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# Development of Bond Strength of Reinforcement Steel in New Generation Concretes

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**Abstract.** The paper presents an experimental investigation of the steel-to-concrete bond using a pull-out test. Namely, the development of bond strength of reinforcement steel in new generation concretes was investigated. In the tests high-performance self-compacting (HPSCC) and vibrationally consolidated concretes (HPC), with the same water-to-binder ratio and made of components with the same properties, were used. For comparison purposes, the normal concrete was also used. For each concrete used in the experiment, a compressive strength development test was performed. To assess the development of bond strength in the tests, cubic specimens with the dimensions 160x160x160 mm were used. In each test element, ribbed reinforcing bar with a diameter of 16 mm was embedded in. Two variants of orientation of reinforcing bars with respect to the direction of concreting were considered - perpendicular and parallel. Test results showed that the development of bond strength between steel rebars and concrete increases with the increasing age. Additionally, the bond strength between steel rebars and concrete escalated with the increasing concrete strength. However, the development of bond stress with age was faster than the development of compressive strength, especially at early test ages. No significant difference was noticed between HPC and HPSCC mixes in terms of bond or compressive strength development with age. The conducted studies showed that in new generation concretes as well as in normal concretes the rebars placed parallel to the direction of concreting obtained higher values of the bond strength in comparison to rebars placed perpendicularly. This behaviour was observed in all stages of bond development.

## 1. Introduction

The new generation of concrete, including high-performance self-compacting concrete (HPSCC) which unites characteristics of high-performance concrete (HPC) and self-compacting concrete (SCC), allows constructors to build more durable structures at lower cost. Rheological properties of fresh mixture such as flowability, segregation resistance and passing ability and high compressive strength of hardened concrete are the most important features of HPSCC. To obtain desired parameters, the mix of that new generation concrete should contain particular components. The most important are increased amount of the Portland cement, the new generation superplasticizer and the mineral additives such as silica fume or fly ash [1-3]. Mixes with lower water-to-cement ratio are known to generate larger autogenous shrinkage [4-7]. Cracking is especially crucial in terms of new generation concrete as it is commonly used in the aggressive environments. Reinforcement is found to be the most efficient way to limit cracking width. Determination of cracking width is linked to early age bond behaviour between reinforcing bars and concrete [8-10]. As for normal and high strength concrete, some research has been



made in this case [8-12]. However, the development of the bond strength between HPSCC and steel is still a remaining concern.

The concept of concrete as a construction material is based on a fundamental aspect, namely bond phenomenon between reinforcement steel and concrete. Bond behaviour is commonly known to be affected by the strength of concrete and by the quality of fresh mixture. Moreover, for early age concrete the bond strength increases with the development of the cement hydration process, so does the compressive strength [12]. The development of bond strength is determined by other aspects such as thickness of concrete cover or bar diameter.

## 2. Previous research

The vast majority of literature covering the topic of bond, focuses on the influence of various factors and other aspects, such as the bond failure or the top-bar effect or the bond stress-slip correlation. All these studies were performed on the mature concrete. While tests on early age concrete (under 28 days) are still in the minority. This paper examines the development of the bond strength in new generation concretes in early age state.

In early 90s, bond strength at the age of 1, 3, 7 and 28 days was investigated [8], with conclusions that bond strength increases with age of concrete. The phenomenon is clearer in the first 3 days of curing. Another study [9] was conducted on deformed rebars using pull-out tests and similar deduction was observed on influence of concrete age. The increase in bond strength with aging of concrete was also viewed in the examination of normal concrete with compressive strength up to 35.67 MPa at the age of 1, 3, 5, 7, 14, 21 and 28 days [10]. Tests on high strength concrete (HPC) were conducted at the age of 1, 3, 5, 7, 14 and 28 days [11]. What is worth mentioning is that it was performed only on one concrete mixture, which contained fly ash. The specimens used to assess the bond strength, with dimensions 160x160x160 mm with embedded rebar of 16 mm in diameter, meet the requirements of RILEM [13]. Apart from the same influence of aging on bond phenomenon, the bond strength increased more than the compressive strength. Another experiment on early age development of bond was comparing the behaviour of SCC and NC [14]. No significant difference in development of bond was noticed between both concretes. The development of bond in both types of concrete was considerably faster up to first 7 days of curing and then slowly rose as the concrete matured. Although, the bond strength at the day: 3, 7, 14 and 28 was a bit higher in SCC specimens than in ones made of conventionally vibrated concrete. On the first day after casting, no difference in the steel-concrete bond was detected between both concretes due to its incomplete development. The difference in normalized bond stress in SCC and NC was more noticeable in the top bars. In comparison to another study on SCC [15], that resulted in much bigger difference between bond strength in SCC and NC. This finding is explained by a better quality of the specimens made of self-compacting concrete.

Lack of information regarding bond behaviour in HPSCC motivated the authors of this paper to investigate the development of the bond phenomenon.

## 3. Experimental program

Conducted studies aimed at evaluating the development of the steel-to-concrete bond as concrete matures. Specimens for “pull-out” test used in experimental program were prepared in accordance with normative guidelines [13, 16]. The examination of bond strength was conducted at the 1, 3, 7, 14 and 28 days of the concrete curing. Simultaneously to the bond test, the development of the compressive strength of the cubic specimens was investigated as defined in the norm guidelines [17]. Performed experiment has shown a direct correlation between the development of bond strength and the development of compressive strength.

### 3.1. Concrete mixtures and reinforcement steel

Three types of concrete mixes were used in an experimental program – normal concrete (NC), high-performance concrete (HPC) and high-performance self-compacting concrete (HPSCC). The mixes of HPC and HPSCC had both binder content (500 kg/m<sup>3</sup>) and water-to-binder ratio (w/b=0.32) fixed.

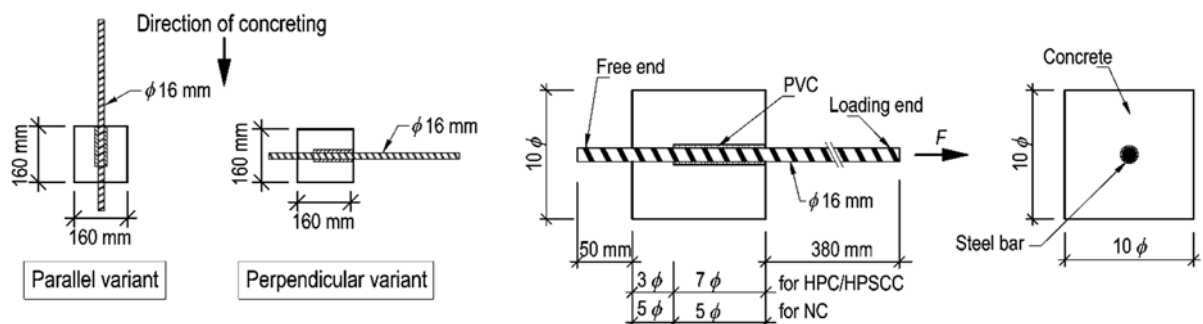
Ingredients of the same properties were used. The normal concrete was treated as reference. The compositions of concrete mixes used in the experiment are given in table 1. The consistency of vibrationally consolidated concrete mixes – NC and HPC – was determined through slump test [18]. As for the self-compacting mix, the consistency was examined by slump-flow test [19]. Neither segregation nor bleeding was noticed in the mix of HPSCC. Moreover, the HPSCC has met the criteria of slump-flow class – SF2 – and viscosity class – VS2. The mixes of NC and HPC were made in S4 class of consistency. The bond tests were performed for ribbed reinforcing bars (B500SP). A bar diameter of 16 mm, representative of the so-called mean diameters (10-20 mm), was used [16].

**Table 1.** Composition by mass of proposed mixes

Composition [kg/m <sup>3</sup> ]	Recipe denotation		
	NC	HPC	HPSCC
Cement CEM I 32.5R	375	—	—
Cement CEM I 42.5R	—	455	455
Water	170	160	160
Sand 0/2 mm	645	668	840
Gravel 2/8 mm	555	—	—
Gravel 8/16 mm	645	—	—
Basalt aggregate 2/8 mm	—	1240	990
Silica fume	—	45	45
Superplasticizer	—	4.05	6.15
Water/binder ratio	0.45	0.32	0.32

### 3.2. Testing of specimens

Experiments were performed on specimens with dimensions that meet the requirements of EN 10080:2005 [16] and RILEM [13]. Test specimens were made as a cubic element with dimensions: 160x160x160 mm with a reinforcing bar (16 mm in diameter) centrally embedded in. The orientation of the rebar was considered in two variants – parallel and perpendicular to the direction of casting. Figure 1 shows the schematic view of the test specimen. Subsequently, the produced specimens were left for 3 days in a formwork. After formwork stripping, the samples were kept in the laboratory in unchanged positions. Before tests, the samples were protected against vibrations and were constantly cared for through water sprinkling. For each concrete mix, 30 specimens for bond strength testing and 15 specimens for the determination of compressive strength were casted.



**Figure 1.** Schematic illustration of test element

### 3.3. Test methods

The bond strength examination was conducted using pull-out test in accordance to EN 10080:2005 [16] and RILEM [13]. The bond strength is calculated assuming a uniform distribution of bond stress along the bond length. It is determined from the ultimate pull-out load using equation (1):

$$\tau_{\max} = \frac{F}{\pi \phi l} \quad (1)$$

where  $F$ ,  $\phi$  and  $l$  stand for the applied load, diameter of reinforcing bar and bond section length, respectively. The bond section length was adopted as  $3\phi$  for HPC and HPSCC, and  $5\phi$  for normal concrete in presented study. The pull-out load was gradually applied until it reached the ultimate bond stress. Two linear variable displacement transducers (LVDT) took the measurement of the slip of unloaded end of the bar. A data acquisition system was used.

#### 4. Results and discussion

The bond stress – slip correlations ( $\tau-s$ ) obtained in the experiment are presented in figure 2. Table 2 shows the results from the performed tests. Mean values of ultimate bond stresses, as well as mean compressive strength at the examined age, were assessed based on the results of test conducted each time on three specimens. Furthermore, for the purpose of the visualisation of bond development, the bond efficiency ratio ( $\alpha$ ) and relative bond strength increase ( $\beta$ ) were determined.

$$\alpha = \frac{\tau_{\max(t)}}{\sqrt{f_{cm(t)}}} \quad (2)$$

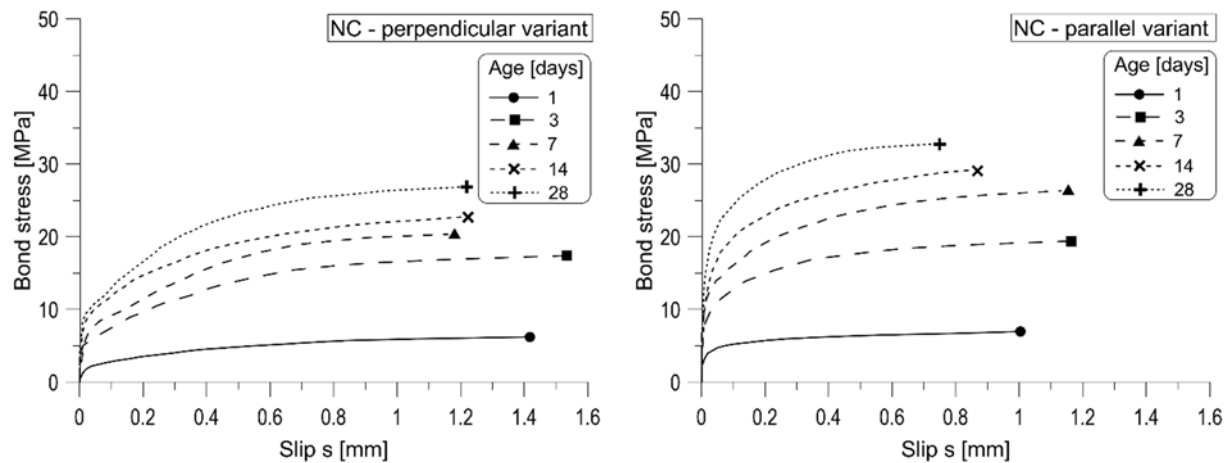
$\tau_{\max(t)}$  - mean bond stress, [MPa],

$f_{cm(t)}$  - mean compressive strength, [MPa].

$$\beta = \frac{\tau_{\max(t)}}{\tau_{\max(28)}} \quad (3)$$

$\tau_{\max(t)}$  - mean bond stress during 1, 3, 7 and 14 days of casting [MPa],

$\tau_{\max(28)}$  - mean bond stress during 28 days of casting, [MPa].



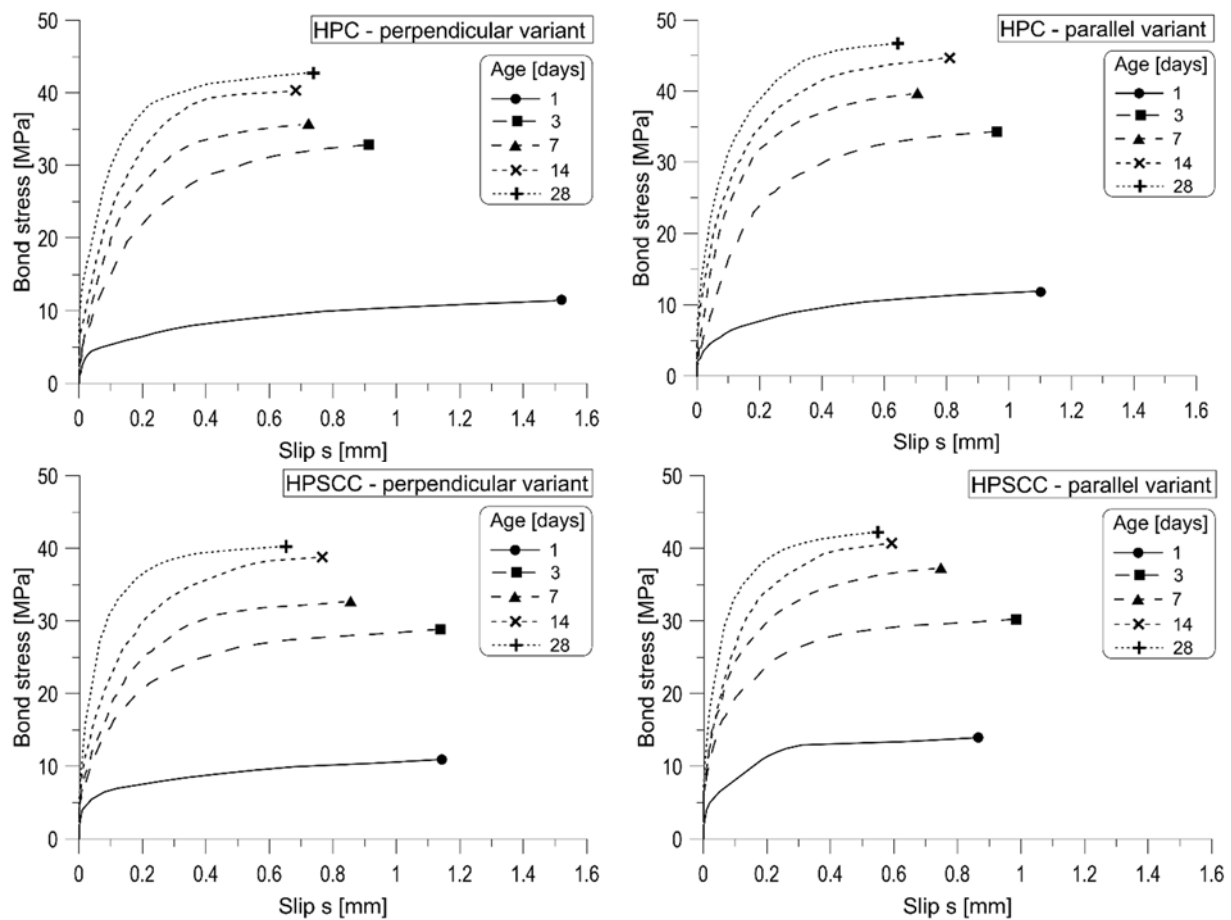


Figure 2. Bond stress – slip relationship

Table 2. The results of conducted studies

Type of concrete	Curing period of the specimens	Compressive strength		Bond strength				Coefficients			
				Perpendicular		Parallel		Perpendicular		Parallel	
		$f_{cm}$ [MPa]	Cov [%]	$\tau_{max}$ [MPa]	Cov [%]	$\tau_{max}$ [MPa]	Cov [%]	$\alpha$	$\beta$	$\alpha$	B
NC	1	6.7	5.1	6.2	7.7	7.0	10.1	2.4	0.25	2.7	0.21
	3	19.4	3.5	17.4	9.8	19.4	4.2	4.0	0.69	4.4	0.59
	7	25.7	3.1	20.4	4.9	26.4	7.9	4.0	0.80	5.2	0.80
	14	33.9	2.6	22.9	11.7	29.3	9.5	3.9	0.90	5.0	0.89
	28	38.4	3.7	25.4	7.1	32.8	7.1	4.1	1.00	5.3	1.00
HPC	1	18.9	6.5	11.4	6.3	11.9	8.7	2.6	0.27	2.7	0.26
	3	48.3	4.5	32.8	8.3	34.3	7.2	4.7	0.77	4.9	0.73
	7	71.1	3.1	35.8	4.3	39.8	5.1	4.2	0.84	4.7	0.85
	14	81.3	1.8	40.3	9.7	44.8	4.8	4.5	0.94	5.0	0.96
	28	88.9	3.1	42.8	8.1	46.8	7.4	4.5	1.00	5.0	1.00
HPSCC	1	20.6	3.5	10.9	10.1	13.9	8.7	2.4	0.27	3.1	0.33
	3	50.3	5.5	28.8	10.3	30.3	3.7	4.1	0.72	4.3	0.72
	7	68.1	3.5	32.8	9.6	37.3	6.1	4.0	0.81	4.5	0.88
	14	78.3	4.7	38.8	4.9	40.8	5.6	4.4	0.96	4.6	0.96
	28	86.2	5.9	40.3	7.4	42.3	3.4	4.3	1.00	4.6	1.00

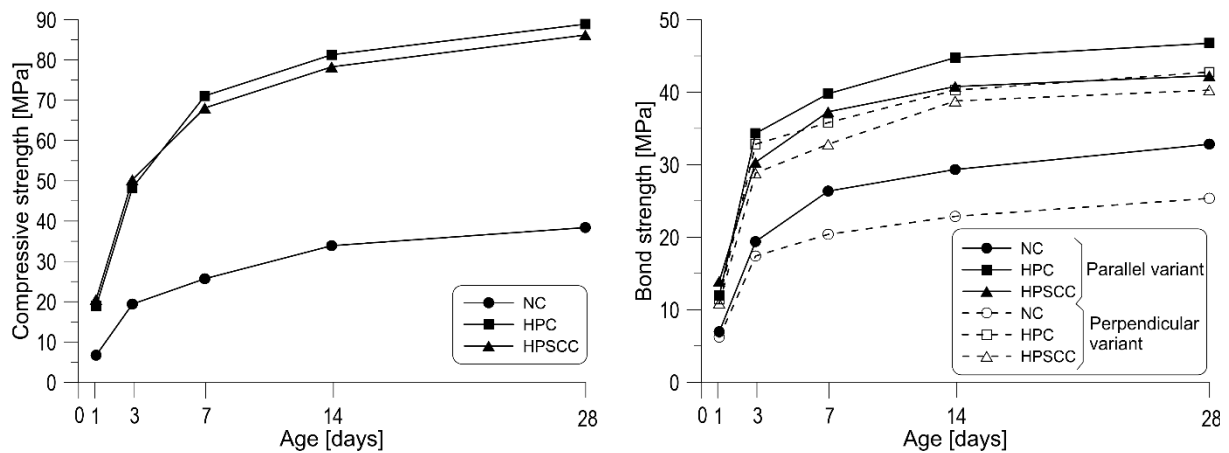


Figure 3. Development of compressive and bond strength

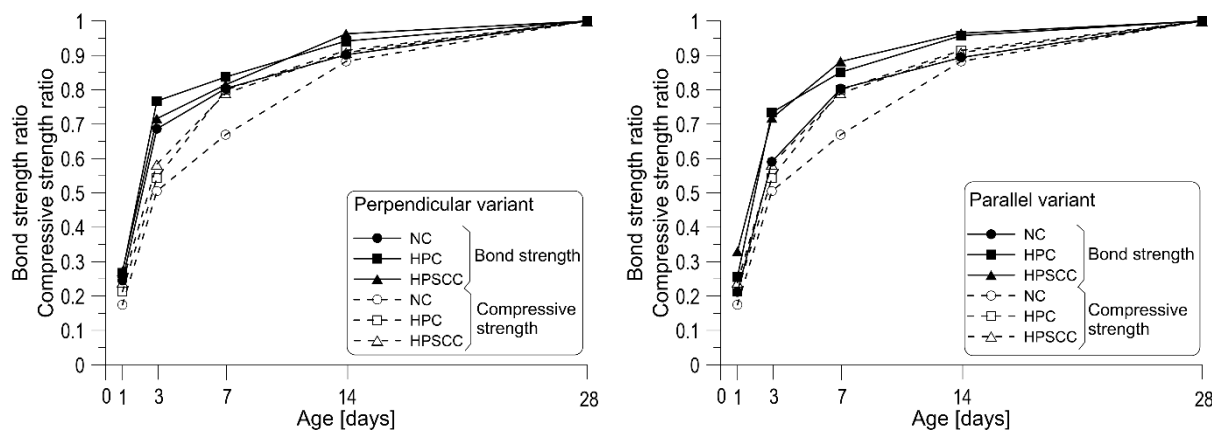


Figure 4. Comparison of relationships between ratio of strengths and age

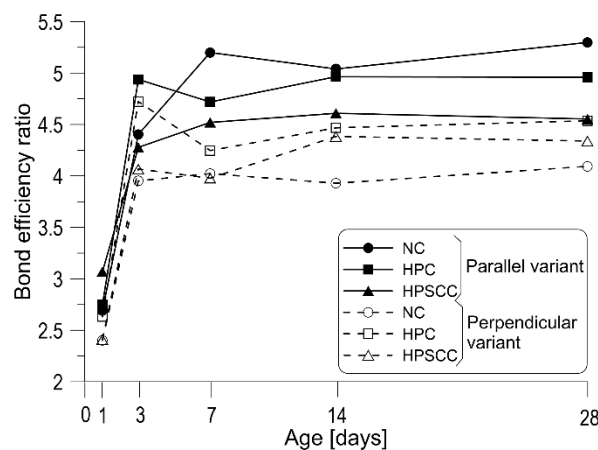


Figure 5. Coefficient of bond efficiency development

The development of both compressive and bond strength are presented in figure 3. The courses of the development of compressive strength – age and bond strength – age relationships are alike. However, there is a difference in ranges of its values. The largest bond stresses were noted at the concrete's age of

28 days. The results of bond strength and compressive strength from tests in present study were in accordance with results in [8, 11]. Thus, the results of bond strength in present study were reasonable.

The examinations showed that for new generation concrete as well as normal concrete, specimens with rebars, orientated parallel to the direction of casting, obtained higher bond stresses than perpendicularly located rebars. This tendency remained throughout the whole bond tests timeframe. It ought to be acknowledged that a lesser difference in bond stresses between two variants of rebars' orientation was noted in HPC and HPSCC than in NC. Regarding HPC and HPSCC, the average reduction of the bond strength in the whole scope of research is, respectively, 7% and 9%. The value obtained for NC is 18%. Higher resistance to bleeding, lesser segregation and surface settlement characterized mixes of HPC and HPSCC in relation to NC. Primary factors that influence negatively the bond strength of reinforcement in new generation concrete are limited due to a high quality of its fresh mixture.

The HPC, from among considered types of concrete, obtained the highest bond strength in the whole process of the bond development. The observation was not affected by a variant of orientation of the rebar. Greater than in HPSCC, value of bond strength could arise from mechanical compaction and increased amount of coarse aggregate in composition of HPC.

Performed tests enabled to compare relative bond strength increase in accordance with the type of concrete as well as the orientation of reinforcement with respect to the direction of concreting (figure 4). In first three days of curing specimens with perpendicularly orientated rebars gained – respectively for NC, HPC and HPSCC – 69%, 77% and 72% of the bond stress at the age of 28 days. Specimens with the second variant of the orientation – parallel – showed an increase up to 59%, 73% and 72%. In the next time period – at the age of 3 to 7 days – the relative increase of bond stresses stood at 7 to 21% for the investigated types of concrete and variants of rebars' orientation. The increase noted at the age of 7 to 14 days reached the range of 8 to 15%. A minor relative bond strength increase was seen after 14 days of curing. No significant differences in bond development were seen with regard to the considered orientation to the direction of concreting. Duration of the fastest increase of bond strength coincided with a period of the fastest increase of compressive strength. This phenomenon was noted in first three days of curing. In the same time period, the biggest rise of the bond efficiency ratio was indicated (figure 5). No noteworthy changes in the studied ratio were observed in the following age of concrete.

## 5. Conclusions

This paper holds a discussion on the development of bond strength of reinforcement steel in new generation concretes in comparison to normal concrete. Obtained results allow drawing the following conclusions:

- Bond between reinforcement and concrete developed along with the process of curing in both NC and new generation concretes.
- The fastest increase of bond strength was noted in the first 3 days of curing. At that time, bond stress reached the level of 69%, 77% and 72% of the bond stress corresponding to the age of 28 days, respectively for NC, HPC and HPSCC, in the specimens with the rebars orientated perpendicularly to the direction of concreting. Specimens with parallelly located rebars acquired the increase up to 59%, 73% and 72%. No significant difference in bond development was noted in relation to orientation of the rebar to the direction of concreting.
- Relative bond strength increase and relative compressive strength increase are alike in the conducted studies. However, the development of bond stress with age was faster than the development of compressive strength, especially at the early test ages.
- Specimens made of new generation concrete as well as those of normal concrete, with rebars orientated parallel to the direction of casting, obtained higher bond stresses than perpendicularly located rebars. This tendency stayed through the whole time of bond development. However, high quality of new generation concretes leads to significantly smaller differences in bond strength in relation to orientation of rebar than those in NC.



- No significant difference was noticed between HPC and HPSCC mixes in terms of bond or compressive strength development with age.

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