concrete-structural concrete of the new generation (Technology of concrete) № 9 (98) pp 40–44.
[2] Holm T.A., Bremner T.W. 2000 State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments p 116.
[3] Zareef M.A.M.E. 2010 Dissertation. Conceptual And Structural Design Of Buildings Made Of Lightweight And Infra-Lightweight Concrete (Berlin) p 119.
[4] Rossignolo J.A., Agnesini M.V.C., Morais J.A. 2003 Cement and Concrete Composites Vol. 25 pp 77–82.
[5] Ponomarev A.N., Yudovich M.I. 2009 RF patent 2355656. Concrete mix / -Publ. 20.05.2009. p 3.
[6] Figovsky O. L., Beilin D.A., Ponomarev A.N. 2012 Nanotechnology in construction: scientific Internet journal № 3 pp 6–22.
[7] Zvezdov A.I., Falikman V.R. 2008 Zhilishchnoye Stroitel'stvo № 5 pp 2–6.
[8] Inozemtcev A.S. 2014 Magazine of Civil Engineering 51(7) pp 31–37.
[9] Inozemtcev A.S. 2015 High-strength lightweight concrete mixtures based on hollow microspheres: Technological features and industrial experience of preparation (IOP Conference Series: Materials Science and Engineering) 71(1) pp 012028.
[10] Inozemtcev A.S., Korolev E.V. 2014 Advanced Materials Research Vol. 1040 pp 176–182.
[11] Inozemtcev A.S., Duong T.Q. 2019 Technical and economic efficiency of materials using 3D-printing in construction on the example of high-strength lightweight fiber-reinforced concrete (E3S Web of Conferences) 97 pp 02010.
[12] SP 20.13330.2011 Loads and impacts. The updated edition of SNiP 2.01.07-85 (Gosstroy of the RF) Stroizdat 2011.