IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

High Performance Concretes in Production of Pre-Tensioned Concrete Hollow-Core Slabs in Poland

High Performance Concretes in Production of Pre-Tensioned Concrete Hollow-Core Slabs in Poland

Marcin Dyba [1]

[1] Institute of Building Materials and Structures, Cracow University of Technology, Warszawska street 24, 31-155 Cracow, Poland

mdyba@pk.edu.pl

Abstract. Pre-tensioned concrete hollow core (HC) slabs have been used in construction for several decades. In Poland, industrial production has been carried out since the 1970's. Currently, due to the dynamic development of precast structures, these elements are gaining in popularity. The article describes the most important changes in the hollow core slabs fabrication technology in Poland within period of over 40 years. Modern elements have gained new features, high load capacity and high quality. The quality and repeatability of characteristics of the slabs is associated primarily with the use of new-generation concretes (with admixtures and additives). The paper describes and analyzes the most important differences related to the production of HC slabs currently, and the production from the 1970's and 1980's of the last century. The advantages and disadvantages of high performance concrete in the context of their application for production of hollow core slabs have been formulated and presented. The theoretical considerations were then extended by results of research carried out on full-scale elements. The analysis is supplemented with a calculation example of determining the bending capacity in commonly used cross-section of HC slab.

1. Prefabrication technology of prestressed concrete hollow core slabs

The first prestressed hollow core slabs were made in Germany in the 1940's. Then in the United States the technology was refined and patented under the name "Spancrete" [1]. Initially, the technology was based on concreting the section in a short form with a layered compaction of concrete.

In the 1950's, the first of two contemporary methods for the production of prestressed hollow core slabs – the slip-forming method – was created, and then in the early 1960's the second – the extrusion method. Both methods are used to create elements on long prestressing beds, without the need for any formwork.

The slip-forming method consists in concreting the cross-section in two stages. The concrete mix is cast first to the bottom flange, and then to the webs and top flange. Concrete compaction is performed by a set of vibrators working in a horizontal and vertical plane inside the forming machine. The drive of the forming machine causes its movement along the bed and shaping cross section of the element.

The extrusion method consists of extruding and compacting the concrete mix by a screw feeder (extruder). This method enables simultaneous concreting, compacting the mix and forming the entire cross-section of an element. The movement of the extruder (forming device) on the bed is caused by the force of inertia. The screw feeders, when forming and compacting the concrete mix, repel the extruder from the previously formed section of the element.

2. Development of production of pre-tensioned concrete hollow core slabs in Poland

In the 1960's, pre-tensioned concrete hollow core floor slabs were already widely used in building construction in most developed countries. In Poland, precast pre-tensioned hollow core "HC" slabs have been mass-produced since the late 1970's. The first experimental elements were made in 1974 in Warsaw, as part of an implementation research project [2]. Industrial production of the slabs by the extrusion method was launched in 1976 in Białe Błota (now Prefabet Białe-Błota SA). Initially, only slabs with a cross-section height of 265 mm [3] and spans up to 12 m were produced.

After a decline in interest in prefabricated structures in Poland at the end of the 1980's and in the 1990's, a continuous increase in the share of precast concrete in newly built facilities has been observed for several years now. Pre-tensioned concrete hollow core slabs are part of this trend and are increasingly being used [4]. Currently in Poland the offer of prefabrication plants includes slabs with cross-section height from 150 to 500 mm. Typical precast members have section heights of 150 (160 or 165), 200, 265, 320, 400 and 500 mm and spans up to 20 m.

3. Production technology

3.1. General requirements for concrete [5,6]

The production of pre-tensioned concrete hollow core slabs is possible mainly due to the use of concretes on concrete mix exhibiting strictly defined properties. The concrete mix must be sufficiently dense, and at the same time allow for tight compaction and cover of prestressed strands. Immediately after forming, it must be stable and able to maintain the geometry of the section without a use of formwork. Hardened concrete must have a good bond to the prestressing steel strands, high early strength, high modulus of elasticity and low rheological deformability.

3.2. Requirements for materials and elements in the past [2,7]

In the period of the Polish People's Republic, the production of "HC" slabs in Poland was strictly regulated, by state guidelines issued by "CEBET" [2, 7]. "The rules of production and use ..." were amended several times and supplemented. These guidelines defined requirements in the field of production technology, applied materials, values of tensile forces applied to tendons and diurnal production cycle. The first guidelines were issued in 1974 [2].

The concrete, or rather the concrete mix used to make the "HC" slabs must have characterized by:

- unchanging "semi-dry" consistency in a subsequent mix,
- tight aggregate pile, guaranteeing the rigidity of the mixture after it is formed by the machine,
- high early strength of concrete, as fast as possible.

The hollow core slabs could have been made of concrete with a guaranteed strength of 40 MPa (after the introduction of the standard [8] at least the class of 40 MPa). Aggregates crushed from igneous rocks and gravel aggregates up to 20 mm grains were allowed to be used for concrete. Concrete could be made only on Portland cement of the brand 450 and on rapid hardening cements. Prestressing was performed using 7ϕ4 mm strands and lower power from steel with a characteristic strength of at least 1700 MPa. The guidelines also defined the value of the tensioning force (for strands 7ϕ4 mm it was 102 kN). At the moment of releasing the tension, the concrete had to have a compressive strength of at least 32.5 MPa, defined on cylinder samples with a diameter of 16 cm and a height of 16 cm. In order to accelerate the process of maturation of concrete, the aggregates had to be heated, and the concrete mixture had to reach a temperature of ~25 °C. Beds after forming elements were to be heated for 8 ÷ 10 hours.

The guidelines also defined (besides material and technological requirements):

- number and location of strands in cross-section,
- typical lengths of precast members,
- principles of perforation (possible cuts) of precast members,
- storage rules for precast members,

- even organization of work of individual brigades of workers when forming elements in a 3-shift cycles (24/24 h).

3.3. Modern hollow core slabs fabrication in Poland

C50/60 class concrete and less frequently C40/50 is used in prefabrication of panels. The concrete mix is made on rinsed crushed aggregate from igneous rocks and gravel aggregate (for smaller cross-sections of hollow core slabs) with the largest grain size up to 8, 12 or 16 mm depending on the manufacturer. Aggregate is fractionated, heated and dried. The actual moisture content of the aggregate is monitored in silos and taken into account by the concrete mixing plant systems in calculating the necessary water consumption for each subsequent concrete mixing. CEM I and CEM II grade 42,5R, 52,5N and 52,5R cement are used. To improve the rheological properties of the concrete mix and the strength characteristics of concrete, usually chemical admixtures and mineral additives are used. Admixtures (plasticizers and superplasticizers) mainly based on polymers serve to limit the water-demand of cement and improve workability of the concrete mix. Mineral additives in the form of finely ground micro-fillers (fly ash, silica dust, etc.) are a substitute for cement (to reduce its consumption), as well as strengthen and seal the concrete matrix in the micro scale. Weighing, dosing and mixing of individual components takes place completely automatically within a strictly defined time. The actual needed water consumption for subsequent mixing is calculated individually for each mix, firstly based on the humidity of the aggregates in the bunkers, and then the humidity of the mix in the mixer. Thanks to maintaining conditions of constant temperature, humidity, recipe and quality of components, concrete has repeatable mechanical properties.

In order to prestress the slabs, seven-wire prestressing strands with the equivalent diameter most often ϕ12.5 mm and less frequently ϕ9.3, ϕ7.8 and ϕ6.9 mm, and others of steel Y1770 and Y1860 are used. Number of tendons in hollow core slab cross-section, a type of strands and values of tensioning forces are different depending on the manufacturer.

Nowadays producers are obliged to apply the requirements of the "Precast concrete - products - Hollow core slabs" standard [9], Eurocode 2 standard [10] and technical approvals as well as mandatory requirements in the area of factory production control /quality control.

A few steps of hollow core slabs production using the extrusion method are shown on photographs below. The photograph on figure 1 contains the face of the formed element on prestressing bed. The cutting lines and holes are marked immediately on the element after passing the forming machine. Then, before foil covering the elements for the time of maturation, openings are made (figure 2). These openings, which are not possible to made on the production line, are made later on building site or warehouse. When the concrete has obtained the required strength, the tension is released, and the element on the bed is cut into individual precast members (figure 3). Cutting the element on individual slabs is the last stage of production before the hollow core slabs are transported to a warehouse (finished product repository) or directly to a construction site.

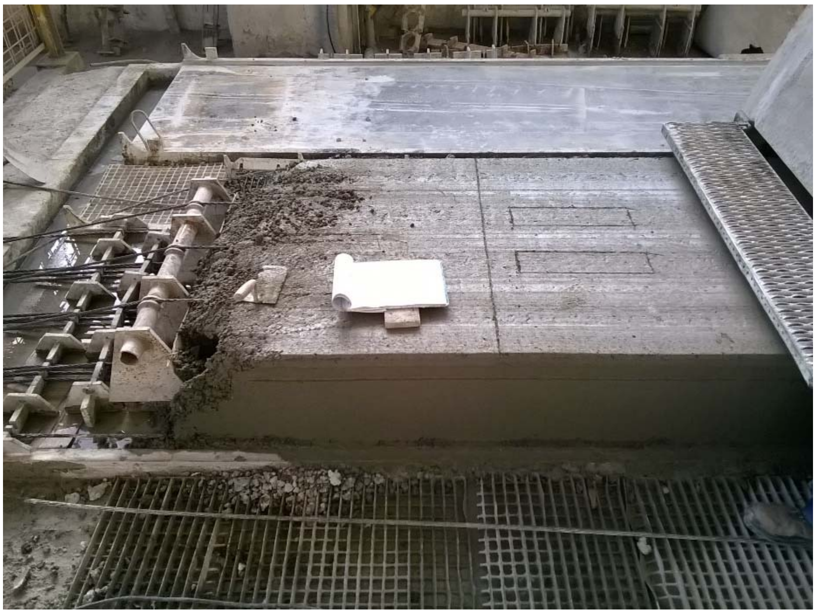

Figure 1. View of a moulded face of an element on a prestressing bed with a marking of the cutting line and technological openings

Figure 2. Making openings - "wet technology"

Figure 3. Face of a slab "HC 320" after cutting on a prestressing bed

Recent pre-tensioned concrete hollow core slabs are designed and manufactured for a specific building investment. Selection of length of the slabs, cross-section height, number and type of prestressing strands and fire resistance class is made for an individual project. Hollow core slab members delivered to the building have all cutouts and technological openings prepared.

4. Influence of modern concrete technology on hollow core slabs prefabrication

4.1. Load-bearing capacity of hollow core slab "HC 265" cross-section in the past and now

The geometry of cross-sections of pre-tensioned concrete hollow core slabs has not changed until today. In order to compare the bending capacity of the cross-section of hollow-core slabs "HC 265" produced in the 1980's and 90's with those produced now, analytical calculations were made. "HC 265" slabs are manufactured in Poland from the beginning of prefabrication of pre-tensioned concrete hollow core slabs, and at the same time were and are the most frequently used. Analyzed slab has a cross-section height (thickness) of 265 mm and a width of 1197 mm. In the cross-section there are 5 longitudinal holes (channels) running through the entire length of the elements. The cross section subjected to the analysis was prestressed with 6 seven-wire strands 7ϕ4 mm made of high strength steel (figure 6). The cross section bending capacity of the "old" slab cross-section was determined for the mechanical properties of B40 concrete (used in the 1980's and 90's), while the "new" was calculated for the C50/60 concrete (currently used).

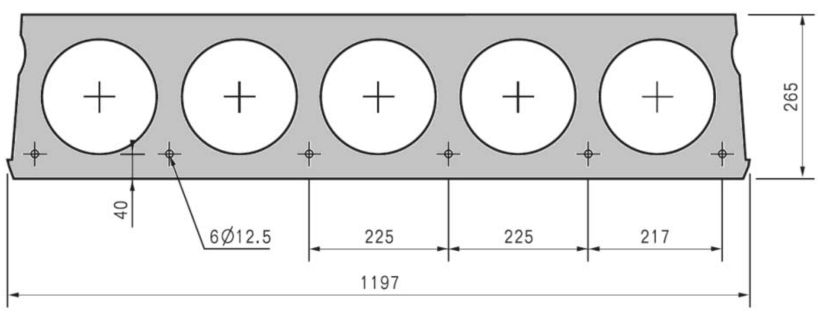

Figure 4. Cross-section of hollow core slab "HC 265"

Strength properties of B40 concrete were adopted for calculations based on the PN-84/B-03264 standard [8]. Strength properties of C50/60 concrete were adopted for calculations based on the Eurocode 2 standard [10].

Table 1. Mechanical properties of concrete for calculation

Parameter	Concrete B40 (1980's)	Concrete C50/60 (2018)
$f_{ck,cube}$ [MPa]	40	60
f_{ck} [MPa]	29.2	50
f_{cd} [MPa]	22.5	35.7

where:

- $f_{ck,cube}$ - characteristic compressive cube strength of concrete at 28 days,
- f_{ck} - characteristic compressive cylinder strength of concrete at 28 days,
- f_{cd} - design value of concrete compressive strength.

Geometric and mechanical features of prestressing steel and pre-tension stresses in steel were also adopted based on Eurocode 2 [10] for 3 types of prestressing steels: Y1770, Y1860 and Y2160.

- A_{p1} = 91,3 mm^2 (area of 1 prestressing 7ϕ4 mm strand),

The remaining coefficients were adopted according to Eurocode 2 standard [10]. The obtained results of calculations are given in table 2.

Table 2. Cross section bending capacity of hollow core slab "HC 265" (figure 4)

Stel	Concrete C50/60 (2018)
	M_{Rd} [kNm]
Y 1770	163.9
Y 1860	171.9
Y 2160	198.2

where:

- M_{Rd} - bending capacity of cross -section (design value).

In the technical design of hollow core pre-tensioned concrete slabs from 1978, the theoretical load-bearing capacity for bending of the cross-section of the "HC 265" slab with 6 strands (figure 4) was declared for the value of 153.98 kNm [7].

Increasing the compressive strength of concrete by 59 % (from 22.5 to 35.7 MPa) does not cause such a large increase in the load bearing capacity of the hollow core slab. For the analyzed pre-tensioned concrete slab, the increase in load capacity for bending of cross-section associated with an increase of concrete class is 6.4 % when using steel strands grade Y 1770, 11.2 % for steel grade Y 1860 and respectively 28.7 % for steel grade Y 2160.

4.2. Advantages of high performance concrete in production of "HC" slabs

The introduction of chemical admixtures to concrete mixes, while reducing the proportion of water, means that hollow core slabs currently produced have a very rapid increase in early concrete strength (50 ÷ 60 MPa after a dozen or so hours) and high 28-day strengths (even up to 90 ÷ 100 MPa depending on the used aggregate and manufacturer). The high compressive strengths of concrete do not translate into an adequate increase in the load-bearing capacity for bending of cross section, although they undoubtedly increase the load-bearing capacity of elements in the shear and support zone [11].

IOP Conf. Series: Materials Science and Engineering 471 (2019) 052085 doi:10.1088/1757-899X/471/5/052085

Figure 5. Measurement of strands slip on a forehead of “HC” slab

The use of modern high performance concretes (HPC) for production of pre-tensioned hollow core slabs has many advantages. High performance concrete mixes are characterized by very good workability and allow for proper compaction in the cross section of an element, without caverns. The distribution of the coarse aggregate is uniform in cross section of "HC" slab. Strands have good concrete-steel bond conditions. The contact zone is properly developed. High performance concretes have high bond stresses to prestressing steels [12, 13]. Thanks to that relatively small values of strand slip are recorded in modern hollow core slabs. Measurements rarely show values above 1 mm (only for small spacing and a large number of strands in one area). In the 1970,s, "HC" slabs were allowed to be installed even with slips up to 5 mm. High concrete-steel bond translates into a reduction in transmission length and an increase in the bearing capacity of the element in the shear zone. Automatic dosing and mixing systems, as well as continuous monitoring, make production very efficient and the number of defective elements is minimal. The use of high performance concretes and modern concrete technology allows very early release of strands tension on concrete of the elements.

4.3. Effect of concrete shrinkage on fabrication of hollow core slabs

The new generation of concretes, with additives and chemical admixtures, also show undesirable features from the point of view of prefabrication of pre-tensioned hollow core slabs. The use of superplasticizers changes the nature of concrete shrinkage and leads to a large shrinkage of concrete, in early adolescence, when the increase in strength is the greatest (figure 6).

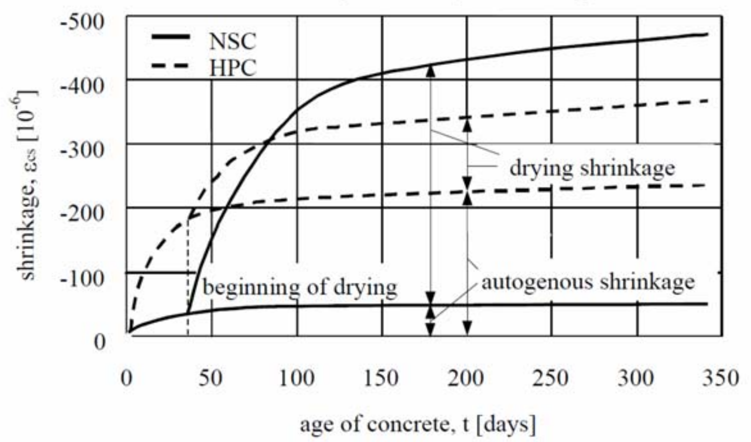

Figure 6. Shrinkage of high performance and normal concrete [14]

High performance concretes have a higher share of deformation caused by autogenous shrinkage in relation to that caused by drying in total shrinkage deformation of the concrete [14].

The large deformation of the autogenous shrinkage of concrete raised during maturing of concrete on prestressing bed can cause cracks and occur regardless of the care conditions (despite the proper care of the concrete and maintenance of the 100% humidity conditions). Cracks usually initiate in zones where the cross-section is weakened [15] – for example near to technological openings (figure 7). As long as normal concrete was used for production of hollow core slabs, ordinary concrete deformations from autogenous shrinkage were small and practically precluded the development of cracks as a result of this deformation.

Figure 7. Cracks caused by shrinkage

5. Summary and conclusions

The use of high performance concretes is reasonable for the production of hollow core slabs due to the special properties of these concretes and the high early concrete strengths that are crucial in prestressed concrete prefabrication. The increase of the concrete class (compressive strength) in the elements is unjustified – it does not affect the load capacity of the prefabricated cross-sections. Increasing the cross section load capacity for bending would be possible provided that the number of strands has been increased (but the geometry of the cross-section is limited) or the introduction of higher power strands.

Rheological characteristics of concrete mixes and the properties of new generation concretes differ from those described in EN 1992-1-1 [10]. Accepted parameters related to concrete-steel bond, transmission and anchorage length and, above all, shrinkage deformations (and especially shrinkage of young concrete) require further research. It is also very important the description of the proper rheological behavior of pre-tensioned concrete hollow core slab "HC" due to the widespread use of high-strength concretes with chemical admixtures and mineral additives.

For this reason, in 2016, as part of the scientific and research work at the Cracow University of Technology, experimental research on "HC" slabs was undertaken, including: development of mechanical and rheological features of currently used concretes for the production of "HC" slabs, transmission length in "HC" slabs, elastic and shrinkage deformation of concrete as well as their development in elements concreted on bed in the production stage, and rheological deformation of "HC" slabs.

IOP Conf. Series: Materials Science and Engineering 471 (2019) 052085 doi:10.1088/1757-899X/471/5/052085

References

[1] www.spancrete.com/, access: 06/2018.
[2] A. Słoniewski: „Principles of production and use of prestressed "HC" slabs formed by the extruding method (spiroll). Information on new technologies”. *Centralny Ośrodek Badawczo-Rozwojowy Przemysłu Betonów „CEBET”, Warsaw,* 1974 (in Polish).
[3] A. Łodo: „Pre-tensioned concrete - equipment, technologies, production possibilities, construction recommendations”. *XVII Ogólnopolska Konferencja Warsztat Pracy Projektanta Konstrukcji, Ustroń*, 2002 (in Polish).
[4] W. Derkowski and M. Surma : „Modern solutions for precast and prestressed concrete slabs”, *Builder may 2014*, pp 54-57, 2014 (in Polish).
[5] „Manual for design of hollow core slabs (second edition)”. *Precast/Prestressed Concrete Institute, Chicago*, 1998.
[6] M. Surma: „Shear capacity of prestressed hollow core slabs with concrete topping on flexible supports”. *PhD thesis. Cracow University of Technology*, 2017 (in Polish).
[7] J. Sikorski: „Prestressed "HC" floor slabs. Design and use of slabs”. *Centralny Ośrodek Badawczo-Projektowy Budownictwa Ogólnego, Warsaw*, 1978 (in Polish).
[8] „PN-84/B-03264. Plain, reinforced and prestressed concrete structures. Static calculations and design”. *Polski Komitet Normalizacji, Miar i Jakości, Warsaw*, 1984 (in Polish).
[9] „EN 1168. Precast concrete - products - Hollow core slabs”. *PKN, Warsaw,* 2011.
[10] „EN 1992-1-1. Eurocode 2. Design of concrete structures - part 1-1: General ryules and rules for buildings”. *European Committee for Standarization, Brussels*, 2004.
[11] A. Ajdukiewicz, A. Kliszczewicz and M. Węglorz: „Shear resistance of pretensioned hollow core slabs – test results vs standards”. *3rd International fib Congres, Maryland*, 2010.
[12] M. Dyba: „Influence of technological parameters on concrete-steel bond between high-performance concrete and prestressing strands”. *PhD thesis. Cracow University of Technology*, 2014 (in Polish).
[13] P. Dybeł and K. Furtak: „The analysis of the influence of the concrete slump on the bond high-performance concrete to reinforcement bars”, *Inżynieria i Budownictwo*, *year 70 (1/2014)*, pp 39-42, 2014 (in Polish).
[14] *„fip* Bulletin no 42. Constitutive modelling for high strength/high performance concrete*”. International Fedreation for Structural Concrete (fip), Lausanne*, 2008.
[15] W. Derkowski and M. Dyba: „Behaviour of End Zone of Pre-tensioned Concrete Elements”, *Procedia Engineering, vol. 193,* pp 19-26, 2017.