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Evaluation of the Development of Bond Strength between Two Concrete Layers

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Abstract. This paper provides an analysis of the development of bond strength in composite members of the concrete-to-concrete type. The experimental study was performed to evaluate the development of the bond strength between two concrete layers. In the study, two different types of concrete were used – normal concrete (NC) and high-performance concrete (HPC). Composite specimens of the substrate and overlay were of the NC-HPC and HPC-HPC types and reference NC-NC specimens were also made. The analysis of the bond strength was performed on composite cubes of size 150x150x150 mm which were subjected to splitting tension tests after 3, 7, 14 and 28 days of curing of the concrete overlay. The results of the study show that the basic phenomenon which affects bond strength is adhesion between concrete layers which develops with curing of the concrete overlay. The highest increase in the value of tensile bond strength was observed in the first 3 days of curing of the composite specimens. In this period the NC-NC composite reaches 53% of its 28-day tensile bond strength, the NC-HPC specimen - 67% and the HPC-HPC - 74%. The experiments showed different modes of interface failure depending on the configuration type of concrete in composite specimens. In the case of composite specimens NC-NC and HPC-HPC the observed dominant interface failure mode occurred within the overlay transition zone. For the NC-HPC specimens, the interface failure mode was observed both in the overlay transition zone and in substrate made of NC. No changes in the modes of bond mechanism failure were observed during curing of the composite specimens. The results obtained were compared with the existing studies in the literature on bond strength in composite concrete members.

1. Introduction

The optimal use of material properties as well as the reduction of undesirable material behaviour lies at the basis of construction material research. This approach allows for an increase in possible application areas and an economic use of the materials. The vast majority of construction elements require combining the merits of different materials in order to increase effectiveness. Composite materials present such an advantage and, particularly, composite members of the concrete-to-concrete type. This type of composite is made by connecting two materials of the same type.

In the last few years, the principal interest in concrete composite research lies in connecting normal concrete with a new generation concrete. This type of concrete is increasingly substituting regular concrete. Composite structures which use both normal concrete (NC) and high-performance concrete (HPC) have the advantages of both materials. During construction, HPC is used in places where elements require reinforcement [9]. This significantly reduces costs as opposed to making use of HPC in the entire construction. Further, high-performance concrete is also used to prepare construction elements for increased loading or for the repair of damaged sites in existing elements [4, 5].

The purpose of using composite members of the concrete-to-concrete type is to ensure the best load transfer. The principal factor which determines the composite strength is the adhesion between concrete layers. This is significant not only in existing construction elements but also in the realization phases where the fresh concrete hasn't reached its full strength yet. Despite numerous research in concrete composites [1-11], few data is available regarding the bond strength and the development of the concrete-to-concrete bond in high-performance concrete. In this study, two types of concrete are used: NC and HPC. Composite specimens of the substrate and overlay of type NC-HPC, HPC-HPC and reference NC-NC were made. The obtained results were compared with the existing literature on the study of bond strength in composite concrete members.

2. Bond between concrete layers

The physico-chemical phenomena which occur at the interface of two materials and which lead to the mutual bonding of the materials, is called adhesion. The force required to separate such two materials is a measure of adhesion. In composite structures, three basic factors contribute to the bond strength: the natural adhesion, friction between concrete layers and the use of reinforcements [10]. Natural adhesion is the result of physico-chemical phenomena occurring at the interface of two materials. Natural adhesion can be further classified as mechanical or specific. Mechanical adhesion occurs when glue penetrates into the irregularities of the surface which creates a bond. In the case of concrete the role of glue is taken by the cement paste of the overlay. The second type of adhesion is specific adhesion, which includes adsorption phenomena (chemical bonding, hydrogen bonds, Van der Waal forces), electrostatics and diffusions.

In the case of two concrete layers the greatest significance is attributed to mechanical adhesion related to the penetration of the cement paste of overlay as well as adsorption. The chemical content of both connected elements is either the same or very similar. Interparticulate forces act from the moment the fresh mixture comes in contact with the existing concrete element. This phenomenon facilitates the penetration of the cement paste of overlay into the pores and irregularities of the concrete substrate. Further, as concrete hardens, chemical reactions occur between the components of the fresh mixture and the unhydrated cement in the concrete substrate. The phenomena which occur at the interface of the concrete composite are similar to the phenomena observed in the bonding of the aggregates with the cement matrix [1, 10]. At the interface between the composite concrete an inter-phase transition zone is formed. In this zone due to higher water content, hydration of the cement grains occurs. As a result of this process empty spaces are formed in place of the grains and hydration products migrate to the intergranular space. Depending on the additives used this zone is characterized by a smaller or larger porosity. In the pores form pockets of portlandite or crystallized ettringite fragments fibers. In the transition zone along with the "wall effect" in the concrete overlay a weaker layer is formed, through which the failure plane of the composite element should run. In the case of high-performance concrete the reduction of the water cement ratio, the use of superplasticizers and especially micro fillers causes a significant reduction in the thickness and porosity of the transition layer and causes its phase content to resemble the cement paste in the cement matrix. The properties of HPC presented herein result in a superior adhesion between the cement matrix containing silica fumes and the substrate for composite structures of the concrete-to-concrete type [6].

3. Experimental procedure

The goal of the experiment was to assess the increase of strength of composite elements of the concrete-to-concrete type (determined by bond strength) during curing of the concrete overlay. As part of the experiment composite concrete specimens without reinforcement at the interface were prepared. Composite specimens, of the substrate and overlay of type NC-HPC and HPC-HPC as well as reference NC-NC were produced. Tests were performed after the substrate concrete cured for 28 days. The analysis of the bond strength was performed on composite cubes of size 150x150x150 mm which were subjected to splitting tension tests after 3, 7, 14 and 28 days of curing of the concrete overlay. For each of the four curing stages the bond strength was determined. In parallel to bond strength experiments, the increase in strength of the reference samples was monitored through compression and splitting tensile tests in accordance to standards [14, 15]. This methodology allows for a direct comparison of the bond strength and the strength of the concrete overlay at every stage of curing.

3.1. Concrete mixtures

In the study two different types of concrete were used, normal concrete (NC) and high performance concrete (HPC). The water/cement ratio used for the NC concrete mixture was 0.45 whereas for the HPC mixture water/binder ratio was 0.32. The consistency of the concrete mixtures used in these experiments were of class S4 [16]. Table 1 shows the composition of the concrete mixtures.

Table 1. Composition by mass of proposed mixes

Composition [kg/m^3]	Recipe denotation	
	NC	HPC
Cement CEM and 32.5R	375	−
Cement CEM and 42.5R	−	455
Water	170	160
Sand 0/2 mm	645	668
Gravel 2/8 mm	555	−
Gravel 8/16 mm	645	−
Basalt aggregate 2/8 mm	−	1240
Silica fume (SF)	−	45
Superplasticizer (PCE)	−	4.05
Water/binder ratio	0.45	0.32

3.2. Test methods

The experiments were performed on composite cubic samples of dimensions 150x150x150 mm. The composite samples were produced in two steps. At first, styrofoam was placed in the forms followed by the concrete substrate. After 28 days of curing in laboratory conditions at a temperature of 20°C and a relative humidity of 95%, the contact surfaces were prepared. The surfaces were cleansed from loose fragments as well as cement grout and their roughness was increased. The contact surfaces were prepared with a rotary steel brush. This type of surface is qualified as a smooth surface according to MC2010 [12] and EC2 [13]. The model of the specimen and the substrate surface are shown in Figure 1. Before pouring the concrete overlay water was applied to the surfaces every time. The samples were secured and constantly overseen.

The analysis of the bond strength was performed on composite samples through splitting tension tests. The procedure was performed in accordance with the standard [14]. The interface between the concrete substrate and overlay was vertically oriented and in the direction of the applied forces (Figure 1). Tensile bond strength was calculated in the way as for the splitting tension according to the following formula:

$$f_{ct} = \frac{2 \cdot F}{\pi \cdot L \cdot d} \tag{1}$$

f_{ct} - splitting tensile strength, [MPa];
F - maximum load, [N];
L - length of contact line, [mm];
d - cross section size, [mm].

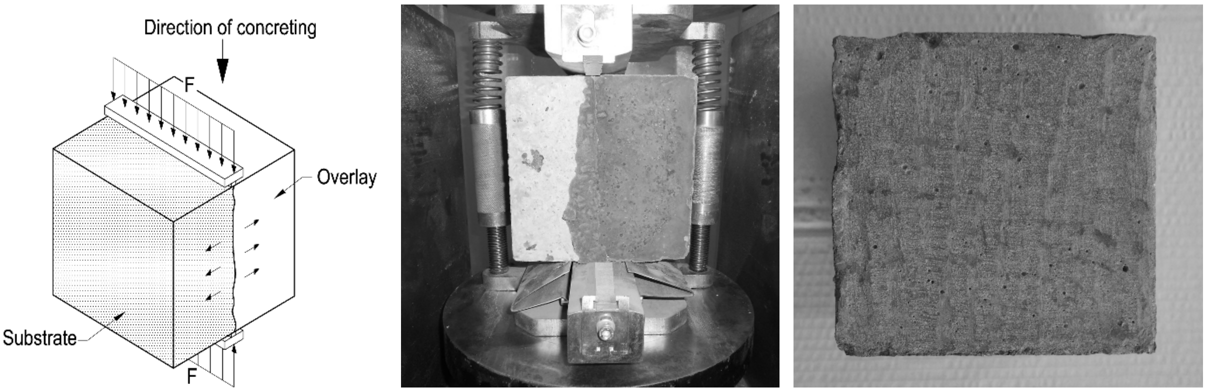

Figure 1. Model of specimen used in tests of tensile bond strength and substrate surface prepared with steel brush

4. Results and Discussion

The results of the experiments are shown in Table 2. The average contact strength values were determined in experiments conducted on 10 samples. The average compressive and tensile strength values of the reference samples were determined on 5 samples. To further study the bonding properties, a coefficient of bond effectiveness (α) as well as a relative increment of bond strength (β) were calculated:

$$\alpha = \frac{\tau_{b(i)}}{f_{ctm(i)}} \tag{2}$$

$\tau_{b(i)}$ - average bond strength of the composite sample, [MPa];
$f_{ctm(i)}$ - average splitting tensile strength of the overlay concrete, [MPa].

$$\beta = \frac{\tau_{b(i)}}{\tau_{b(28)}} \tag{3}$$

$\tau_{b(i)}$ - average bond strength of the composite sample after 3, 7, 14 days, [MPa];
$\tau_{b(28)}$ - average bond strength of the composite sample after 28 days, [MPa].

Figure 2 shows the development of tensile bond strength and splitting tensile strength. The development of strength for both these cases is similar although they represent different range of strengths. The greatest bonding strength was noted for the composite samples at day 28 of curing. For the HPC-HPC specimens, the strength value was 2.66 MPa, for the NC-HPC specimens it corresponded to 2.13 MPa and for the NC-NC, the strength value equaled 1.89 MPa. The values of splitting tensile strength for the monolithic HPC and NC concrete overlay were significantly higher, that is, 5.12 MPa and 3.13 MPa. It must be noted, however, that the bonding strength values are strongly dependent on surface preparation [7, 8]. Such considerations, however, are outside the scope of this study.

Table 2. Results of the experiments

Series	Curing period of the composite specimens	The strength of concrete at the time of test of composite specimens								Tensile bond strength		Coefficients	
		Substrate				Overlay							
		f_{cm} [MPa]	Cov [%]	f_{ctm} [MPa]	Cov [%]	f_{cm} [MPa]	Cov [%]	f_{ctm} [MPa]	Cov [%]	τ_b [MPa]	Cov [%]	α	β
NC-NC	3	**37.1**	3.5	**2.98**	8.7	**23.1**	7.1	**2.28**	8.9	**1.01**	11.2	**0.44**	**0.53**
	7	**38.7**	2.1	**2.74**	4.3	**31.2**	5.4	**2.74**	7.1	**1.31**	8.6	**0.48**	**0.69**
	14	**38.6**	1.4	**3.04**	10.7	**34.7**	3.5	**2.89**	10.7	**1.66**	9.2	**0.57**	**0.88**
	28	**39.7**	3.5	**3.18**	6.7	**39.8**	5.1	**3.13**	6.2	**1.89**	12.4	**0.60**	**1.00**
NC-HPC	3	**37.1**	3.5	**2.98**	8.7	**58.3**	2.7	**3.83**	5.9	**1.42**	8.7	**0.62**	**0.67**
	7	**38.7**	2.1	**2.74**	4.3	**72.4**	3.1	**4.33**	9.4	**1.72**	10.9	**0.63**	**0.81**
	14	**38.6**	1.4	**3.04**	10.7	**86.5**	4.2	**4.65**	11.4	**1.92**	13.4	**0.66**	**0.90**
	28	**39.7**	3.5	**3.18**	6.7	**90.5**	2.4	**5.12**	3.9	**2.13**	7.3	**0.68**	**1.00**
HPC-HPC	3	**89.1**	3.5	**5.24**	10.1	**58.3**	2.7	**3.83**	5.9	**1.97**	6.1	**0.51**	**0.74**
	7	**90.3**	5.5	**5.15**	15.6	**72.4**	3.1	**4.33**	9.4	**2.44**	7.4	**0.56**	**0.92**
	14	**91.7**	4.9	**5.39**	7.3	**86.5**	4.2	**4.65**	11.4	**2.54**	6.9	**0.55**	**0.95**
	28	**92.1**	4.6	**5.25**	5.4	**90.5**	2.4	**5.12**	3.9	**2.66**	5.5	**0.52**	**1.00**

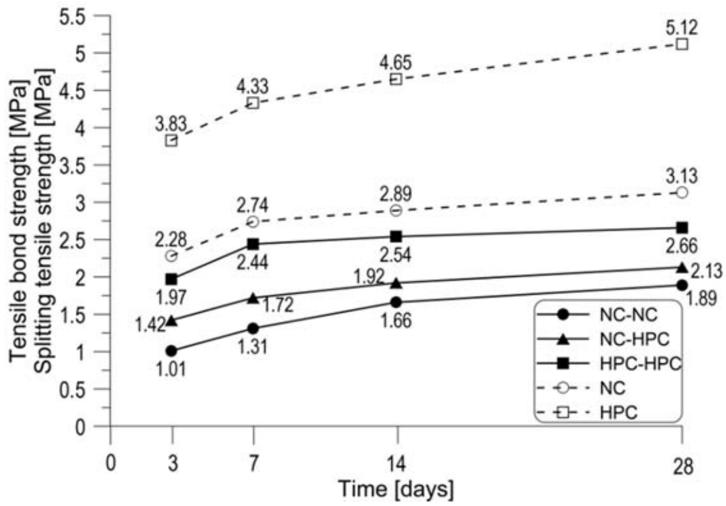

Figure 2. Tensile bond strength and splitting tensile strength development

A comparison of the relative increase of bond strength was possible for the different concrete types. In the first three days, the NC-NC composite reaches 53.4% of the 28-day bond strength. For the NC-HPC specimens, this value is 67.0% and for the HPC-HP, the strength reaches 74.1%. Between days 3 and 7, the increase in bond strength was similar, and its value varied from 15.9% to 18.8%. A growth slowness can be observed in the increase of the bonding strength between 7 and 14 days for the HC-HPC and HPC-HPC type of 9.4% and 3.8% respectively. For the NC-NC specimens, however, a further increase to 18.5% can be observed during the same period. After day 14 of curing, for all three composites, a small relative increase in the bond strength of the concrete occurs. The greatest increase of the value of bond strength occurs at the same time as the greatest increase of the splitting tensile strength for the concrete overlay which occurred after 3 days of curing. As can be seen from Figure 3, the relative increase of bond strength of specimens of type HPC-HPC and NC-HPC is similar to the relative increase of the splitting tensile strength. For the NC-NC reference specimens, a slight delay in the development of bond strength with respect to the development of tensile strength of the concrete overlay can be observed. The use of silica fume additives creates a uniform mixture irrespectively of the distance to the surface. The morphology of the C-S-H phase, which contains silica fume, also affects surface adhesion to the concrete substrate. Experiments show that a change of the contact boundary of the concrete composites is visible already within a few days.

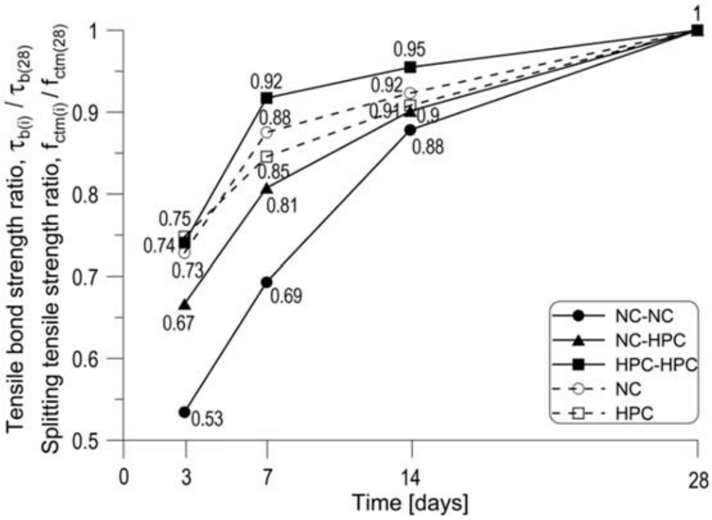

Figure 3. Relative development of increment of tensile bond strength and splitting tensile strength.

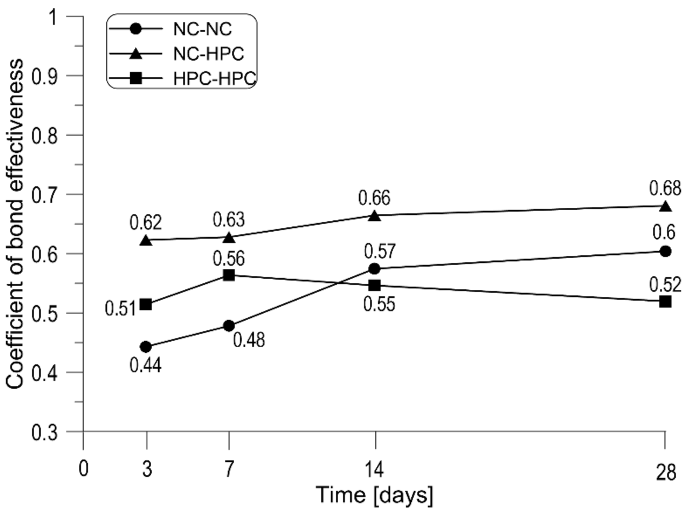

Figure 4. Coefficient of bond effectiveness development.

For all types of composite specimens, no significant changes were observed in the coefficient of bond effectiveness with respect to curing time (Figure 4). The reason for this is that the development of bond strength and splitting tensile strength with time is similar. The greatest bond effectiveness was noted for the NC-HPC specimens.

The failure of all composite samples occurred through interface failure. An example of failure is shown in Figure 5. The dominant, i.e., most common, interface failure mode was observed to occur within the overlay transition zone (OTZ). This type of interface failure was characterised by a thin layer of the overlay added to the old concrete substrate. Therefore, failure occurred principally in the micro-concrete material. For NC-HPC specimens the interface failure mode was observed both in the overlay transition zone and in substrate made of NC. This indicates a strong adhesion of the matrix HPC (which contains silica fume) to the concrete substrate. The observed failure mode is related to the physico-chemical action of the silica fume which cause a reduction in thickness and porosity of the transition layer and causes its phase content to be similar to the matrix. No changes in the modes of bond mechanism failure were observed during curing of the composite specimens.

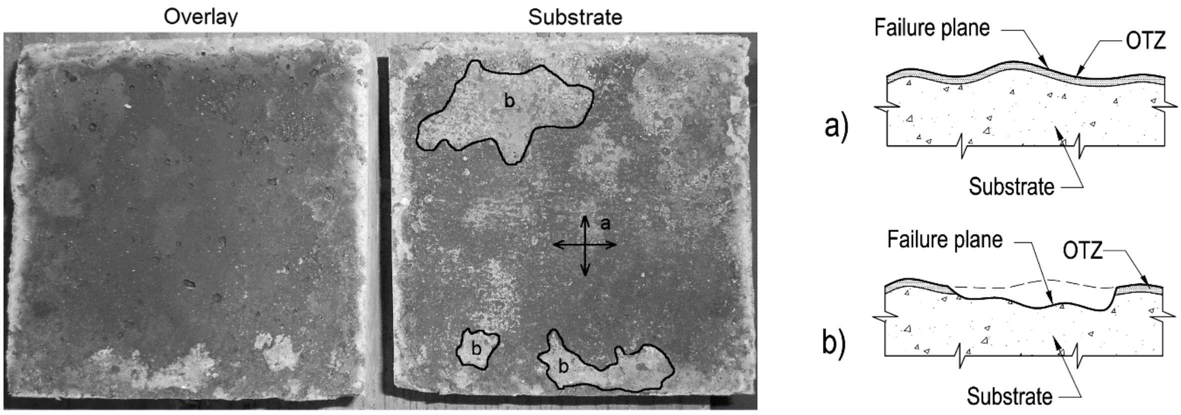

Figure 5. Failure modes detected in the tested specimens type NC-HPC under splitting tension

5. Conclusions

Based on the experiments pertaining to the development of bond strength in composite members of the concrete-to-concrete type, the following conclusions can be drawn:

- The results of the study show that the principal phenomenon which affects bond strength is adhesion between concrete layers which develops with curing of the concrete overlay.
- The greatest increase in the value of bond strength was observed in the first 3 days of curing. In this period the HPC-HPC composite reached 74% of the 28-day bond strength, the NC-HPC specimen - 67% and the NC-NC - 53%.
- The relative increment in bond strength of composites HPC-HPC and NC-HPC is similar to the relative increment in the splitting tensile strength of overlay concrete. In the case of composite NC-NC, such behaviour was not observed.
- The greatest bond strength were noted on day 28 of curing: for composite HPC-HPC - 2.66 MPa, for NC-HPC - 2.13 MPa and for composite NC-NC - 1.89 MPa.
- The experiments showed different modes of interface failure depending on the configuration type of concrete in composite specimens. In the case of composite specimens NC-NC and HPC-HPC the observed dominant interface failure mode occurred within the overlay transition zone. For NC-HPC specimens the interface failure mode was observed both in the overlay transition zone and in substrate made of NC.
- No changes in the modes of bond mechanism failure were observed during curing of the composite specimens.

References

[1] H. Beushausen, M. G. Alexander, "Bond strength development between concretes of different ages", *Magazine of Concrete Research*, vol. 60 (1), pp. 65–74, 2008.
[2] P. M. D. Santos, E. N. B. S. Júlio, "Interface Shear Transfer on Composite Concrete Members", *ACI Structural Journal*, vol. 111 (1), pp. 113–122, 2014.
[3] H. Aysha, K. R. Ramsundar, M. Arun, and G. Velrajkumar, "An Overwiev of Interface Behaviour between Concrete to Concrete", *International Journal of Advanced Structures and*

Geotechnical Engineering, vol. 3 (2), pp. 110–114, 2014.
[4] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Yen Lei Voo, "Evaluation of Bond Strength between Normal Concrete Substrate and Ultra High Performance Fiber Concrete as a Repair Material", *Procedia Engineering*, vol. 54, pp. 554–563, 2013.
[5] B. A. Tayeh, et al., "The role of silica fume in the adhesion of concrete restoration systems", *Advanced Materials Research*, vol. 626, pp. 265-269, 2013.
[6] M. Mohammadi, R. Moghtadaei, and N. Samani, "Influence of silica fume and metakaolin with two different types of interfacial adhesives on the bond strength of repaired concrete", *Construction and Building Materials*, vol. 51, pp. 141-150, 2014.
[7] E. N. B. S. Júlio, F. A. B. Branco, and V. D. Silva, "Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface", *Construction and Building Materials*, vol. 18 (9), pp. 675–681, 2004.
[8] D. S. Santos, P. M. D. Santos, and D. Dias-da-Costa, "Effect of surface preparation and bonding agent on the concrete-to-concrete interface strength", *Construction and Building Materials*, vol. 37, pp. 102–110, 2012.
[9] B. Sadowska-Buraczewska, A. Łapko, „The concept of strengthening of compressive zone in RC beams using HPC-HSC", *Proc. of the 9th International Conference: Modern building materials, structures and techniques*, pp. 752-757, 2007.
[10] A. Halicka, „A study of the stress–strain state in the interface and support zones of composite structures with shrinkable and expansive concretes. Lublin: *Publications of Lublin University of Technology*; 2007.
[11] A. Halicka, D. Franczak, „The effect of the age of concrete on the load capacity of the joint in "concrete-concrete" combined elements", *Przegląd Budowlany*, vol. 1, pp. 46–51, 2012.
[12] FIB (Fédération Internationale du Béton), Bulletin No. 65: Model Code 2010 – Final Draft Volume 1. FIB, Lausanne, Switzerland, 2012.
[13] EN 1992-1-1, Eurocode 2 – Design of Concrete Structures – Part 1: General Rules and Rules for Buildings, European Committee for Standardization, Brussels, Belgium, 2004.
[14] EN 12390-6, Testing Hardened Concrete – Part 6: Tensile Splitting Strength of Test Specimens, European Committee for Standardization, Brussels, Belgium, 2004.
[15] EN 12390-3, Testing Hardened Concrete – Part 3: Compressive Strength of Test Specimens, European Committee for Standardization, Brussels, Belgium, 2009.
[16] EN 12350-2, Testing Fresh Concrete – Part 2: Slump Test, European Committee for Standardization, Brussels, Belgium, 2009.