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# The effect of aggregate composition on a bond between the steel reinforcement and the normal and high-performance concrete

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# The effect of aggregate composition on a bond between the steel reinforcement and the normal and high-performance concrete

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**Abstract**. This paper is focused on verification and evaluation of the influence of the coarse aggregate size used in concrete mix composition on the bond properties between ribbed steel reinforcement and concrete. The mechanism of the bond between reinforcing steel and concrete is highly dependent on the mechanical properties of the concrete, such as its tensile strength or splitting, and on the intensity of the "aggregate interlock" phenomenon, which involves the interlocking of concrete particles in the ribbed spaces of the reinforcing steel. Given this, the aggregate composition used in the production of a concrete mix can have a significant role to play in the process of transferring loads from steel to concrete and the vice versa. As a part of the study, the bond and the compressive strength of specimens made of three high-performance concretes and two normal concretes. The research has shown that the choice of the aggregate composition used in the concrete mixture, depending on the type of ribbing of the main reinforcing bars, may increase the bond strength of the reinforcement to the concrete. Due to the different properties of HPC in relation to the NC, it can be assumed that the bond mechanism runs similarly in the concrete, while the individual phases of the bond failure may occur at different intensities and with the other ranges of displacement of the bar relative to the concrete.

## 1. Introduction

The phenomenon of concrete bond to reinforcing bars is widely described in the literature [1–3]. In the currently used reinforcement, the analysis of the interaction between the ribbed bar and concrete is of primary importance. Thanks to the bond in reinforced concrete elements, forces are transferred from concrete to steel and vice versa. This applies both to ordinary concretes as well as to new generation concretes [4–7], including high-performance concretes (HPC), which are more and more commonly used. It should be noted that with respect to HPC the same theoretical models are repeatedly used in calculation procedures as in ordinary concretes. However, these concretes differ significantly from each other. The differences concern not only the strength, but also above all the concrete microstructure. Due to the mechanism of HPC failure, which causes relatively flat and smooth crack surfaces, the effect of aggregate interlock and bridging effect are significantly reduced in them. Naturally, this can directly affect the bond between steel and concrete, where the phenomenon of interlocking plays a significant role. Therefore, it seems quite important to know which aggregate is used to produce a specific concrete. This refers both to its type (natural or crushed-stone) and most importantly to its grain size distribution. In addition, in the case of HPC, the correlation between bond stresses and only the compressive or tensile strength of concrete may prove to be misleading. This is due to both completely different relationship between these strengths in HPC and the content of silica fume in its mixture. Thus, it is desirable to describe the effects of both ordinary concretes and HPC in the context of their bond to reinforcing steel and the used coarse aggregate.

## 2. The bond between concrete and reinforcing steel

### 2.1. Bond mechanism

The issue of bond in reinforced concrete structures is related to the interaction between individual materials, namely concrete and reinforcing steel. Under a certain load, the rebar is extracted from the concrete specimen, which results in a bond failure due to loss of friction and chemical adhesion (Figure 1). As a result, the initial bond disappears. In the case of ribbed bars, a secondary bond occurs because of the transfer of forces from each bar to concrete through the surface of the ribs. This eventually causes diagonal cracks running from the ribs - the so-called second phase of bond failure. A further development in bond stress in the bar causes the concrete to crush under the ribs and increases the slip of the reinforcement in relation to the surrounding concrete, which describes the third phase of the bond failure. During this phase of the bond failure, the concrete cover ruptures, which means that it works not as a closed ring, but as a concrete bracket (Figure 2).

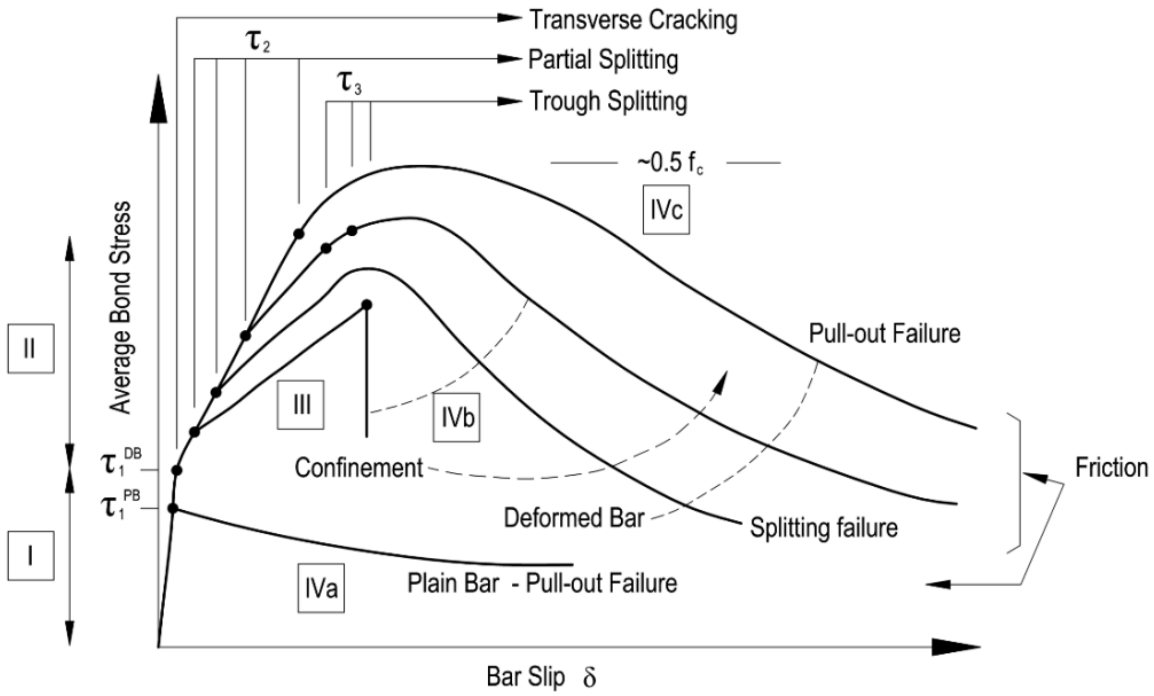


**Figure 1.** Typical bond stress-slip relationship [8]

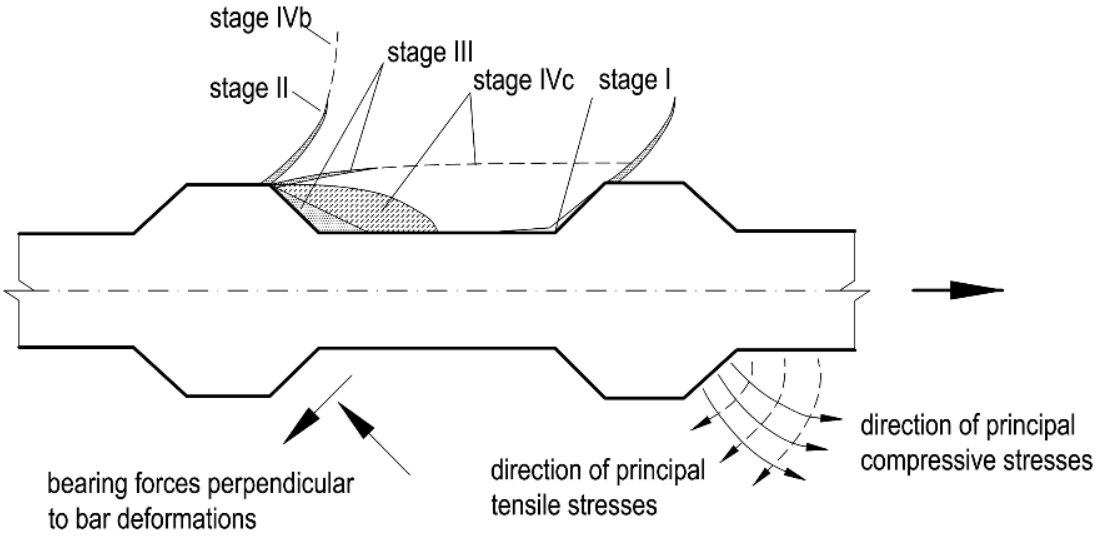


**Figure 2.** Cracking and damage mechanisms in bond [8]

It should be emphasised that a detailed assessment of the bond phenomenon is complicated because it depends on several factors. Many authors [2] believe that the compressive strength, the modulus of elasticity and in particular the tensile strength of the concrete have a decisive influence on the bond loss. Therefore, for high performance concretes, it can be assumed that the bond mechanism is similar. Each phase of the bond failure may occur at different intensities and with different ranges of displacement of the bar in relation to the concrete. Equally, the contributions of the various factors causing a bond, namely adhesion, shear and friction, may play a different role in the individual failure phases [9, 10]. In general, the higher compressive strength of HPC and its higher tensile strength may result in a different bond behaviour. It should be noted that the relationship between the bond strength and a limited number of properties, i.e. compressive strength and tensile strength, in the case of HPC may prove to be incorrect. This is because the brittleness of the material is much higher because of a disproportionate increase in tensile strength to the growth of compressive strength. Moreover, as silica fume is used in HPC, it can be concluded that it affects the contact zone of concrete with reinforcement steel. The results of previous studies [11–15] indicate that the use of silica fume significantly reduces the porosity of the transition zone of the cement matrix with the surface of the steel rebar. Thus, it strengthens that bond. On the other hand, in the case of secondary bond, silica fume changes the mechanism of its failure [12].

### 2.2. Effect of bridging and aggregate interlock on bond

The bridging effect means wedging of aggregate grains in the cross-section of local cracks, is illustrated in Figure 3a. During cracking, the aggregate grains used in the concrete mix are wedged on the edges of the cracking surface, hence increasing the resistance in the analysed area. Surely, this phenomenon has a positive effect on the load-bearing capacity of the cross-section only to a certain extent of cracking and largely depends on the type (natural and crushed aggregate) and size of the aggregate.

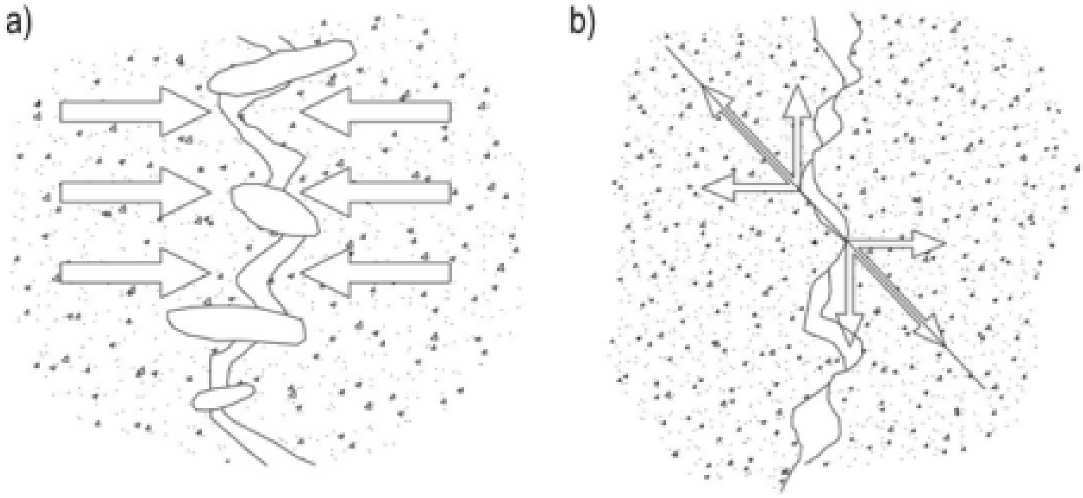


**Figure 3.** Phenomenon model: a) „bridging effect”, b) „aggregate interlock” [16]

A phenomenon similar to the "bridging effect" is the phenomenon of "aggregate interlock", i.e. interlocking of mutually unequal edges of the resulting cracks (Figure 3b). The mechanism of this phenomenon and the impact on the analysed cross-section is the same as in the case of the "bridging effect". The similarity of these two effects is so strong that very often they are treated as one in literature and occur under the common name of "aggregate interlock".

The importance of these phenomena is so great that it is commonly assumed that they are taken into account when defining physical models describing reinforced concrete [16, 17]. Moreover, it was shown that the PARC (Physical Approach for Reinforced Concrete) model describes a performance of reinforced concrete elements made of HPC quite well. This is an interesting statement because one could expect a much lesser impact of the effects of bridging and aggregate interlock on the behaviour of high-performance concrete at the time of cracking. Observing the failure surfaces in HPC specimens, it can be noticed that the failure surface is much more regular than in normal concretes and that there are basically no exposed aggregate parts due to their destruction - the failure surface also runs through aggregate grains in these concretes (Figure 4). Therefore, it can be assumed that also in HPC with relatively small crack openings, the effects of bridging and aggregate interlock have an impact on the bearing capacity of the cross-section, but their significance is slightly smaller than in the case of ordinary concretes.


**Figure 4.** A view of a destroyed concrete specimen: a) normal concrete - the destruction of the matrix with simultaneous maintenance of aggregate grains, b) high-performance concrete – the destruction of the matrix and aggregate grains

## 3. Test plan

### 3.1. Description of specimens

The aim of the study was to determine the influence of coarse aggregate grain size on the bond of ordinary and high-performance concrete to reinforcement steel. Natural gravel aggregate with fractions of 2.0/8.0 mm, 8.0/16.0 mm and 16.0/32.0 mm was used in the tested ordinary concrete. In the case of HPC concrete, basalt aggregates with fractions of 2.0/6.3 mm and 6.3/16.0 mm were used. The selection of the aggregate composition in particular concrete mixes was dictated by the necessity to achieve appropriate compressive strength of the analysed concretes and the desire to demonstrate the influence of aggregate granulation on the bond between reinforcing steel and concrete. The grading curves of the aggregates are shown in Figure 5.

The composition of individual concretes was determined on the basis of the adopted quantity of cement and the water-to-cement ratio for NC and HPC concretes, as well as a constant mass volume of a particular coarse aggregate. Natural sand with a nominal grain size of 0.0/2.0 mm was also used for the production of concretes. The aggregate composition was based on own previous research. Additionally, in the case of HPC concrete, in order to obtain a mixture with specific rheological properties, the proportion of admixtures was experimentally determined. It should be emphasized that the superplasticizer was dosed to individual HPC mixtures in such volumes that they could be classified in a consistency class of S3. The same consistency class was determined for NC mixes. The compositions of the concrete mixes are presented in Table 1.

Test specimens were made as a cubic element with dimensions: 160x160x160 mm with a reinforcing bar (16 mm in diameter) centrally embedded in. The required development lengths were obtained using PVC pipe fragments installed on the individual reinforcing bars. In NC concretes, the bond section was assumed to be 80 mm and in HPC concretes 50 mm [18].

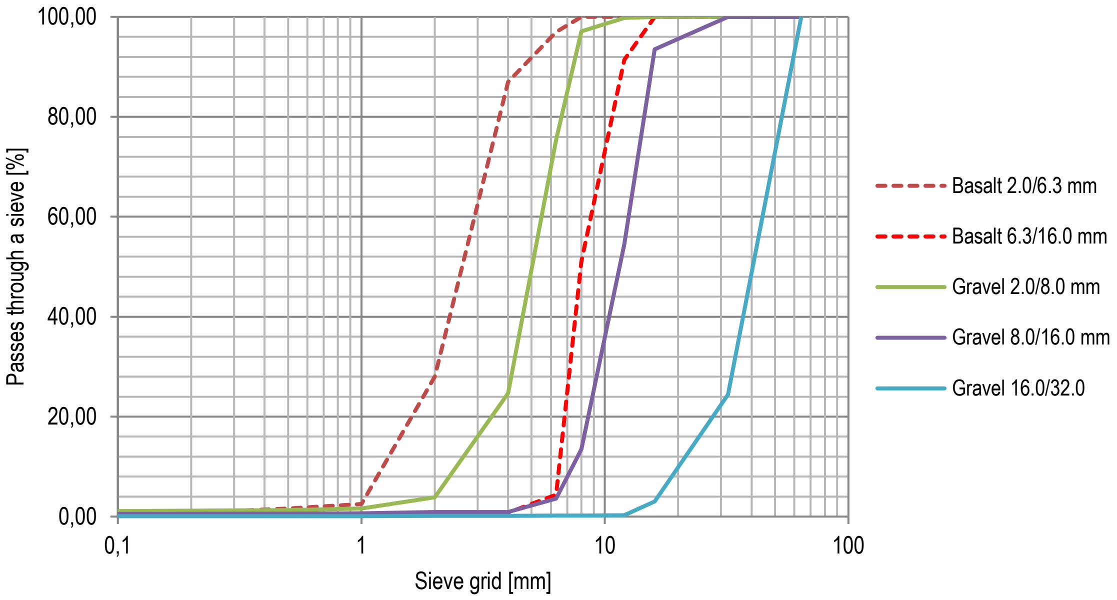


**Figure 5.** The grading curves of the aggregates

**Table 1.** Composition of concrete mixtures [kg/m$^3$]

| Ingredients | NC–I | NC–II | NC–III | HPC–I | HPC–II |
|---|---|---|---|---|---|
| Cement CEM I 32.5N | 380.00 | 380.00 | 380.00 | - | - |
| Cement CEM I 42.5R | - | - | - | 500.00 | 500.00 |
| Water | 199.22 | 191.76 | 193.33 | 150.00 | 150.00 |
| Sand | 530.98 | 530.98 | 586.67 | 615.39 | 615.39 |
| Coarse aggregate: | | | | | |
| - gravel 2.0/8.0 mm | 976.86 | - | - | - | - |
| - gravel 8.0/16.0 mm | - | 976.86 | - | - | - |
| - gravel 16.0/32.0 mm | - | - | 986.67 | - | - |
| - basalt 2.0/6.3 mm | - | - | - | 961.45 | - |
| - basalt 6.3/16.0 mm | - | - | - | - | 961.45 |
| Silica fume | - | - | - | 35.00 | 35.00 |
| Superplasticizer | - | - | - | 4.05 | 3.85 |

### 3.2. Test methods

The compressive strength of concrete was determined on cubic specimens of approximately 150 mm side. The bond tests were carried out using the pull-out test method recommended by RILEM [19]. Adoption of a test model compliant with [19] allows assuming that the changes in deformation along the bar length will be linear [20]. Therefore, it is possible to determine the bond stress as a function of displacement. On the assumption of constant values of bond stresses, they are calculated from the relationship given in equation 1

$$\tau = \frac{F}{\pi \cdot d \cdot l} \tag{1}$$

where *F, ϕ, l* are*,* respectively: the applied load, the diameter of the reinforcing bar and the bond section length. The measurement of the slip of the unloaded end of the rebar was taken using linear variable displacement transducers (LVDT). The specimens were loaded gradually until the bond stress limits were reached. For each concrete mixture, the bond tests were performed on 15 and 9 specimens and in the case of NC and HPC, respectively. All strength tests were carried out after 28 days of concrete curing.

### 3.3. Analysis procedure

The paper adopts three different representative values of bond stresses, which are often used in the literature on the analysed problem. The ultimate bond stress corresponding to the bond failure - $\tau_{max}$ is assumed due to the unambiguous definition of this criterion [14, 21, 22]. The second representative value frequently accepted in the literature [23] is the critical bond stress corresponding to the displacement of the rebar in relation to the concrete of 0.01 mm - $\tau_{0.01}$. In the literature, this limit is often taken as the beginning of the second phase of the bond failure. The chemical adhesion forces are overcome and the bond stresses are transferred via ribs surface. The third value, $\tau_{0.1}$, corresponds to a 0.1 mm displacement of the reinforcement. It is identified with overcoming the bond of the ribbed bar by the pulling force. With this displacement, the perpendicular component of the bond stress usually leads to the destruction of the concrete cover.

In order to compare the results obtained with other literature data, a commonly used normalization of bond stresses in relation to the square root of compressive strength - $\tau/f_c^{0.5}$ [14, 22-25] determined on 150 mm side cube specimens was introduced.

## 4. Result and discussion

The relationships between normalised bond stresses and the corresponding rebar slips ($\tau/f_{cm}^{0.5}$ - s) are shown in Figures 6 and 7. The graphs show the results of tests of all samples in each concrete mixes. In the case of NC, the dominant method of a bond loss was splitting the concrete cover. It resulted from the assumed bond section length and lower strength parameters of this concrete in comparison to HPC. The failure of the steel-concrete bond as a result of pulling the ribbed bars out of the specimens was recorded in the case of HPCs. The effect of the described process of the bond loss in NCs was to obtain relatively small slips of the reinforcement in those concretes, which in many cases slightly exceeded the value of 0.1 mm ($\tau_{max} \approx \tau_{0.1}$). Table 2 summarizes the test results and calculated values of normalised bond stress related to levels of $\tau_{max}$, $\tau_{0.01}$ and $\tau_{0.1}$.

**Table 2.** Concrete mix composition

| Ingredients | NC–I | NC–II | NC–III | HPC–I | HPC–II |
|---|---|---|---|---|---|
| | MPa | MPa | MPa | MPa | MPa |
| Average compressive strength $f_{cm}$ | 45.08 | 43.08 | 46.58 | 88.35 | 87.08 |
| Ultimate bond stress $\tau_{max}$ | 8.67 | 7.98 | 6.35 | 45.23 | 44.17 |
| Normalised bond stresses $\tau_{max}/f_{cm}^{0.5}$ | 1.29 | 1.22 | 0.93 | 4.81 | 4.73 |
| Bond stresses $\tau_{0.01}$ | 3.81 | 2.74 | 2.32 | 14.81 | 11.05 |
| Normalised bond stresses $\tau_{0.01}/f_{cm}^{0.5}$ | 0.57 | 0.42 | 0.34 | 1.58 | 1.18 |
| Bond stresses $\tau_{0.1}$ | 8.63 | 7.89 | 6.23 | 32.49 | 32.72 |
| Normalised bond stresses $\tau_{0.1}/f_{cm}^{0.5}$ | 1.28 | 1.20 | 0.91 | 3.46 | 3.51 |

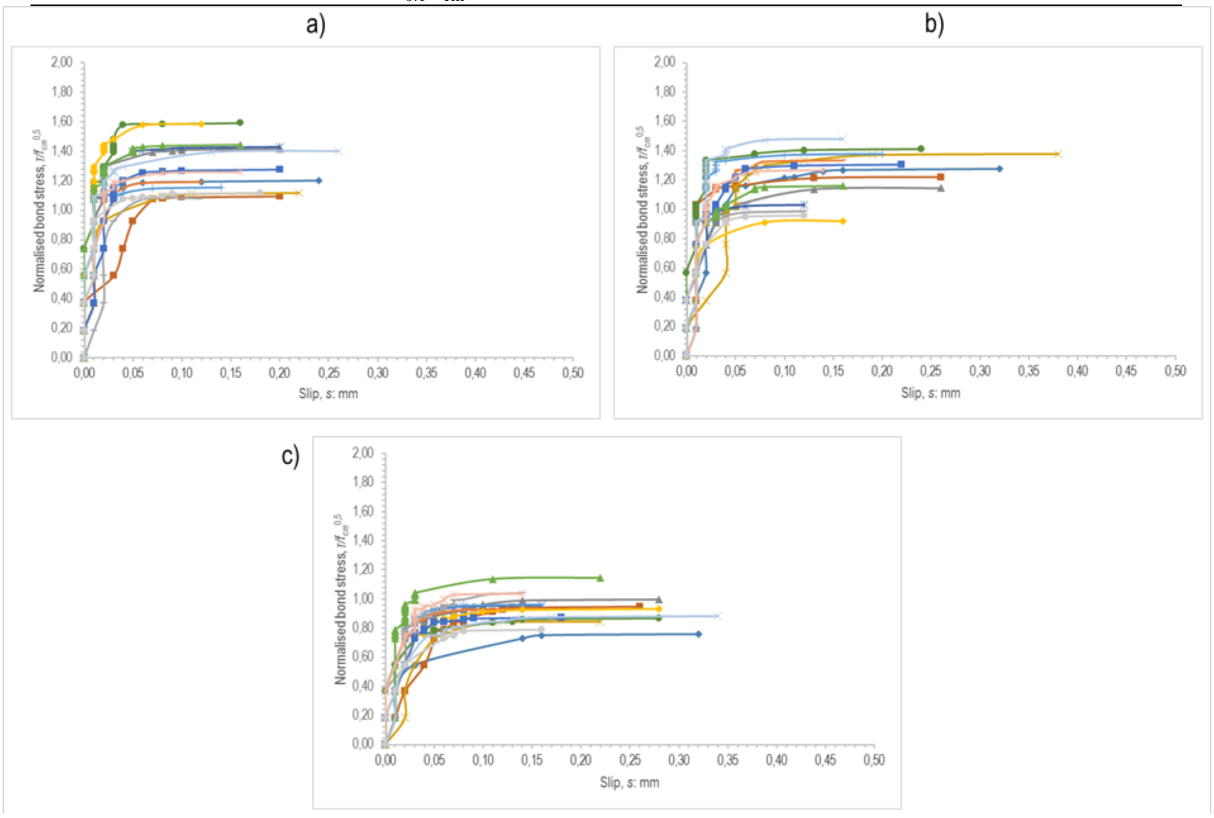


**Figure 6.** Relationships $\tau/f_{cm}^{0.5}$ – s for normal concretes, a) NC-I, b) NC-II, c) NC-III

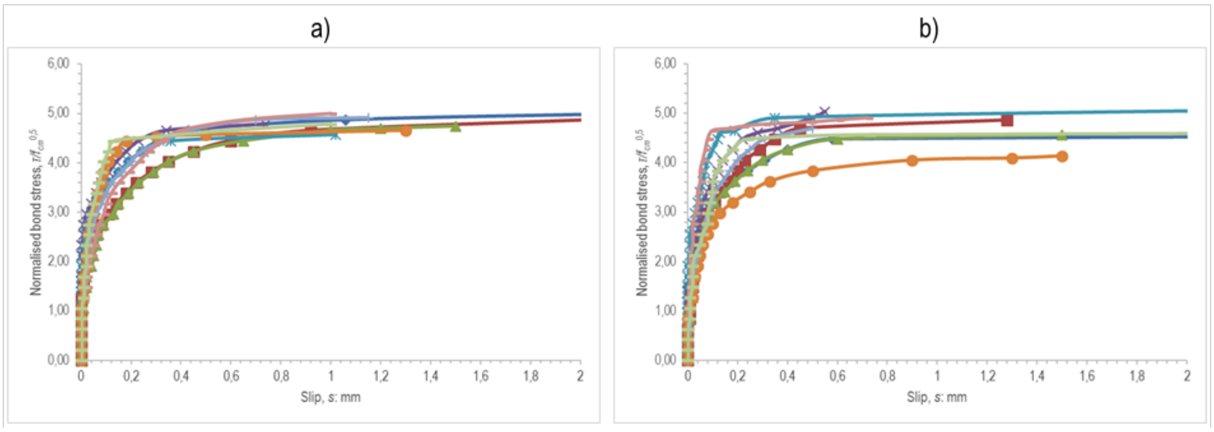


**Figure 7.** Relationships $\tau/f_{cm}^{0.5}$ – s or high-performance concretes, a) HPC-I, b) HPC-II

The analysis of the results indicates that in the case of NC, there is a direct correlation between the applied aggregate grain size and the bond between steel and concrete. In mixtures containing increasingly coarse aggregate grain, smaller values of bond stress were obtained for all values of $\tau_{max}$, $\tau_{0.01}$ i $\tau_{0.1}$ (Figure 8). The decrease of normalised bond stresses of $\tau_{0.01}/f_{cm}^{0.5}$ in NC-II and NC-III blends compared to NC-I was 26.3% and 40.3%, respectively. In the case of normalised bond stresses of $\tau_{0.1}/f_{cm}^{0.5}$ in NC-II and NC-III blends a significantly lower reduction was recorded, resulting in a decrease of 6.2% and 28.9% respectively. Due to similar values of $\tau_{max} \approx \tau_{0.1}$ in the case of $\tau_{max}/f_{cm}^{0.5}$ similar values of decrease of normalised bond stresses were recorded. The obtained results confirm the potential occurrence of bridging and aggregate interlock phenomena in NC. In mixtures containing aggregate fractions of 2.0/8.0 mm there is a higher probability of aggregate grain being located in the direct contact zone between steel and concrete. With the increase in aggregate grain size, due to among other things the "wall effect", the number of grains in the contact zone would be significantly smaller and they would usually be separated from the steel with a layer of cement matrix.

In the case of the HPC (Figure 9), no significant influence of the size of coarse aggregate grain on the bond between steel and concrete. Thus, there is no possibility of occurrence of bridging and aggregate interlock phenomena. For bond stresses, $\tau_{max}$ and $\tau_{0.1}$ similar results were obtained, which may indicate a relatively smooth failure surface passing through both the cement matrix and the aggregate. Only for $\tau_{0.01}$ the reduction of normalised bond stress $\tau_{0.01}/f_{cm}^{0.5}$ in relation to HPC-I mixture was achieved at the level of 25.3%. It is a similar level of a drop of that bond stress as in the case of NC. It is a similar level of drop $\tau_{0.01}/f_{cm}^{0.5}$ as in the case of NC concrete. The physical basis of this phenomenon may be related to the formation of water lenses under the aggregate grain of larger sizes. This may result in the formation of pores, affecting the bond strength of steel to concrete.

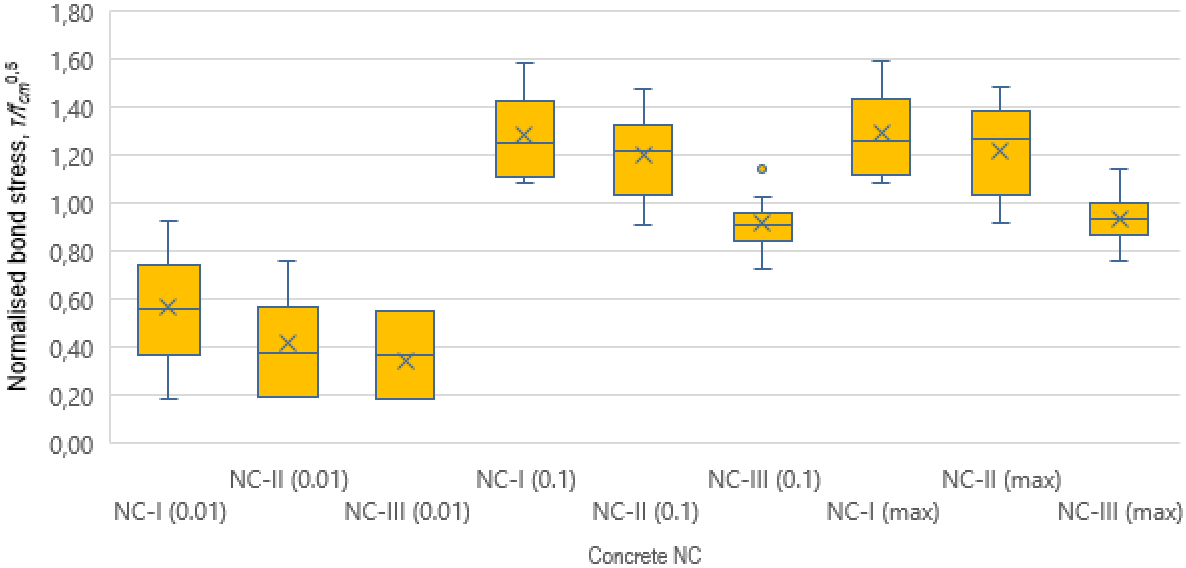


**Figure 8.** Relationships $\tau/f_{cm}^{0.5}$ – s for normal concretes, a) NC-I, b) NC-II, c) NC-III

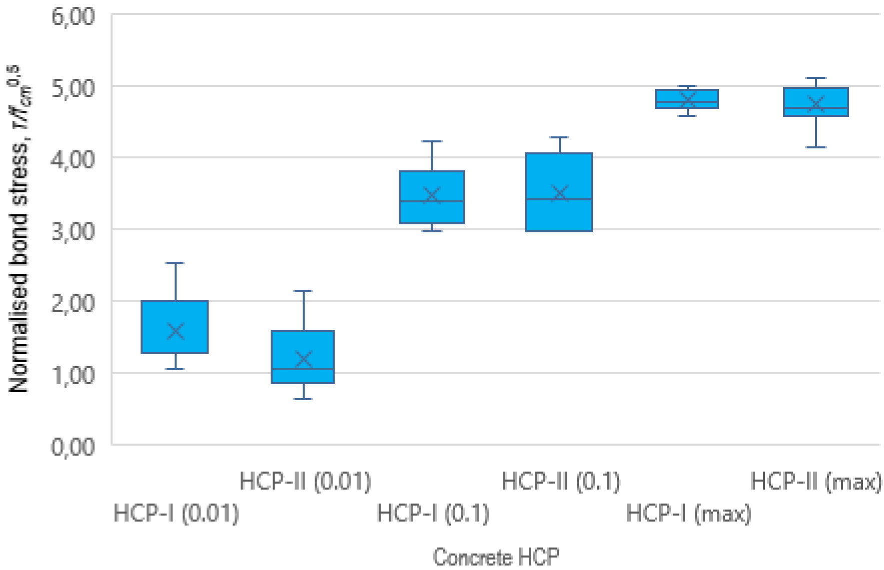


**Figure 9.** Relationships $\tau/f_{cm}^{0.5}$ – s or high-performance concretes, a) HPC-I, b) HPC-II

## 5. Conclusions

The aim of the study was to determine the influence of coarse aggregate grain size on the bond of the normal and high-performance concrete to the reinforcement steel. Based on the acquired results the following conclusions can be drawn:

1) Due to different properties of HPC in relation to the NC, it can be assumed that the bond mechanism runs similarly in the concrete, while the individual phases of the bond failure may occur at different intensities and with the other ranges of displacement of the bar relative to the concrete. Similarly, the proportion of the individual factors causing bond (adhesion, shear and friction) may play a different role in the different phases of HPC bond failure.

2) In the case of NC, in mixtures containing increasingly larger aggregate grain, lower bond stress values were obtained for all representative values of $\tau_{max}$, $\tau_{0.01}$ and $\tau_{0.1}$. That confirms the possibility of bridging and aggregate interlock phenomena occurring in this concrete. In mixtures containing smaller aggregate particles, there is a higher probability of aggregate grains locating in the direct steel-concrete contact zone, which in case of cracking may have a significant impact on the shear resistance of the concrete when pulling out the reinforcing bar.

3) In the case of the HPC, in general, no significant influence of the size of coarse aggregate on the bond between steel and concrete. Only for bond stress of $\tau_{0.01}$, a reduction of normalised bond stress $\tau_{0.01}/f_{cm}^{0.5}$ in relation to HPC-I mixture was obtained at the level of 25.3% and it is a similar level of reduction $\tau_{0.01}/f_{cm}^{0.5}$ as in the case of NC. This can be associated with the formation of water lenses under the larger aggregate grains, which may result in the formation of pores affecting the primary bond between steel and concrete.

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