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Trends in the Polish research on high-performance concrete

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Abstract

This paper is of general nature. The main trends in the research on high- performance concrete (HPC) in Poland are presented and discussed. Some examples of the relevant investigations are given. The fundamental engineering and economical problems concerning the structural applications of HPC in Poland are presented as well as the needs justifying the increased use of this material are briefly described.

Keywords: Applications of HPC; High-performance concrete; Research on HPC in Poland; Polish experience in HPC

1. Introduction

It is known that high-performance concrete (HPC) is used in various structural applications not only because of its considerable high compressive strength but also because of other properties, like durability. According to Malier [1], a review of structures built worldwide up to 1990 revealed that the use of HPC would be economically justifiable in only 15–25% of them if high compressive strength were the only criterion. It seems to be also true at present. For instance, in the case of bridge structures, HPC is mainly used because of its high short-term strength and an evident improvement in durability compared with normal-strength concrete. The high short-term strength is especially important during erection of the structures because it allows more rapid execution. Some other profits resulting from the use of HPC in bridge engineering consist in reduction of the total concrete volume [2], reduction of the number of precast girders or increasing their span in composite bridges [3], compared with the application of normal concrete. The similar effects, especially improvement in the material and structural durability, can be observed in other structures, such as multi-storey or industrial buildings, sewage-treatment plants, tanks, silos, marine structures, etc.

Although the unit price of HPC is generally higher than that of normal strength concrete (usually from 15% to 25%), its use is in general economically profitable because of the above-mentioned effects.

However, it should be emphasized that HPC is also known to be more brittle than ordinary concrete. Therefore, it requires sometimes to be reinforced in a special manner in structural applications using traditional reinforcing bars and stirrups or, but relatively rarely so far, using fibre reinforcement, like for example in Japan, where carbon fibre has been used in bridge columns for retrofitting against seismic forces [4].

It should be also emphasized that in spite of some proposals presented in the recent period [5,6], a lack of standard or code recommendations fully sufficient to design the structures using HPC could be noticed. Concrete classes over 60 MPa were for a long time beyond the scope of the national and international standards or codes and design methodologies. Fortunately, the most important international standards have introduced finally these higher classes, e.g. Eurocode 2 ([7]) takes into consideration classes (f_{ck}) up to 90 MPa since 1999. The new Polish Standard (PN-B-03264:1999, approved in 2000) concerns concrete classes up to B70 ($f_{ck,cube}$).

As the general recommendations in this area are very fresh, therefore, prior to structural applications of HPC many experimental investigations have to be performed for the determination of both the material characteristics and the behaviour of the structural members under various types of loading. HPC has been extensively

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studied during the last decade in many countries, mainly in France, Germany, Japan, Norway, Canada and US. An evident growth of interest concerning HPC and its recent use in various types of structures can be also noticed in Poland, where the relevant investigations are carried out in several research and academic centres. It has been reflected among others in the special issues of the Polish engineering journals and increasing number of papers prepared for national and international conferences. The first Polish paper dealing with use of HS/HPC in structures was presented abroad in 1993 [8].

Despite some general presentations given in certain more of less official recommendations [9,10] the research on HPC requires to be performed in the individual countries. This is because of the lack or insufficient information on some material characteristics of HPC when local constituent materials are used for its production. Moreover, the economical analysis of the use of HPC should be performed in accordance to the domestic conditions.

The most important problems concerning the needs justifying the development of the research on HPC in Poland are synthetically presented below, mainly based on previous papers [11,12].

2. High-performance concrete in Polish civil engineering

2.1. Durability problem

In Poland the durability of many concrete structures has shown to be highly insufficient. It is illustrated by the concrete bridges, in which durability of structural material has been expected to be much higher than it has been found in reality. Nearly 20% of the total number of about 22,000 concrete highway bridges in Poland are structurally deficient and therefore have to be repaired or strengthened. This situation can be estimated as more or less similar to many other countries in the world, including highly developed ones. In some of them the situation is even more critical (e.g. over 40% of more than 577,000 highway bridges in the US have been classified as either structurally deficient or functionally obsolete [13]).

One of the most important reasons leading to the insufficient durability of concrete structures built in past years in Poland has been too low strength concrete used in many structural applications. For instance, in the relatively long period 1950–1980, concrete B15 (i.e. concrete with characteristic compressive cubic strength 15 MPa) to B25 have been usually used to construct reinforced concrete bridges. In the same time concrete B30–B40 has been used to erect prestressed concrete bridges or for precast structural members (mostly pretensioned ones). Moreover, too weak structural systems (especially the precast ones) and low quality of bridge accessories (e.g. expansion joints) as well as too poor maintenance programme additionally have affected the loss of the required bridge durability. However, the above-mentioned material factor has shown to be the decisive one in a great majority of cases.

Fortunately, in the last decade the standard requirements concerning concrete quality in bridge applications have become higher. For instance, according to the official Polish design Standard concrete with a minimum class of B30 and B35 should be used for reinforced concrete and prestressed concrete bridge superstructures, respectively.

2.2. Improvement in concrete quality

A considerable improvement in concrete quality in its bridge applications can be noticed in Poland in the past few years. For instance, the superstructure of the Border Bridge in Cieszyn, located between Poland and Czech Republic, 760 m long, completed in 1991 and constructed using incremental launching, is of concrete not less than B45. The superstructure of the motorway bridge over Vistula river near Torun (the central part of Poland), 955 m long with three central spans of 130 m, constructed using cast-in-place cantilever balance and completed in 1998, is of concrete not less than B50 (Fig. 3).

The tendency to apply HPC in Poland is demonstrated among others by the projects submitted in December 1996 for competition concerning a new bridge over Vistula river in Plock (Central Poland). From 14 projects, six concrete bridges of various structural systems have been proposed, i.e. two with the continuous box-girder structural system and four with cable- stayed structural system. In five of them, B60 concrete (i.e. the conventional lower limit of HPC) as a minimum has been proposed (Fig. 1).

More simple structural bridge system with application of HPC was introduced with good results few years earlier. The superstructure of the bridge in Chabowka (South of Poland), 267 m long, constructed by incremental launching and completed in October 1996, was made of concrete B60 with a total volume of about 1.600 m^3 (Fig. 2).

2.3. Material and economical problems

Generally, there are no major material obstacles in obtaining HPC in Poland. This problem has been presented and particularly analyzed elsewhere [14].

According to the economical analyses performed according to the Polish conditions [15], total cost of concrete works (i.e. concrete and labour together) in case of bridge structures can be generally estimated as 16% of the total construction cost. The material (i.e. concrete)

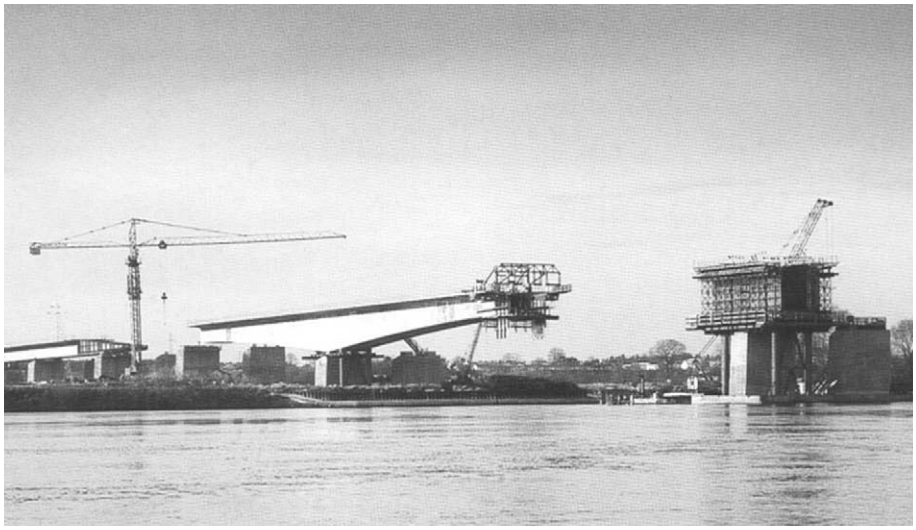

Fig. 1. Bridge over Vistula river near Torun under construction.

Fig. 2. Viaduct over railway trucks in Chabowka with superstructure from concrete class B60.

cost is 56% of the concrete work cost, i.e. about 9% of the total construction cost.

The economical comparison between concrete classes B40 and B60 performed in connection with the construction of a viaduct in Warsaw (208 m long, completed in 1992) has shown that the total unit cost of concrete B60, including transport and quality control costs, is only 16% higher [16]. According to an analysis performed in France, the unit cost of B60 concrete is about 25% higher than that of B35 concrete.

The above-cited data indicate that the use of B60 concrete in bridge structure instead of B40 concrete with the same volume, increases the total construction cost by only about 1.5–2.5%. Some other results indicate that the use of concrete up to B90 increases the total construction cost by about 3–5% compared to the use of B40 concrete with the same volume. Therefore, an evident improvement in the bridge durability can be not too costly.

Taking into account the other profits, first of all the reduction of the total concrete volume even by 20–30% depending on the bridge type, the use of HPC in bridge structures is economically justifiable.

The economical profits resulting from the use of HPC instead of normal strength concrete are also evident in many other structures, as mentioned previously.

2.4. Further potential structural application of HPC

The growth of the Polish economy in the last decade leads also to the development of various domains of civil engineering. For instance, the most important task for bridge engineering in Poland in the near future is the construction of a number of bridges in connection with the Project of Motorway Construction. This project also includes three new Trans-European Motorways: A1 (North–South: Helsinki–Lodz–Budapest), A2 (West–East: Berlin–Warsaw–Moscow) and A4 (West–East: Berlin–Cracow–Lvov) with a total length of about 2000 km, which should be constructed by the year 2010. It also requires more than 500 bridges with a total length of more than 35 km (excluding approach structures) and about 1600 culverts.

The basic criteria for designing the motorway bridge structures have been defined as durability, minimum maintenance cost and structural solutions enabling easy inspection and easy replacement of bearings, expansion joints, etc. The use of HPC is one of the most effective ways to reach high durability of bridges, as well as pavements, and minimize the maintenance costs, including the repair works. It is expected that a great majority of motorway bridges will be constructed using B60 concrete as a minimum. It is endorsed by some new projects under construction.

3. Review of Polish research on HPC

3.1. Research fields

The needs presented in the previous section require the extensive investigations of HPC. The Polish research on this material is at present more advanced than its structural applications. Such situation is similar to that observed in many other countries. It results mainly from an insufficient knowledge on the properties of HPC and its behaviour in structures subjected to actions of various types, such as external loads, thermal effects, shrinkage and creep, interaction with the steel reinforcement, etc. The main fields of the Polish research seem to be in accordance with the world's ones and can be classified in the following groups:

- testing technique,
- research on mix design,
- testing on the mechanical characteristics,
- research on freezing and thawing resistance,
- research on hydration and thermal effects,
- research on bond strength between steel reinforcement and concrete,
- research on structural applications,
- strength tests on structural members subjected to various types of loading.

These research fields are briefly illustrated below by some chosen investigations performed in Poland in the recent years.

3.2. Testing technique

High compressive strength and brittle behaviour of HPC provide some experimental difficulties to determine the strength with sufficient accuracy. Moreover, the tendency to get some uniformity in the determination of compressive strength can be noticed since the period of 1988–1990. The most extensive research concerning standardization of the relevant testing technique have been performed in France [17], where the concrete specimens with "sand-box" capping have been applied.

The extensive comparative tests have been also performed in Poland [18]. It has been found experimentally and theoretically that the sand-box-capping method assures much more uniform distribution of the load on the upper and lower planes of cylindrical specimens and eliminates the influence of local imperfections of these planes. Statistical distribution of results of specimens testing is significantly more concentrated versus other methods of specimens preparation.

The sand-box-capping method seems to be universal because it may be successfully used for testing concrete with a very wide range of the compressive strengths – from the normal strength to the very high one. Therefore, this method of testing for cylindrical specimens ($\varnothing 150 \times 300$ mm) has been introduced in the main research centres. It should be mentioned that cylindrical specimens have been established as a basis for concrete classification by new Polish Standard (PN-B-03264:1999), correlated with Eurocode 2 [7].

3.3. Research on mix design

Many technological research works in this area are focused on studying the influence of aggregates, admixtures and additives and other factors on the properties of HPC, including its workability and the early compressive strength. Domestic and imported products have been taken into account as well as optimization of HPC using various constituent materials and additives.

Among others, an analytical model for concrete mix design has been developed and verified experimentally for HPC with the compressive strength ranging from 60 to 100 MPa [19]. Concrete mix design of 36 MPa strength after one day has also been studied using commercially available constituent materials and admixtures and conventional technique [20].

The effects of superplasticizers and silica fume on workability of HPC have been also studied and presented by other authors [21]. The results showed that workability of HPC depends on the dose, time of introducing and origin of superplasticizer and the amount of silica fume. An increase of the dosage of superplasticizer, retardation of its introducing into the concrete mix and presence of silica fume significantly improves the workability.

3.4. Testing of the mechanical characteristics

Design of structures with use of HPC requires assumptions of some fundamental material characteristics. For instance, it is necessary to assume the realistic values of modulus of elasticity (E_c) and the Poisson's ratio (v_c). The knowledge of the Poisson's ratio is especially important when any two-dimensional problems require to be solved, e.g. in the design of bridge deck slabs.

The study on deformability of normal strength concrete versus HPC, as well as on values of E_c determined according to the various national and international standard recommendations has been performed and verified by the original experiments [22]. The series of concrete with a compressive strength from 35 to 90 MPa have been tested.

It has been found that the ultimate deformation of concrete with granite aggregate is relatively high (more than 0.003) compared to concrete with basalt aggregate (0.0025) and rounded, quartzite aggregate (about 0.0022). The values of ultimate strains corresponding to the maximum stress values are similar for each group of concrete irrespective of their strength. This observation is contradictory to some previous research indicating that the deformability of concrete decreases with an increase of the compressive strength of the material. However, the deformability evidently depends on the kind of aggregate used [23].

Moreover, it has been found that the values of correction coefficients for determination of the modulus of elasticity (E_c) given in CEB-FIP MC90 recommendations and summarized by Neville [24] are somewhat different in case of aggregates available in Poland. For instance, especially evident differences concern the granite aggregates: the correction coefficient based on the tests performed in Canada and US is equal to 1.08 [24], while the coefficient resulting from the tests performed in Poland varies from 0.83 (for HPC) to 0.87 (for normal-strength concrete) [23].

It should be emphasized that the values of Poisson's ratio given in standards, codes and other recommendations show to be also different. For instance, in CEB-FIP MC 90 the values from 0.1 to 0.2 are given, while in FIP-CEB Report (1990) the values from 0.18 to 0.24 are recommended for HPC. The value 0.2 is given in Eurocode 2 as well as in the Polish Standard. It should be also noticed that the experiments concerning the Poisson's ratio for HPC are not sufficiently developed as yet. The tests have shown that the values of Poisson's ratio evidently depend on the kind of aggregate irrespective on the material compressive strength [23].

All the above test results indicate that two fundamental material properties, i.e. modulus of elasticity and Poisson's ratio, decisive for deformability of concrete, depend not only on its compressive strength but also on other factors, mainly on the kind of aggregate. Therefore, the standard recommendations can be considered as highly approximate, especially in relation to HCP. It can be noticed that the greater strength of concrete, the greater differences in values of E_c and v_c for similar concrete classes but from various aggregates can be observed. Therefore, in spite of some general formulae given in more or less official design regulations, especially in international ones, it seems to be necessary to consider and examine the properties of HPC made with the use of local material.

3.5. Freezing and thawing resistance, sorptivity

One of the most important characteristics of concrete, especially in its bridge applications is the freezing and thawing resistance of the material. This material property mainly influences also the structural durability. The relevant studies of this problem have been performed in several research centres in Poland.

For instance, in research [25] B70 and B90 concretes have been subjected to freezing and thawing cycles according to ASTM C 666 (A-method, freezing in water) and the Polish Standard (similar to ASTM B-method, freezing in the air) procedures. Two groups of HPC specimens have been tested – with and without air entrainment process. The test results have shown, among others, that the air entrainment does not evidently improve the freeze resistance of HPC irrespective of the freezing and thawing procedure applied. Summarized decrements of strength, as a result of air entrainment and freezing/thawing processing are much greater for air-entrained specimens, particularly in case of tests according to ASTM method (Fig. 3).

In research [26], concrete mixes containing silica fume in the amount of 0%, 5%, 10% and 15% as cement replacement have been tested. The influence of silica fume on the concrete sorptivity (Fig. 4), water and chloride permeability, freeze resistance under simultaneous action of frost and deicing salts has been examined. It has been shown that the addition of silica fume in the amount of 5% considerably improves all of the above-mentioned material properties, but the optimal improvement has been observed in case of 10% silica fume addition.

On the other hand, however, it should be noticed that in spite of its high strength, HPC shows sometimes relatively low frost resistance. Silica fume in HPC is not sufficient to attain its high frost resistance when other

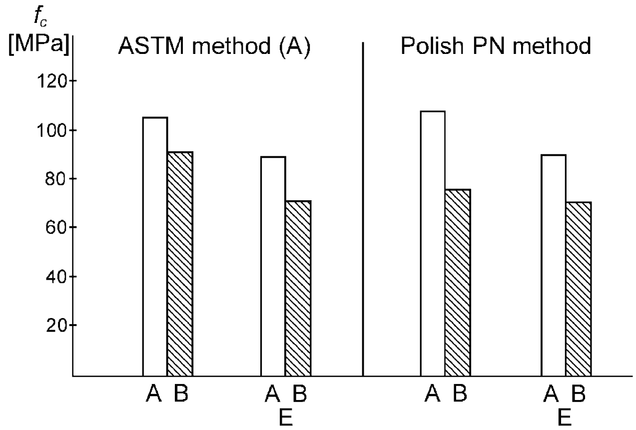

Fig. 3. Decrement of compressive strength due to freezing/thawing 300 cycles for air-entrained and not-entrained concrete. A: accompanying specimens. B: freezed/thawed specimens. E: air-entrained concrete.

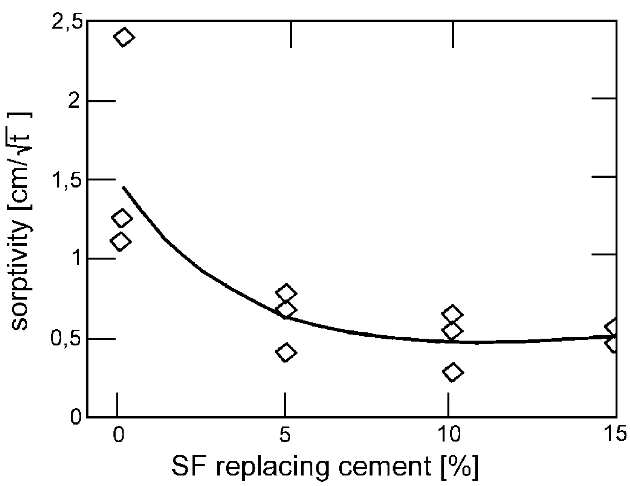

Fig. 4. Influence of silica fume content on water sorptivity of concrete.

conditions concerning mainly w/c ratio and air entrainment are not met.

Relationship between w/c ratio in HPC and its frost resistance has been also tested in Poland in connection with the bridge applications of the material [27]. The tests have been performed according to ASTM C 666 (A) procedure on HPC with various contents of silica fume, however, the air entrainment process has not been used. It has been found that irrespective whether silica fume is added to concrete or not, the required freezing and thawing resistance of the material can be attained when $w/c < 0.37$. When $w/c > 0.37$, silica fume does not probably improve this resistance – such a concrete requires the use of air entrainment to be frost resistant. In case of HPC this process is rather difficult and may decrease its high strength. It has been also pointed out that $w/(c + \mathrm{SF})$ ratio seems to be not an appropriate parameter to design and assess the frost resistance of HPC. This is because the same value of $w/(c + \mathrm{SF})$ ratio may correspond to the concrete with different value of w/c ratio, i.e. higher or lower than 0.37. However, $w/(c + \mathrm{SF})$ ratio can be applied to design HPC with respect to its strength instead of traditional w/c ratio.

3.6. Research on hydration and thermal effects

The thermal stresses caused by self heating of concrete resulting from exothermic process of cement hydration is a significant problem when designing and constructing various structures, especially massive ones. Many investigations have been performed for normal strength concrete, whereas it is not sufficiently recognized as yet in HPC.

Increased amount of cement and the presence of silica fume in high-performance concrete causes thermal effects that are of prime interest. Research has been performed over the last several years with the use of special equipment to provide the adiabatic conditions of hardening [28].

Among others, it has been found that there is a certain relationship between the hydration progress, expressed by the amount of emitted hydration heat and the development of mechanical properties of HPC hardening in various thermal conditions. The investigations have also shown that heat evaluation depends strongly on the initial temperature, i.e. 10°C, 25°C and 35°C, corresponding to the summer and autumn conditions of concrete placing in Poland. These effects are radically different from those observed in the normal strength concrete. Therefore, relations concerning these concretes should be verified in case of HPC. Moreover, the presence of fly ash added to the concrete mix reduces the amount of heat and initial concrete strength. However, after seven days of curing, the strength of concrete with fly ash is approximately the same as that of concrete without fly ash. Tests have been carried out using all the components, except superplasticizer, from Poland.

3.7. Bond strength

Bond between concrete and steel reinforcement belongs to the most important factors in structural applications of HPC. A comparative study has been performed in Poland using concrete classes B30 and B90 [29].

Investigations have been carried out on ribbed bars subjected to axial pulling out at anchorage equal to five bar diameters. It has been found experimentally and theoretically that the model of bond concerning normal-strength and HPC is somewhat different. The most important findings are that the anchorage length of the reinforcing bars should not be reduced proportionally to the increase of concrete compressive strength and that the influence of the form of bar ribbing on the limit value of bond is smaller in HPC than in normal strength one.

3.8. Research on structure of hardened concrete

This research consists mainly in finding a relationship between mechanical properties of concrete and its structural characteristics. The relevant research has been also performed in Poland [30]. On the basis of testing of seven mixes with water to binder ratios from 0.52 to 0.32 (B50–B90 classes), a numerical model to predict strength development of normal and high-performance concrete has been formulated. As a basic structural parameter in this model the porosity factor was used. A good correlation between numerical and experimental data has been obtained when using the general formula

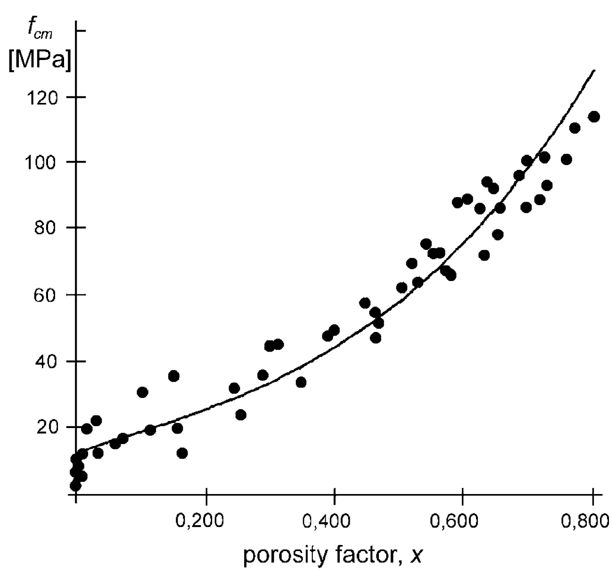

Fig. 5. Relation between compressive strength and porosity factor for HPC (70–90 MPa).

$$f_c = f_0 x^a \exp[b(1 - x)],$$

where f_c is the actual compressive strength at the considered stage of development of concrete microstructure, f_0 the theoretical compressive strength when $x = 1$ (i.e. hardened gel only), x the porosity factor,

$$x = \frac{\varpi_{gel}}{\varpi_{gel} + \varpi_{capilar} + \varpi_{air}},$$

$\varpi_{gel}, \varpi_{capilar}, \varpi_{air}$ the volumes of gel, capillary and air pores, respectively, and a, b are the parameters experimentally determined for each concrete mix.

The illustration of this relation for HPC with similar basic mix but with different porosity presents Fig. 5. In this case the main parameters were as follows: $f_0 = 225.2$ MPa; $a = 0.074; b = -2.546$, and resulted coefficient or regression $r = 0.966$.

3.9. Testing of structural members

Strength tests on HPC structural members performed so far in Poland concern mostly beams and columns subjected to various types of loading.

For instance, the tests of columns 3.0 m long, with cross-section 140×250 mm, made of B90 concrete to verify the original analytical CEB-FIB MC90 formulae concerning stress–strain relation have been successfully tested [31].

Other example concerns the tests of composite slab-column connections with the use of concrete up to B70 [32]. In slab-column structures, the part of slab in the vicinity of column is in general the most stressed. Therefore, a structure composed from head and column joint into one precast member from HPC and normal-strength concrete slab has been proposed for framework of multi-storey buildings. This idea can be also useful in some structural systems of bridge structures [33]. The tests have been performed on the models with slab depth

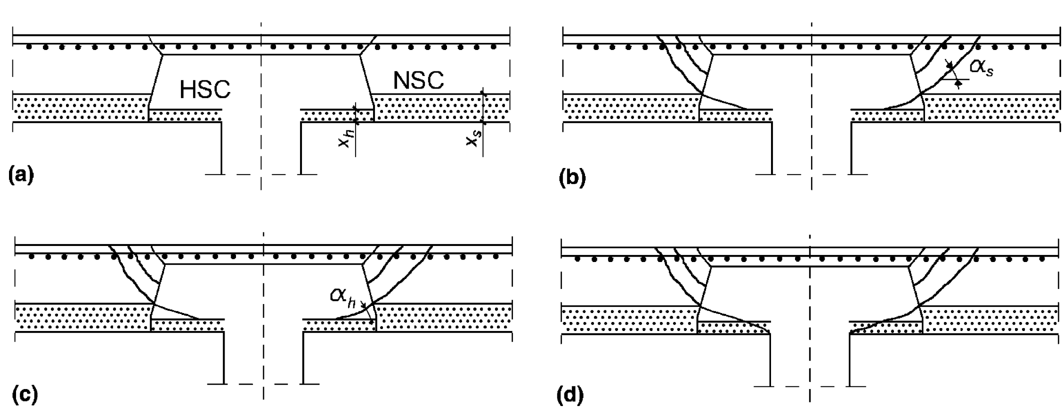

Fig. 6. Composite joints in flat-plate structures (with precast HPC head- and-column members and monolithic slab). Simplified phases of behaviour under loading up to failure: (a) first circumferential crack running to the edge of head, (b) development of further cracks, (c) first phase of punching failure – rotation and creation of crack in the head, (d) second and final phases of failure.

of 260 mm, head diameter of 600–1200 mm and column diameter of 250 mm. The tests have shown a specific two-stage mechanism of failure of the slab-column structure (Fig. 6). The differences between the failure modes of the normal strength concrete and HPC members have been determined. The failure model became a basis for the relevant design methodology.

Reinforced concrete beams made of normal strength concrete B35 and HPC of B70 subjected to combined torsion and bending up to failure have been also tested in Poland [34]. It has been found, among others, that the torsional stiffness of the beams in their span zone does not depend on the quality of concrete, but in the support zone, the loss of the stiffness depending on the concrete quality can be observed due to the shear effects. It has been also found that deformations of concrete and steel reinforcement under the same load level are evidently smaller in the beams made of B70 concrete than in the beams made of B35 concrete. Moreover, the test results indicate that the failure mechanism of the beams made of B70 and B35 concrete is significantly different. In case of B70 concrete, the strains in the stirrups at the beam failure correspond to almost the yield point of the steel and they are a decisive factor, while in case of B35 beams the failure of concrete and the stirrups is almost simultaneous. Corresponding calculations performed according to Eurocode 2 using strut-and-tie models have revealed that there is a serious difference between calculated and observed angle of inclination of compressed concrete struts (about 30° and 45°, respectively).

4. Concluding remarks

(a) There are no severe material or technological obstacles to produce and develop HPC in Poland. The need to improve durability of concrete structures, especially bridges, endorses technically and economically the wider use of HPC.

(b) Research on HPC prior to its structural application is at present intensively performed in Poland. Fundamental research on HPC is also being performed. The main fields of the Polish research seem to be in accordance with the world's trends.

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