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Post-Tensioned Concrete Long-Span Slabs in Projects of Modern Building Construction

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Abstract. Nowadays, design of modern an architectural building structures requires the use of slender and free from numerous supports slabs. The most suitable solution for above requirements are the post-tensioned slabs with unbounded tendons. Slabs prestressed by unbounded tendons are successfully used worldwide for several decades. During that time many recommendations dealing with the forming of geometry and prestressing, dimensioning and erection technology were issued. During the recent years prestressed slabs characterized by span and slenderness substantially exceeding recommended limitations were designed and erected with success in Poland. During the slabs erection and in two years of their using, the deflection of three oversized slabs were monitoring. In spite of designed the slabs significantly larger and slenderer than the recommended maximum value of span and span to depth ratio, the deflection of the slabs is definitely far from the limit value. The paper shows the geometry, characteristic and deflection of erected slabs and conclusion. Description of a very large span slab (21.3m), that was designed regarded to the information obtained from the previous realisation, is presented in this paper.

1. Introduction

Global increase of nations wealth imposes constant improvement of developed throughout the years and well known architectural forms, both visually and functionally. This forces the necessity to search for slenderer horizontal shell elements with greater spans. However, apart from general stability and capacity, those have to provide both good thermal and acoustical features, as well as vibration resistance, which becomes problematic in case of slender slabs. Despite number of disadvantages, all of the abovementioned factors may be reconciled by concrete, more precisely - prestressed concrete. Quite large span is achieved using pre-tensioned hollow core slabs. The use of hidden steel beams and concrete topping [1] significantly increases the attractiveness of this type of slab. The flat slab with large span is achieved in this way. However, much more slander slabs can be constructed using post-tensioned concrete.

For years, post-tensioned concrete long-span slabs have been used as structural floors in buildings in the USA, Australia, Hong Kong and Singapore. Hereafter, they have been introduced to Europe. In Poland, its growth dates back to the last ten years. During several decades of effective application of prestressed slabs many design guidelines were prepared and implemented in order to enable the simple engineering approach to the design of selected slab type. In Europe there were published works [2], [3], [4], [5] and [6]. Also in Poland there were published several works on the design and implementation of post-tensioned slabs [7], [8], [9], [10] and [11] in the last decade.

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Table 1. Recommended span to depth ratio according to [4].

Slab type	Span/depth
Solid one-way slab	30÷45
Ribbed slab	25÷35
Solid flat slab	35÷45
Waffle slab	35÷45

Guidelines that have been published give recommended values of span to depth ratio of a slab basing it on the type of the structure, imposed load (the load over the self-weight) and permissible deflection. For instance, according to [5], the span to depth ratio for solid continuous slabs of two or more spans in each direction not exceed 42 for floor slabs and 48 for roof slabs. Khan and Williams [4], beginning with the crack free condition in the cross section of the slab, and basing on the performed calculations give the required depth to span ratio for the various load levels. Generally, the highest span to depth ratios do not exceed the value of 45. The scope of this ratio for various slab types is listed in the table 1. Moreover, in the FIB Bulletin No. 31 [6], the minimum slab depth and maximum slab span for various support conditions and load levels are listed in a more detailed way (figure 1).

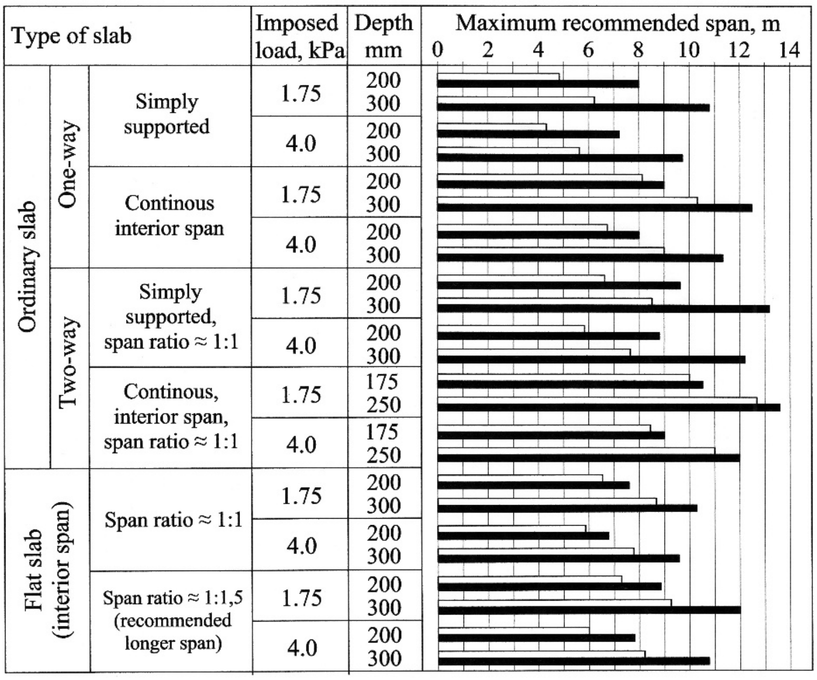

Figure 1. Examples of slab thickness and indication of maximum span for solid slabs with ordinary (▭) and prestressed (■) reinforcement according to [2].

The allowed recommended span lengths for continuous slabs are equal to 13.6m for two-way slabs and to 12.5m for unidirectional slabs. The published recommendations resulted in that the constant depth slabs are erected worldwide with the maximum span limit set at around 12÷13m.

Adduced guidelines in design of prestressed slabs are dictated by two factors: necessity of stresses level reduction to the values guaranteeing lack of cracks and necessity of long-term deflection limitation. Assuring lack of cracks occurrence is essential due to excessive stiffness decrease of cracked sections, and hence dramatic increase of deflection. Resistance to cracking of slabs may be easily increased by use of concrete of higher class. It may seem that use of higher strength concrete would allow design of slenderer and thinner slabs. However, significantly lower rate of increase of elasticity modulus in comparison to rate of increase of tensile concrete strength is problematic. Figure 2 shows the dependence between tensile concrete strength and elasticity modulus of higher strength concrete classes to values obtained for concrete class C30/37, which is recommended as a minimum class and widely used in post-tensioned slabs construction. It may be easily noticed that while concrete compressive characteristic strength f_{ck} increases from 30 to 90MPa, tensile strength increases by 72% and elasticity modulus only by 38%. Therefore, use of higher strength concrete does not imply the possibility of slabs thickness reduction due to not sufficient increase of modulus of elasticity, but significantly increases costs of slab construction. For this reason, the most reasonable would be use of concrete of characteristic compressive strength within range 30÷50MPa.

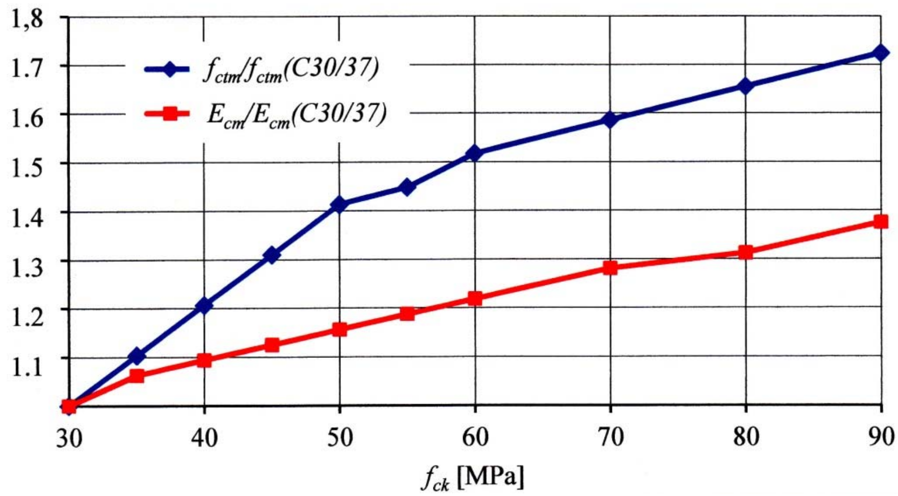

Figure 2. Increase of tensile strength and modulus of elasticity of higher class concrete relative to class C30/37

One of the main problems during design of thin slabs is to assure required deflection. As long as the required initial negative deflection (camber) may be achieved easily by modification of slabs position by prestressing, the increase of deflection in time may be troublesome. As many may know, the final deflection (long-time deflection) of reinforced concrete slabs may be four to six times higher than the value obtained from elastic analysis.

In case of prestressed slabs this ratio is slightly less, however still problematic. According to guidelines given in [5], value of long-time deflection of prestressed slabs may be estimated basing on deflection value calculated during elastic analysis and additional magnifying factor taking into consideration time-dependent effects. The abovementioned factor is 1.5 for dead load and prestressing, and 3.0 for live load.

Although providing small deflection values of thin slabs is problematic, the authors of this paper think that the design of significantly longer spans and greater slenderness than those given in available recommendations and currently presumed as maximal is feasible. In recent years several floor slabs having span and slenderness significantly exceeding the recommended values have been prepared and erected by the employees of the Building Materials and Structures Institute of the Cracow University of Technology and TCE Structural Design & Consulting [11]. The slabs were being tested number of times and the positive results are the basis for the design of next ones, having significantly greater spans.

2. The oversized slabs in the building of Artistic and Cultural Center in Kozienice

Three extremely slender slabs prestressed with unbonded tendons were designed and erected in the building housing the Artistic and Cultural Center in Kozienice, which opened in summer of 2015 (figure 3). Three post-tensioned slabs with unbounded tendons were designed (figures 4 and 5):

- slab S1-1 at the level of +9.68m, having the span of 11.15m and depth of 200mm directly above the theater hall. The span to depth ratio is 55.8,
- slab S1-2 at the level of +14.08m, having the span of 12.86m and depth of 250mm in the roof above the theatre hall. The span to depth ratio is 51.4,
- slab Sl-3 at the level of +13.68m, having the span of 17.65×19.6m and depth of 350mm over the cinema hall. The span to depth ratio is 50.4.

These values substantially exceed the recommended values, both in terms of slenderness and span.

During construction of the slabs the development of deflections and strains of concrete in mid-span cross-section were tested. Some details and results from construction were presented in work [11]. Additionally, after the construction, whilst the biggest slab was being loaded with a test load, the deflections, concrete strains and stresses in prestressing tendons were tested. Moreover, the element was tested under dynamic load action by triggering its vibration and testing of accelerations. The deflections of all three slabs have been monitored from the moment of their construction up to now. Immediate load test revealed the sensitivity of the slab to service load. The observation of deflection (their range and speed of development) during 2.5 years, gave information about influence of time on slabs behaviour.

Figure 6 shows plan of the roof panel Pl-2 with span equal to 12.86m, thickness 250mm and span to depth ratio equal to 51.4. Abovementioned drawing shows plan and the prestressing profile. Prestressing was conducted with use of 7ϕ5 unbounded tendons made of steel of characteristic tensile strength of f_{pk}=1860MPa, spaced every 250mm. Slab was made of concrete class C35/45, prepared with portland cement CEM I 52.5. Besides sand, dolomite grits with a grain size of 2÷16mm was used. Slab was reinforced with upper and lower reinforcing mesh ϕ10 every 150 mm. Tensile force of equal to 220kN was introduced into each tendon after 14 days from casting.

On the top of the slab the next finishing layers were constructed: hydroisolation, thermal insulation of 200mm and 50÷70mm of grits aggregate. Self-weight of roof cover layers was about 110kg/m^2, while the weight of utilities and equipment installed on the slab was estimated to be 110kg/m^2.

Figure 7 represents the propagation of deflection of the slab during first two years from the moment of construction. Prestressing (5th August 2014) caused the camber of the slab of 4.5mm. However, after disassembly of the formwork slabs deflection was equal to 4.5mm. This indicates flexibility of supports (below located slab and auditorium structure) on which it was supported during concrete casting. Until the completion of all finishing layers and utilities on the roof (January 12, 2015) the slab reached a deflection value of 13.0mm and for a further 18 months (until June 27, 2016) a value of 22.5mm. Therefore, deflection value after about 23 months after prestressing and formwork removal was L/572, whereas the increase in the deflection after removal of the formwork was L/714 (18.0mm).

Although the slab was constructed as one-way with very high slenderness (L/h=52.4), deflections measured after two years of using are significantly lower than recommended as acceptable value. Moreover, decrease of their growth rate (figure 7) allows to conclude that the limit value will never be exceeded.

In similar manner, the other slabs deflection was within acceptable range. For largest slab Pl-3, of span equal to 17.65m and depth 350mm, deflection increase after about 23 months from the moment of formwork removal was 35mm, which is 1/504 of span length. Unfortunately, the shortest span panel Pl-1 (11.15m), however the slenderest (thickness 200mm) slab, was monitored for only 7 months from the moment of prestressing. Though, it is interesting that the increase of deflection in this period of time, despite the load of finishing layers and heavy partition walls of total weight 390kg/m^2, was only 6.0mm (L/1817). This relatively small value was achieved despite span to depth ratio 55.8 and one-way slab. The measured deflection is significantly lower than calculated one, and currently remains is a mystery for the authors.

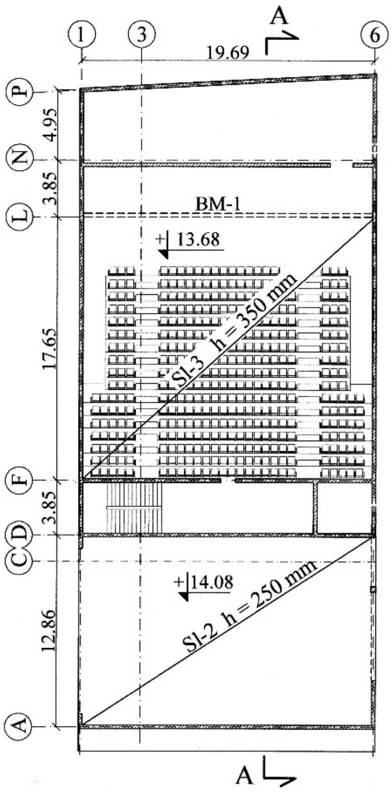

Figure 4. Plan of the building segment with post-tensioned slabs

Figure 3. Visualization of CKA in Kozienice.

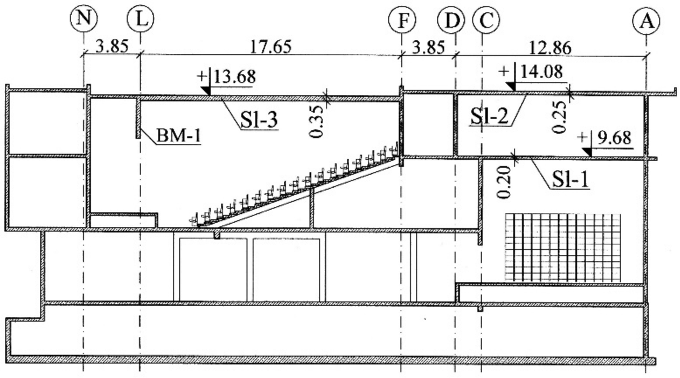

Figure 5. Cross section A-A

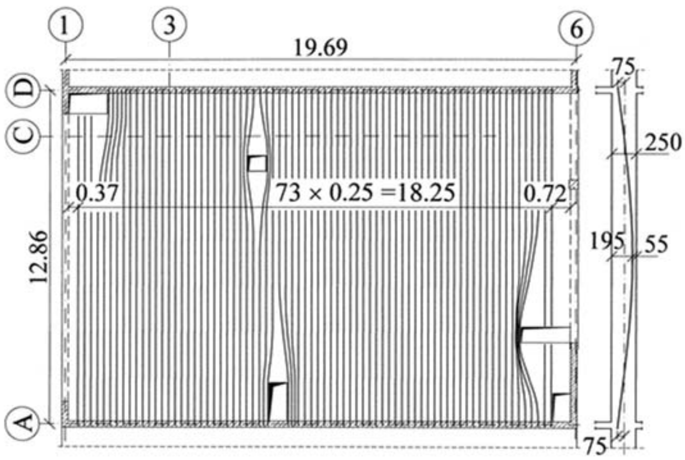

Figure 6. Geometry and prestressing arrangement of roof panel Sl-2

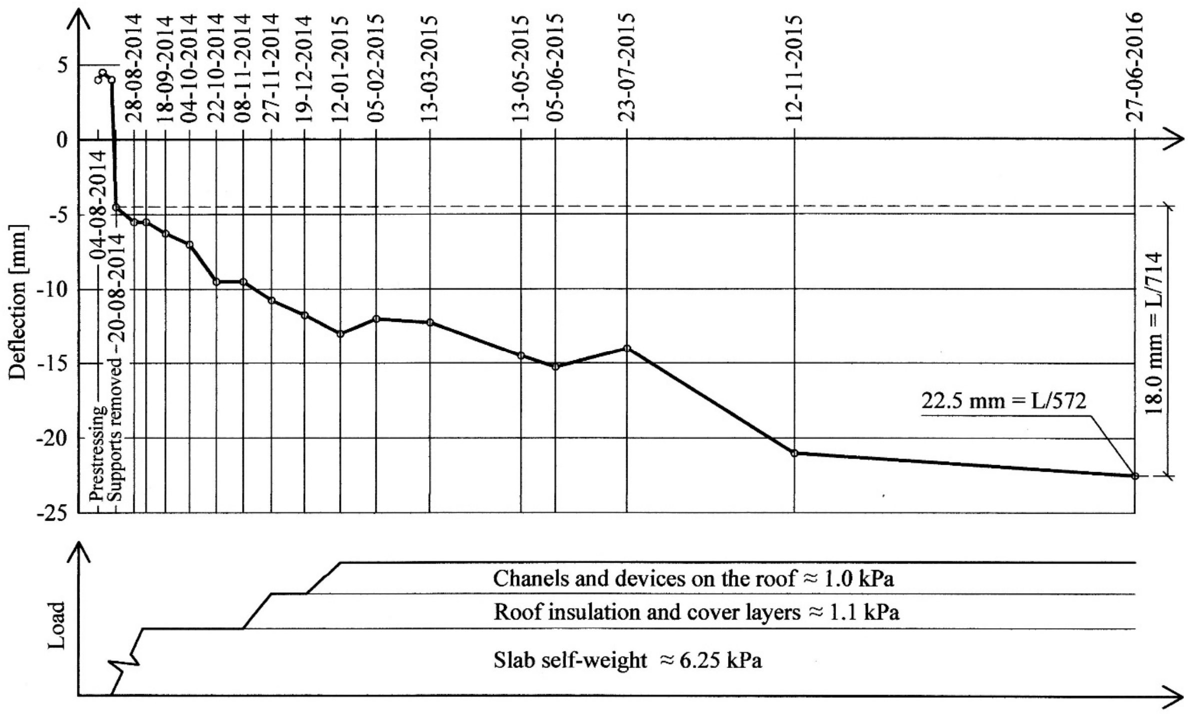

Figure 7. Deflection of roof panel Sl-2.

3. The large span slab in Busko-Zdrój Cultural Center building

In the current year the project of enlargement and modernization of the Self-Government Center of Culture in Busko-Zdrój was completed. The fact that there are many large rooms in this building, implied necessity of design of slender long-span prestressed slabs. The real challenge for the designers of the structure (the authors of this paper) was slab over the cinema-concert hall.

The axial plan of the room is 21.26×32.31m (figures 8a and 8c). Placing numerous sound system equipment and stage lighting below the ceiling, required construction of working platforms to support them (figure 8b). Legal regulations dictate the necessity of preserving space over such platforms with the height of 2.2m. This condition eliminated the traditional reinforced concrete slabs supported on reinforced beams or steel trusses. The challenge was to find solution allowing for design of slab as thin as possible that would not interfere with the hall space. As a result, the one-way post-tensioned slab with axial span equal to 21.26m and depth equal to 0.55m was designed. The achieved span to depth ratio is equal to 38.6. However, it should be noted that it is a one-way simply supported slab because the reinforced concrete walls with a width of 0.24m are only slight fixed supports.

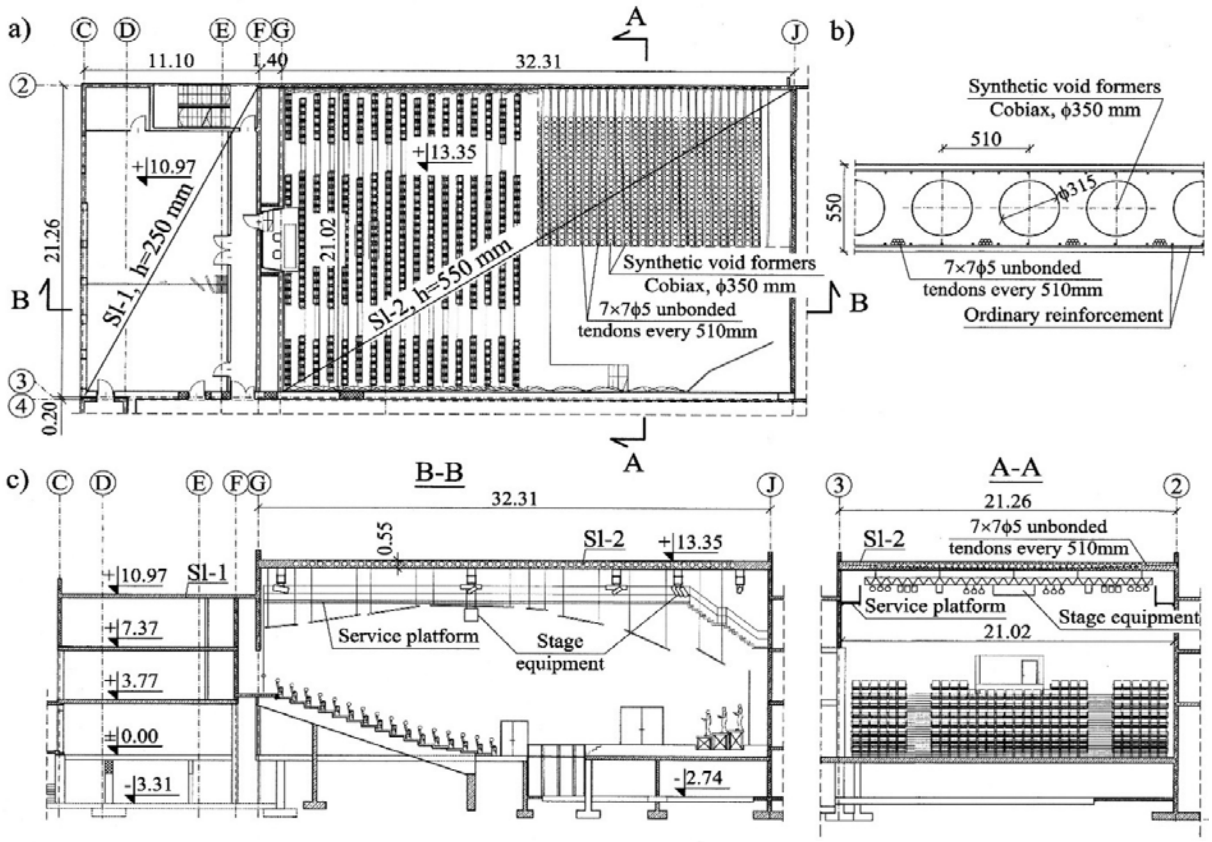

Figure 8. Post-tensioned long-span slab in Self-Government Center of Culture in Busko-Zdrój

The designers used the synthetic void formers of 350mm diameter, utilised as internal relief fillers. Between the rows of balls (figures 8a and 8b), at a spacing of 510 mm, seven-strands unbounded 7ϕ5 tendons were laid, with the profile as shown in figure 8c. Using the synthetic void formers decreased self-weight by 280kg/m^2 (20%), while the section modulus was decreased by 10%. This clever solution allowed for significant decrease of estimated deflection. However, the span to depth ratio is not impressive, the span length is still unprecedented. Though, results achieved during two-year observation of slabs in Kozienice, allow to conclude that this slab behaviour will be satisfying.

4. Conclusions

The following paper presents representative projects of realized and future designs of long span prestressed slabs. It has been proven, with regard to two-year monitoring behaviour of slabs constructed in Kozienice, that design of elements exceeding values recommended by dated guidelines, of span lengths and span to depth ratios is feasible. The conclusions that have been made, will allow for the construction of longer span and slenderer slabs than it was in the past. The authors will continue to successively observe effects of future long span prestressed slabs designs and report the findings in technical and scientific literature.

It can be noted that the research of possibility to use lightweight aggregate concrete in construction of long-span post-tensioned slabs has begun in Cracow University of Technology. It is commonly known that it is difficult to provide the desired concrete modulus of elasticity with this type of aggregate [12]. On the other hand, preliminary computational analysis carried out by the authors [13] indicate that important decrease of slab self-weight can lead to reduction of amount of prestressing or deflection in comparison with dense concrete of similar strength. The successful results from observation of full-scale post-tensioned slabs in laboratory tests may contribute to design and realisation of long-span post-tensioned slab with lightweight aggregate in buildings in the future.

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