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Study of application of lightweight aggregate concrete to construct post-tensioned long-span slabs

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Abstract

In Poland, in the last few years, there have been attempts to construct post-tensioned concrete slabs with above average spans and slenderness. Some very thin slabs with spans of up to 17.6m have been designed and made. At work, an example of the construction of such slabs accompanied by the results of monitoring of the deflections of one of them for one year has been presented. Also, the results of the calculation analysis of concrete stress and deflections of the slab in an implemented version and with lightweight concrete with a density of 1710kg /m^3 have been presented. The opportunities and benefits of the use of such concrete for the construction of post-tensioned large-span slabs have been discussed.

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Keywords: lightweight concrete, post-tensioning, prestressed slab, unbonded tendon.

1. Introduction

Post-tensioned concrete large-span slabs were used as floors in the buildings in the United States, Australia, Hong Kong and later in Europe a few decades ago. In Poland, post-tensioned floors had and still are obstructed path of development. The first such construction was implemented in the Platinum Towers building in Warsaw in 2008. Within a few decades, numerous guidelines and recommendations for the design and construction of such structures [1-4] have been issued in Europe.

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The published guidelines give the recommended ratio span of the thickness of the slab making it dependent on the type of construction, load and allowable deflection. For example, according to [1], this ratio should not exceed 42 for floor slabs and 48 for roof slabs for full continuous slabs for two or more spans, in either direction. Khan and Williams [5] give the required slenderness for different load levels (Table. 1) on the basis of calculations carried out and on condition that lack of cracking is considered.

Table 1. The recommended ratio span / thickness of the slab [10].

Slab type	span / thickness
Solid one-way slab	30÷45
Ribbed slab	25÷35
Solid flat slab	35÷45
Waffle slab	20÷30

fib (Fédération Internationale du Béton) in [2] gives maximum recommended spans and a minimum depth of slabs. For example, for one-way continuous slabs supported on the edges, the span should not exceed the value of 12.6m at a thickness of 300mm and the imposed load equal to 1.75kPa. The largest recommended span for continuous two-way slabs is 13.3m with a thickness of 250mm and the imposed load of 1.75kPa. At an imposed load of 4.0kPa and similar thicknesses, allowable spans are already 11.4 and 12.0m. The result of the above recommendations is that the scientific and technical literature has no reports on the references to the implementation of monolithic post-tensioned slabs with spans in excess of 12-12.5m.

In the years 2014-2015 in Poland, after own calculation analysis, the post-tensioned slabs with spans and slenderness far exceeding recommended values (point 3) were designed and successfully executed.

One of the main loads of such floors (especially roof slabs) is most often self-weight. This is sometimes reduced by using weight-relieving inserts. This solution, however, poses some technological and economic problems. A good solution may be to use a lighter concrete with a density less than 2000kg/m^3. Such solutions have repeatedly been used in the world to construct the building structure but have not found wider application for large-span slabs. Lightweight aggregate concrete, although it is made using aggregates as waste products instead of natural aggregates, is still significantly more expensive and difficult to manufacture and deliver to the building site as compared to dense concrete. In Poland, it may be made from commonly available expanded clay aggregate or less available and more expensive fly ash. However, cheaper expanded clay aggregates do not allow to obtain sufficiently high mechanical parameters (compressive strength up to 16MPa) and fly ashes significantly increase the cost of concrete. Its use in the reinforced concrete slabs or post-tensioned slabs with standard spans and thicknesses is not economically justified. If the slabs of abnormal spans and slenderness are constructed, the use of lightweight aggregate concrete is, however, technically justified. The lower weight compensates the lower values of elastic modulus in relation to dense concrete with comparable strength. In point 4, the advantages of the use of lightweight concrete in place of ordinary concrete are shown on the basis of the results of computational analysis of one of the completed floors.

2. Characteristics of lightweight aggregate concrete and their application in the construction industry

Lightweight aggregate concrete finds its origins in ancient times when the Romans and Greeks made it mainly from natural pumice stone and other porous rocks of volcanic origin. To this day, we can see the buildings dating back to those times, including the Roman Pantheon made of tufa and puzzolan concrete. They are known mainly as being used for decorative elements. However, they are increasingly used for the erection of structural elements. Lightweight aggregate concrete was first used as a structural material in 1928. The concrete was used for the superstructure of eight additional floors in the Bell Telephone Company skyscraper in Kansas City. One year later, a 28-storey Park Plaza Hotel skyscraper was built in St. Louis. Its entire structure was made of lightweight aggregate concrete.

There are fourteen classes of lightweight concrete from LC8/9 to LC80/88 (2 classes less than dense concrete). In practice, high strength concretes are rarely found. However, the examples of achieving the compressive strength of 140MPa [6] are known, but they have not found practical application as a large number of additives increases the cost of concrete making.

Light concrete is characterized by increased homogeneity that results from similar elastic modulus of aggregate and cement matrix, better mutual adhesion, tight construction of the contact zone and regular shape of the grains of aggregate. Owing to this different structure, lightweight concrete reacts differently under load and has a different failure mechanism in comparison with conventional concrete. In lightweight aggregate concrete, there are no three stages of development of cracks as compared to ordinary concrete, i.e. first cracks appear when the tensile stress reaches about 85-90% of concrete strength [7]. The stored elastic energy during load causes rapid propagation of cracks, which inadvertently leads to the destruction of the material. As a result, lightweight concrete elements can be used in the uncracked state under large tensioning. The process and mechanism of destruction of lightweight concrete in a compression test as compared to normal concrete is shown in Figure 1. It can be seen that the stress-strain dependency in uniaxial compression test has a rectilinear course. Different destruction of lightweight aggregate concrete stems not only from the stress, during which cracks appear, but also from the location of such cracks. In dense concretes, destruction usually occurs in the in contact area (aggregate-cement), which is the weakest part of the concrete structure and, at the same time, most loaded because of the stress concentration resulting from significant differences in elastic modulus of the matrix and aggregates. In turn, in lightweight aggregate concrete, destruction takes place in the cement matrix due to the higher strength of contact zone and higher modulus of elasticity of the matrix than in the case of aggregate. The destruction of normal concrete is caused in most cases by a detachment of the aggregate from the matrix. Instead, in lightweight concrete, cracks are formed due to excessive stress in the matrix according to the direction of the load. Therefore, the destruction is caused by the splitting of aggregate particles. Lightweight aggregates are less stiff and are not able to block the propagation of cracks forming in the matrix, resulting in more brittle destruction.

Due to the low modulus of elasticity, lightweight aggregate concrete is characterized by increased shrinkage (up to 50%) [16]. Higher shrinkage is confirmed by numerous studies [8-10]. Lightweight concrete has the predisposition for internal care. Therefore, shrinkage is less dependable on the time and conditions of internal care as well as outdoor temperature and humidity conditions. The factor that most affects the shrinkage of lightweight concrete is a type of aggregate. Its density and structure are also important. Aggregates sintered at high temperatures exhibit less shrinkage than the aggregate produced from the same raw material in hardening technology [7]. It was also found that creep and creep rate development for lightweight concrete is higher than for conventional concrete. These statements, however, were based on older research results and lower grades of concrete. It is well known that the higher the strength, the lower degree of creep occurs. This rule also applies to lightweight aggregate concrete. Creep for higher classes is similar, and sometimes even smaller than for dense concrete [11,12]. Due to lower density, lightweight concrete has worse mechanical properties than dense concrete. With the increase of strength, the differences are much smaller. The studies [13] have demonstrated that the value of Young's modulus for lightweight concrete with fly ash aggregate with a density of 1580 and 1710 kg/m^3 is lower by 30% for dense concrete made of the same cement mortar of similar strength (Fig. 2).

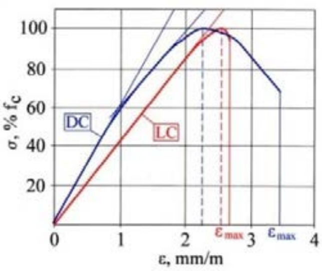

Fig. 1. Stress-strain dependence in compression test for dense concrete (DC) and lightweight aggregate concrete (LC) with the same strength.

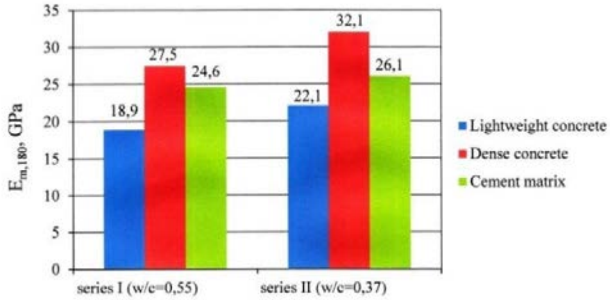

Fig. 2. The mean value of Young's modulus (E_m) of lightweight aggregate concrete, dense concrete and cement mortar used to their execution.

However, lower density improves certain properties, such as thermal insulation or resistance to dynamic action. Owing to the extended range of operation in the state of resiliency, lightweight aggregate concrete can be subject to greater fatigue resistance. Due to the lower weight of the structure, lightweight concrete is commonly used in buildings exposed to seismic activities. Stresses on the structure during earthquakes are directly proportional to the weight of the structure. Many studies, e.g. [14,15] show that, under dynamic loads, lightweight concrete receives higher damping coefficients. Therefore, the structure in the state of vibration will be dampened quicker.

3. Oversized post-tensioned concrete slabs

In 2015, in Poland, the Cultural and Arts Centre building in Kozienice (Fig. 3) was made available for use. The design of the facility was prepared in 2013. The building belongs to public utility facilities and performs cultural, artistic and educational functions. 2 segments of the building with expansion joints of a different structural arrangement were designed on a rectangular plan with dimensions of 61.5×42.5m. Figure 3 shows a plan view (at the level of the top floor) and vertical cross-section of the segment located between the 1 and 6 axes. In this segment, a cinema hall (between the F and N axes) and theatre (between the A and C axes) were located. These premises required large space free of supports. Additionally, due to the nature of buildings in the area, the total height of the building was limited. Those factors necessitated the use of thin and slender horizontal partitions. Therefore, 3 slab spans post-tensioned by unbonded tendons were designed, i.e. the floor slab above the theatre hall in the position of 9.68m (Sl-1) and two spans of the flat roof: over the theatre hall in the position of +14.08m (Sl-2) and over the cinema hall in the position of +13.68m (Sl-3).

Concrete class C35/45, based on cement CEM I 52,5 N-HSA-NA in an amount of 396 kg/m^3 (w/c = 0.5) was used for making the concrete slabs. Passive reinforcement of all post-tensioned slabs was designed as upper and lower bar ϕ10mm every 150mm. For post-tensioning of the slabs, unbonded steel tendons were used (monostrands) Y1860S7 with a diameter of 15.7mm (seven-wire strand 1×5.7+6×5mm, strand area - 143mm^2, characteristic strength - f_{pk} = 1860MPa).

The Sl-1 slab in the position of 9.68m is a one-way post-tensioned slab located between the 3 and 6 axes, and A and C (Fig. 3). The span of slabs in the axes of the walls is 11.15m. The thickness of the slab is 200mm and the thickness of the walls is 240mm. The ratio of span to thickness is 55.8. The slab was post-tensioned by unbonded tendons at a spacing of 300mm (Fig. 4). The Sl-2 slab in the position of 14.08m is also a one-way post-tensioned span. The range of the span in the axes of the walls is 12.86m and the thickness of the slab is 250mm. The ratio of span to thickness is 51.4. The slab is post-tensioned with monostrands at a spacing of 250mm.

The Sl-3 slab over the cinema hall in the position of 13.68m is the largest span. The range of the slab in the axes of the walls (as well as the BL-1 beam in the L axis) is 17.65×19.6m and its thickness is 350mm. The ratio of span to the thickness (for a shorter span) is 50.4. The slab is post-tensioned in two directions by two unbonded tendons at a spacing of 220mm.

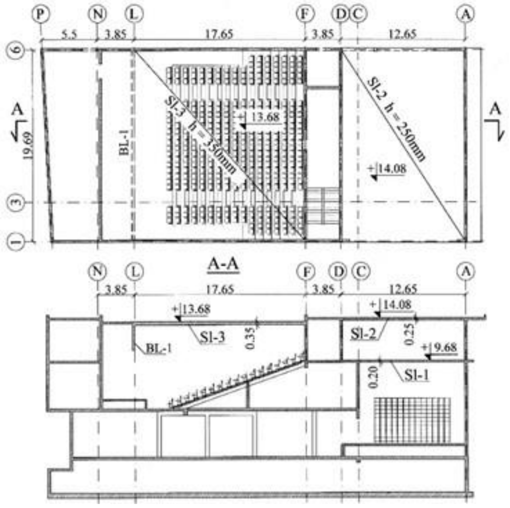

Fig. 3. Plan and vertical cross-section of building part with post-tensioned slabs.

Table 2 shows the loads on the post-tensioned slabs at the time of commissioning of the building. It can be noticed that the main load is self-weight of the slab. Despite exceeding the recommended spans and slenderness of the slabs, the deflection of all three spans were at a satisfactory level at the time of commissioning of the building (about a year after the concreting of the roof slab). The deflection values counted from the level of concreting was 12mm, 13mm and 31 mm for the Sl-1, Sl-2 and Sl-3. These values represent 1/929, 1/989 and 1/569 of the span. For sure, they are not final long-time deflections but their level, and a decline in the growth of rate suggests that the limit values will be maintained.

The next point shows the results of computational analysis of the Sl-2 slab, based on the concrete used on the slab and lightweight aggregate concrete.

4. Computational analysis

The Sl-2 slab was subject to computational analysis. To this end, the model of a fragment of the building was built in FEM system (Fig. 5). The model is built on four-node surface elements with dimensions of 0.5×0.5m. The post-tensioning was modelled with substitute load (surface load and the linear moment on the edge of the slab). The analysis was performed in the linear-elastic range.

The following parameters of concrete were used for calculations:

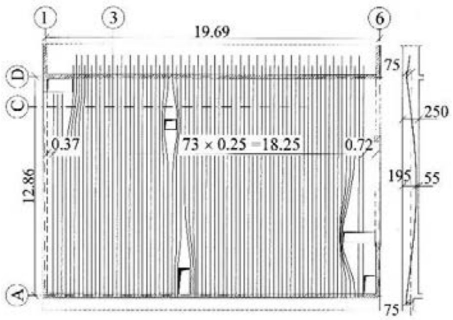

Fig. 4. Geometry and prestress arrangement of Sl-2 slab.

- the C35/45 ordinary concrete in accordance with point 3. The concrete strength and elastic modulus were adopted on the basis of the tests of cylindrical samples of 150×300mm, i.e. 29.7MPa and 30.2GPa at the time of post-tensioning (14 days after concreting) as well as 33.8MPa and 33GPa after 28 days,

Table 2. Permanent load for slabs.

Load type	Value [kN/m2]
Self-weight	6,25
Finishing layers	1,1
Equipment	1,0

- lightweight aggregate concrete for fly ash aggregate with self-weight of 1710kg/m^3. The concrete parameters were adopted in accordance with [8] – resistance to 30MPa compression, 23.1GPa elasticity modulus.

For the slab made of traditional concrete, the substitute load of the post-tensioning based on the measured elongation of post-tensioning cables during their tension was adopted. The cables were tensioned with the force of 220kN. The average value of the post-tensioning force after tensioning equal to 212.0kN was obtained assuming that the elasticity modulus of the strand was equal to 190GPa. The value reduced by a loss of elastic slab deformations of concrete equal to 0.9% (based on calculation). The value of initial prestress force was 210.0kN finally. The value of a substitute load directed upward equal to 5.96kN/m^2, and the linear edge moment value on the outside wall of 63.6kNm/m was obtained for such a force in the tendon. For lightweight aggregate concrete measured force 212.0kN was reduced by losses of elastic deformations equal 1.2% also (208kN was obtained).

Two computational situations were considered:

- the situation after post-tensioning, in which post-tensioned loads (as described above) and the loading caused by self-weight of the slabs according to Table 2 were assumed. For lightweight concrete, similar post-tensioning and loading caused by self-weight of the slabs appropriate for concrete density were assumed.
- the situation when all existing loads are in use. The post-tensioning was reduced by rheological losses calculated for each of the considered time. For lightweight aggregate concrete, the shrinkage of concrete was increased by 30% as compared to ordinary concrete and creep at a similar level [8] were assumed for calculating the losses of prestressing. The last value of prestress force in considered time period (to 23 July 2015) was 192.6kN for used concrete and 186.6kN for lightweight aggregate concrete.

Figures 6 and 7 show the deflection of slab caused by their self-weight (Fig. 6) and post-tensioning (Fig.7) for used and lightweight aggregate concrete. It can easily be seen that, for lightweight concrete, the deflection caused by self-weight is smaller than for normal concrete. Also, for lightweight concrete, the effect of post-tensioning is higher (lower Young's modulus). The deflection after post-tensioning, resulting from the sum of self-weight and caused by post-tensioning, is 4.6mm (down) for used dense concrete and -1.8mm (up) for lightweight concrete.

Figure 8 shows the computational development of elastic deflections of made slab, lightweight aggregate concrete slab and the results of deflections measured during the construction of the object. For used ordinary concrete, elastic deflection under the full load (about one year after construction) is 11.9mm, while for lightweight concrete is 6.8mm. Figure 8 further illustrates the development of deflection measured during the making of the analyzed slab. It is hard to expect the compliance of deflections measured with calculated deflections in the post-tensioning analysis in a longer period. The compliance can be most expected in deflections designated at the time of post-tensioning. At this stage, 4.7mm from the calculations and 4.5mm from the measurements were obtained.

Table 3 presents the value of concrete stress in transfer direction in the middle of the span after prestressing (self-weight+prestressing). These are +2.6MPa (compression) at the top layer and 4.1MPa at the bottom layer for dense concrete. The value of the initial stresses were magnified to -3.1MPa at the top and +9.9MPa at the bottom layer due to reduction of slab self-weight. A small tensioning occurs at the top layers of lightweight concrete, but it is allowable for high tension resistant lightweight aggregate concrete. Additionally, minimum area of passive reinforcement near the top surface is always used against uncontrolled cracking. On the other hand, high level of initial compressive stress at the bottom surface is useful to reduce the long-time deflection increase.

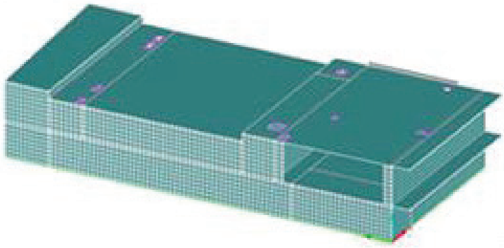

Fig. 5. Model of building part made in RFEM software.

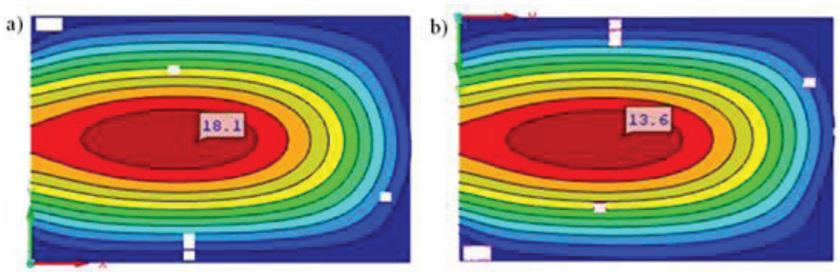

Fig. 6. Maps of deflection from self-weight: (a) used (dense) concrete; (b) lightweight aggregate concrete.

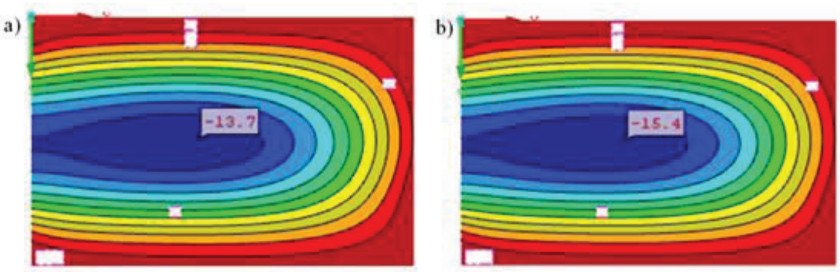

Fig. 7. Maps of deflection caused by prestressing: (a) used (dense) concrete; (b) lightweight aggregate concrete.

Table 3. Middle-span cross-section bending moment and concrete stress values.

	M [kNm/m]		*Prestresss force*	*Prestress eccentricity*	*Stress σ [MPa]*	
	self-weight	prestressing	*P [kN/m]*	*e [mm]*	top layer	bottom layer
Used concrete	51,1	-42,6	840	70	2,6	4,1
Light concrete	34,0	-42,3	832	70	-3,1	9,7

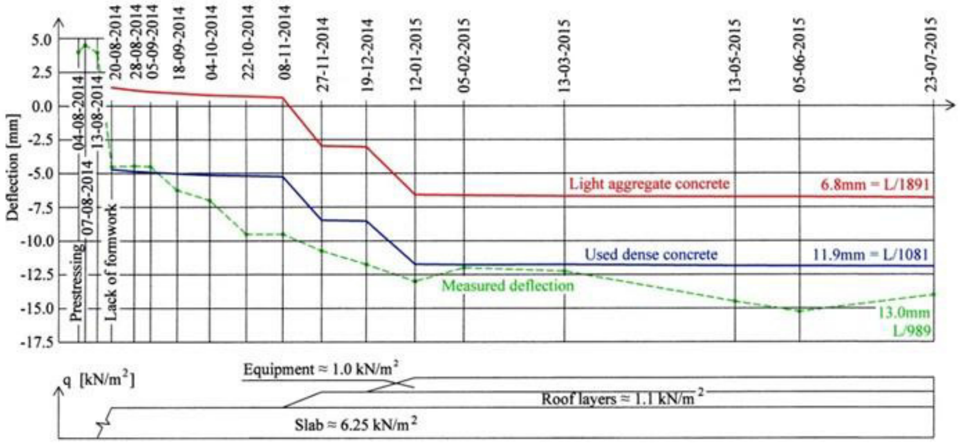

Fig. 8. Development of calculated and measured deflection.

The correct structure of designed slab is determined by, however, long-time deflection rather than immediate elastic deflection. According to [2], for uncracked slab, long-time deflection may be determined on the basis of the deflections resulting from elastic analysis with an appropriate increasing ratio of 3.0 for dead loads and post-tensioning, and 1.5 for life load. Assuming that for concrete with strength classes not lower than 30MPa, the creep of lightweight aggregate concrete does not differ from dense concrete, this factor appears to be legitimate also for the lightweight aggregate concrete of adequate strength. Additionally, rheological deflection increase in lightweight aggregate concrete may by reduced due to higher initial compressive stress at the bottom surface, in compare to dense concrete. Therefore, the expected long-time deflection (including of the snow load of 1.0kN/m^2) is 40.1mm for used concrete and 25.2mm for lightweight aggregate concrete. The presented measurement results indicate that one year after making of the slab, the maximum deflection of the slab (15.0mm) is far from being three times the value of calculated elastic deflection (11,9×3 = 35.7mm), which suggests that, for lightweight concrete, the expected deflection can also be significantly lower than the calculated value.

5. Conclusions

The paper presents the results of a comparative analysis of the concrete stresses and deflection of the post-tensioned slab with a span of 12.86m and thickness of 250mm, made of ordinary dense and lightweight aggregate concrete. It was shown that, despite a lower modulus of elasticity of lightweight aggregate concrete, better deflection values with similar amount of post-tensioning can be obtained (long-time deflection amounted to 25.2 instead of 40.1mm) as a result of the reduction of the mass of the concrete.

Discussed results indicate that lightweight aggregate concrete can be better suitable for the construction of post-tensioned slabs with large spans. It is possible to achieve longer spans and higher slenderness than in the case of dense concrete.

Another important fact is also better reaction of the elements of lightweight aggregate concrete exposed to dynamic loads. The frequencies of natural vibrations of lightweight concrete structures are higher, and the amplitudes of vibrations are lower. A positive aspect is the damping ratio of such vibrations, which, for lightweight concrete, is higher, and thus the vibrating structure is dampened quicker. For thin slabs, the problem of vibrations is particularly important. However, they may be reduced by replacing ordinary dense concrete with lightweight aggregate concrete.

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