A critical review of the effect of concrete composition on rebar–concrete interface (RCI) bond strength: A case study of nanoparticles

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Abstract

Minimum concrete cover for rebar, rebar diameter, concrete compressive strength, embedded length of rebar, and lateral reinforcement by stirrups are the crucial factors considered in existing predicting equations and regulations for predicting rebar–concrete interface (RCI) bond strength. However, considerable effects of concrete composition on RCI are ignored in design codes and investigations. This paper intends to comprehensively highlight the critical aspects of this research gap. Additionally, a practical experimental approach is described in the present study to efficiently consider the effect of the new generations of concrete on RCI bond strength. Finally, nano-concrete is considered as a case study to show the importance of nanoparticle types on RCI bond strength. Overall results show that studying the microstructure of the transition zone at RCI is essential to accompany with the RCI bond strength for considering new generations of concrete in reinforced concrete structures. Additionally, the current study emphasizes that more investigations are necessary to be conducted by future works to fill the existing research gaps in RCI.

Keywords Bond–slip · Concrete composition · RCI · Calcium hydroxide · Nano-concrete

Abbreviations

CSH	Calcium silicate hydrate
EDS	Energy dispersive spectroscopy
LWC	Lightweight aggregate concrete
NC	Normal concrete
OPC	Ordinary Portland cement
PPC	Portland pozzolana cement
PSC	Portland slag cement
RAC	Recycled aggregate concrete
RC	Reinforced concrete
RCI	Rebar–concrete interface (RCI)
rebar	Reinforcing bar
SCC	Self-consolidating concrete
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy

List of symbols

c	Concrete cover
d_b	Rebar diameter
f_c	Concrete compressive strength
f_y	Rebar yield strength
K_{tr}	Confinement index
l_d	Development length
w/c	Water-to-cement ratio
λ	Lightweight concrete factor
α	Rebar location factor
β	Epoxy coating factor
γ	Rebar size parameter
τ	Bond stress
τ_{NC}	Maximum bond strength of normal concrete

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τ_{nano} Maximum bond strength of nano-concrete
 τ/f_c Normalized bond strength

1 Introduction

1.1 Importance of steel rebar–concrete interface (RCI or SCI) bond

Relative movement between reinforcement and surrounding concrete, known as the “bond–slip” phenomenon, plays a crucial role in the structural behavior of reinforced concrete (RC) members [1]. This phenomenon strongly affects the behavior of RC members in both fields of limit and ultimate states [2–4]. Bond–slip phenomenon affects the structural efficiency of different sub-elements in an RC frame including column, foundation, interior and exterior beam–column joint, beam (crack pattern, crack width, and failure mode), and RC slabs (Fig. 1). In the case of RC columns subjected to bending at the beam–column joint or footing–column interface, significant end-rotations have been reported due to the anchorage slip [5, 6]. In addition to the rotation calculated from flexural analysis of an RC column, bond–slip phenomenon (or reinforcement slip), additive rotation of reinforcement slip outside the flexure length causes higher drift of columns, beams, and walls under lateral forces [7, 8]. By ignoring this additive rotation, the predicted lateral deformations may be significantly underestimated [9]. Energy dissipation capacity of joint [10], lateral deformation of RC frame [11–13], stiffness of RC frame [12], beam-end rotation [14–17], and natural frequency of RC frame [12] are the main effects of the bond–slip phenomenon on the structural behavior

of interior and exterior beam–column joints. Due to the high slippage of reinforcing bar (rebar), columns in the interior joints can generally tolerate lower flexural moments, as compared to those obtained for the conditions without slippage (perfect bond). This can affect the dynamic behavior of RC frames, so that natural frequency values of a structure without bond–slip consideration are slightly larger, as compared with those determined by the modal analysis of a frame with bond–slip, showing a stiffer model. Additionally, energy dissipation of the RC frame with a perfect bond (without slippage) is considerably higher than that with bond–slip behavior. Regarding interior joints, stress gradients are much steeper along the internal beam–column joint as compared with the beams framing into the joint. This shows a higher bond demand in the beam–column joint region. So the bond strength is much vital than along the beam. High bond stress in the interior beam–column joints results in the reinforcement slippage, which can diminish the flexural strength and ductility index of the adjacent beam. This can be attributed to the tensile stress in the compression steel rebar embedded in joints [18]. Accordingly, the bond–slip phenomenon changes the curvature distribution in the inelastic zone region at the girder ends [19–21]. In the case of crack pattern, increasing applied loading causes an increase in the depth of the cracks, while the steel rebar between the cracks continues to take the tension. Inadequate bond illustrating by the rebar pull-out results in the formation of much larger cracks, as well as premature failure of the beam [22]. Regarding shells in RC frame, many experimental studies reported that bond–slip phenomenon directly affects the failure displacement and mode of RC slabs [23–26]. This fact was severally confirmed by numerical

Fig. 1 Influences of the bond–slip phenomenon on structural behavior of RC frame

models [1, 27], so that Cashell et al. [24, 28] considered RCI bond strength in predicting the failure displacement of RC slabs. They showed that a relatively high RCI bond strength results in failure at an early stage of loading, while a lower bond causes a considerably higher ductility (larger displacement) [1].

Previous studies strongly support the findings that the bond–slip phenomenon has considerable impacts on various sections of an RC frame, which is summarized in Fig. 1. Precisely studying this phenomenon can significantly help design codes to improve the reliability index of their performance. The present study intends to critically discuss an important neglected parameter in the field of the bond–slip studies. Accordingly, the following section will comprehensively explain the current considered approach in the concrete codes and previous studies, and also describe the missing parameter.

2 Effect of concrete type on RCI bond strength

The minimum length of rebar in surrounding concrete to develop tensile stress is called development length [29]. Rebar with proper bond strength requires a shorter

length to transfer interfacial stress. ACI 318R-08 [30] introduces Eq. (1) to measure development length of tension-loaded straight steel rebar in normal concrete (NC), l_d (in):

$$l_d = \frac{3}{40} \left(\frac{f_y}{\lambda \sqrt{f_c}} \right) \left[\frac{\alpha \beta \gamma}{\left(\frac{c + K_{tr}}{d_b} \right)} \right] d_b \quad (1)$$

where f_y is yield stress of rebar in psi, and c is concrete cover in inches. Factors α , β , and λ determine the influences of rebar location, epoxy coating, and lightweight concrete respectively. A rebar location factor of 1.3 is used in ACI 318R-08 [30] for a rebar located with more than 12 in. (300 mm) of the fresh concrete cast below, and 1.0 for other locations. ACI 318R-08 [30] considers different values for coating factor including 1.5 for a epoxy-coated rebar with concrete cover less than $3d_b$ or clear spacing less than $6d_b$, 1.2 for other epoxy-coated rebars, and 1.0 for uncoated rebar. CSA A23.3-14 [31] and ACI 318R-08 [30] standards consider 0.75 for lightweight concrete and 1.0 for normal-weight concrete. The value of the rebar size parameter (γ) is 0.8 for the rebar diameter of NO. 6 (19.05 mm) or smaller, and 1.0 for other diameters. K_{tr} determines the impact of stirrups and confinement on

Table 1 Predicting equations for the maximum bond strength (L denotes the embedded length of rebar in the equations)

References	Equations
Orangun et al. [43]	$\tau_{max} = \sqrt{f_c} \left(1.2 + \frac{3C_{min}}{d_b} + \frac{50d_b}{L} + \frac{A_{st1}f_{yst}}{500S_{st}d_b} \right)$
Xu [44]	$\tau_{max} = \left(1.6 + 0.7 \frac{C_{min}}{d_b} + 20 \frac{A_{st1}}{C_{min}S_{st}} \right) f_t$
fib Model Code [45]	$\tau_{max} = 2.5\sqrt{f_c}$ for good bond condition, $\tau_{max} = 1.25\sqrt{f_c}$ for other bond condition
Harajli et al. [46]	$\tau_{max} = 0.78\sqrt{f_c} \left(\frac{C_{min} + 7 \frac{A_{st}}{S_{st}n}}{d_b} \right)^{2/3}$
Esfahani and Kianoush [47]	$\tau_{max} = \tau_c \frac{1+1/M}{1.85+0.024\sqrt{M}} \left(0.88 + 0.12 \frac{C_{med}}{C} \right) \left(1 + 0.015 \frac{A_{st1}A_s}{C_{min}S_{st}} \right)$
Wu and Zhao [48]	$\tau_{max} = \sqrt{f_c} \left(\frac{2.5}{1+3.1e^{-0.47 \left(\frac{C_{min}}{d_b} + 33K_{st} \right)}} \right)$
Mousavi et al. [38]	$\tau_{max} = \sqrt{f_c} \left(-14.42 + 0.37 \frac{C_{min}}{d_b} + 3.17 \frac{d_b}{L} + 24.38 \frac{\text{fine aggregate}}{\text{all aggregate}} \right)$
Mousavi et al. [37]	$\tau_{max} = \sqrt{f_c} \left(\frac{3.9}{1+12e^{-0.54 \left(\frac{C_{min}}{d_b} + 10 \frac{d_b}{L} \right)}} \right)$ $l_d = \frac{f_y d_b}{\sqrt{f_c}} \left(0.0038 + 0.217 \frac{d_b}{C_{min}} + 0.01 \frac{\text{all aggregate}}{\text{fine aggregate}} + 0.0003 \frac{\text{Cement}}{\text{admixture}} \right)$
Mousavi et al. [39]	$\tau_{max} = K \sqrt{f_c} \left(\frac{3.9}{1+12e^{-0.54 \left(\frac{C_{min}}{d_b} + 10 \frac{d_b}{L} \right)}} \right)$ $K = 2.07 - \left(1.297 \frac{\text{fine aggregate}}{\text{all aggregate}} \right) - \left(0.819 \frac{\text{water}}{\text{powder}} \right) + \left(3.56 \frac{\text{super plasticizer}}{\text{water}} \right) - \left(0.0215 \frac{\text{slump}}{C_{min}} \right)$

the RCI bond strength. Equation (1) considers the effect of surrounding concrete cover by the normalized ratio c/d_b .

Concrete compressive strength (f_c), type of concrete aggregate (λ , normal vs lightweight), and top rebar effect (α) are the concrete-dependent parameters considered in determining the development length. Also, as summarized in Table 1, most of the existing predicting equations for the maximum bond strength only considered concrete compressive strength. Previous review articles, in the field of the bond–slip phenomenon, also ignored the effect of concrete composition, and only concentrated on concrete compressive strength [32–35]. However, results reported by the literature show a different trend in which powder types and content, aggregate types and contents and also admixture can significantly change the bond properties [36]. Accordingly, Mousavi et al. presented some models for predicting the maximum bond strength of rebar

embedded in self-consolidating concrete [37–39]. They considered the content of fine aggregate, cementitious materials, and admixtures in the equations. Generally, the concrete composition is defined by four main parameters including water-to-cementitious material ratio, powder, aggregate, and admixture (Fig. 2). Changing each of these factors in both fields of the quality and the quantity can considerably change rebar–concrete interface properties [37, 40, 41]. In this field, recently, Mousavi et al. [42] confirmed the hypothesis that type and dosage of the used powder in concrete can change the rebar–concrete bond strength, and improve the damaged layers around the rebar caused by the pre-cracked phenomenon.

In the past decade, different concrete types have been introduced by researchers, including various lightweight aggregates (LWC), fly ash concrete, geopolymer concrete, metakaolin concrete, nano-concrete, recycled aggregate

Fig. 2 Concrete composition as a key parameter in the bond–slip phenomenon

Fig. 3 Types of concrete used in the literature reviewed

concrete (RAC), silica fume concrete, slag concrete, rubberized concrete, and self-consolidating concrete (SCC). Figure 3 shows the percentage of bond studies corresponds to different types of concrete, from 2009. Statistics show that only 7.0% of previous studies are dedicated to NC, while 93.0% belongs to innovative generations of concrete. Nano-concrete is the latest type of concrete introduced by researchers so that 5.6% of the referenced researches is devoted. To clarify the effect of concrete composition on bond strength, a comprehensive review was conducted which is summarized in Table 2. The effect of different types of concrete on bond properties was considered in this review. The relative effectiveness of different types of concrete on bond strength as compared with NC is illustrated in Fig. 4. Conflicting observations were reported by researchers for every type of concrete, which are distinguished by three categories of *Improved*, *Reduced*, and *Non-effect* in Fig. 4. As summarized in Table 2

and Fig. 4, in the case of fly ash concrete, various observations were reported, so that there is no clear trend for the rebar–concrete interface (RCI) bond strength, as compared with the NC. Additionally, the review shows that slag concrete and concrete containing rubberized particles (as fine or coarse aggregates) have lower bond strength, as compared with NC. Although dominant numbers of previous studies confirm that recycled aggregate concrete (RCA) and lightweight concrete (LWC) have also lower bond strength than NC, some conflicting results were reported. Although a reduction factor was considered for development length in Eq. (1) to increase the development length of rebar due to the lower bond strength between rebar and LWA, emerging new types of lightweight aggregates can challenge Eq. (1). Review of the previous results (Fig. 4) illustrates that geopolymer concrete, metakaolin concrete, silica fume concrete, and nano-concrete have higher bond strength as compared with NC. However,

Table 2 Effect of concrete types on the bond strength

Concrete types	Normalized results		
	Improved	Reduced	No effect
Fly ash concrete	[54, 55]	[56]	[57–59]
Geopolymer concrete	[60–65]	×	[66]
Self-consolidating concrete	[37, 40, 67–80]	[81]	[50, 82–86]
Lightweight concrete	[87–90]	[91–97]	[98, 99]
Metakaolin concrete	[100, 101]	×	×
Recycled concrete	[102–106]	[103, 106–113]	[114, 115]
Rubberized concrete	×	[116–119]	×
Silica fume concrete	[40, 49, 60, 87, 120–131]	[132–134]	×
Slag concrete	×	[135–138]	×

Fig. 4 Effect of the concrete type on bond strength (adapted from Table 2)

there is no regulation for considering the effect of these concrete types, causing overestimation for development length (Eq. 1). Regarding self-consolidating concrete (SCC), the dominant number of studies reported higher bond strength as compared with NC (Fig. 4). However, some conflicting results were observed, which are summarized in Table 2. The main question is that there is no specific regulation, code consideration, and research paper to explain the reason for these observations for every type of concrete. Regarding SCC, Mousavi et al. [37–39] distinguished this research gap and proposed some calibrated bond model, which is summarized in Table 1. Their results indicate that the content of fine aggregate, powder, and superplasticizer can affect the bond properties of rebar embedded in SCC (Fig. 5). Ratios of fine aggregate content-to-all aggregate (Fine/All), water-to-total powder content (W/Powder), superplasticizer-to-water content (SP/W), and slump flow-to-concrete cover (slump/c) are considered in Fig. 5. Based on their results, fine aggregate in concrete has the most important influence on bond strength compared to other parameters, which can be attributed to the filling effect. However, different types of powders (and fillers) were used for producing SCC, which can affect the rebar–concrete interfacial properties [40, 49, 50]. This can clearly affect the structural performance of reinforced SCC frames. For instance, Said and Nehdi [51] conducted reversed cyclic loading tests on large-scale beam–column joints to compare the structural behavior of SCC in RC frames, as compared with NC. Their results indicate that increasing the fine aggregate content in SCC mixtures can reduce the contribution of the aggregate interlock mechanism to total shear resistance, causing a more rapid deterioration of joint exposed to cyclic loading. Similarly, Schiessl and Zilch [50] found that SCC specimens have lower shear stress resistance under monotonic loading. They reported that crack surfaces of SCC are smoother as compared with NC. In this field, Ghadban et al. [52] showed

that using SCC reduces displacement ductility and energy dissipation of RC bridge columns, while increases drift ratio at failure. Similar results were obtained for beam–column connection, so that SCC specimens have lower energy dissipation capacity as compared with NC, under reversed cyclic loading [53]. The effect of the bond–slip phenomenon on these RC elements was depicted before in Fig. 1. Hence, there is a direct relationship between concrete composition and RCI characteristics.

3 Potential scenarios

Despite the extensive research on rebar–concrete bond strength, there are few studies on explaining the main reasons for changing the RCI due to using different concrete compositions. Accordingly, two existing scenarios were described by some scattered experimental studies including (a) *interface porosity*; and (b) *calcium hydroxide content*. The following subsections will discuss each of these scenarios.

3.1 Interface porosity at RCI

Various types of concrete have a considerable impact on the heterogeneous layer between steel and concrete, denoted as the “transition zone” [139]. This interlayer has high porosity, and the porous zone thickness can affect the RCI strength [140–142]. Kenny and Katz [143] showed that the porous zone thicknesses at RCI are 40 and 400 μm for vertically and horizontally cast rebars respectively, which considerably affect the RCI bond strength [144–146]. However, there are only a few and scattered studies performed on interface porosity at RCI for different types of concrete. For instance, Zayed [140] reported that adding silica fume to concrete mixture has a significant impact on reducing the interface porosity, as compared with NC

Fig. 5 Effect of the concrete composition on normalized bond strength of steel rebar in self-consolidating concrete (SCC) (adapted from Mousavi et al. [37–39])

Fig. 6 Effects of silica fume on porosity percentage of the transition zone (adapted from Zayed [140])

(Fig. 6), by densifying the RCI and no effect on the bulk porosity. As illustrated before in Fig. 4, this porosity reduction due to the using silica fume in concrete causes higher bond strength as compared with NC. As the hydration time increases, the interface porosity decreases. Similar observations were reported to determine the effects of silica fume additions on the concrete–aggregate interface [147–149]. In this field, Chen et al. [150] reported that water-to-cement ratio of concrete has a considerable impact on porous zone thickness (Fig. 7), so that the pores and voids at RCI increase with the w/c ratio. Higher w/c ratio generates RCI of higher porosity and lower content of calcium hydroxide. Similar findings were showed by some previous studies [146, 151, 152]. For instance, Elsharief et al. [151] reported that as w/c ratio decreases from 0.55 to 0.40, thickness of the porous zone reduces.

Fig. 8 Scientific database used in the present study for the second scenario of the RCI bonding

3.2 Calcium hydroxide content at RCI

The second scenario for explaining the mixture-dependency of RCI bond strength is calcium hydroxide content at RCI. Despite the first scenario, many previous studies concentrated on the effect of calcium hydroxide content at RCI (Fig. 8). Most of the previous studies in this field have been performed before 2000 (around 68%), while less than 10% have been conducted from 2010 to 2020 (Fig. 8). Hence, it can clearly show that present findings are not reliable for new types of concrete.

Many studies reported the enriched content of calcium hydroxide at the RCI, as compared with the bulk cement paste [140, 146, 150, 153–158]. The existence of calcium hydroxide at the RCI was severely observed by the SEM images and EDS analysis [139]. To explain this phenomenon, Moreau [159] reported that the cement particles inclined to detach from the matrix, generating a slender zone around the rebar with fewer cement grains and more water. This provides a layer in which

Fig. 7 Effect of the water-to-cement ratio on porous zone thickness at RCI (adapted from Chen et al. [150])

Ca^{2+} ions may diffuse from outside the interface area, causing the creation of the considerable content of calcium hydroxide [146, 159]. Although there is no considerable changes in porous zone thickness concerning time, the hydration products (such as calcium hydroxide and other hydration products) vary regarding the curing time [139]. Quantity of the hydration products at RCI affects the RCI bond strength. The formation of calcium hydroxide can be affected by changing concrete types, resulting in changing bond strength. However, only some scattered research studied this important phenomenon for limited numbers of concrete types. In this field, Zayed [140] reported that additions of silica fume to mixture causes a drastic impact on reducing the calcium hydroxide content at the close proximity of RCI (Fig. 9). The formation of this region is due to the presence of some water-filled voids at RCI. Bentur and Cohen [160] similarly showed that by adding 15.0% silica fume by weight of cement, the microstructure of the interfacial zone is considerably modified without the presence of a considerable calcium hydroxide content. Goudar et al. [139] used the atomic weights of the calcium/silicon ratio for illustrating the existence of calcium hydroxide or calcium silicate hydrate (CSH) at RCI. They found that the calcium/silicon ratio more than 1.70 shows the presence of calcium hydroxide, while the range 0.70–1.80 for calcium/silicon ratio shows the presence of CSH gel at RCI. Their results indicate that the calcium/silicon ratios at the RCI for ordinary Portland cement (OPC), Portland pozzolana cement (PPC), and Portland slag cement (PSC) concrete were 2.88, 2.44, and 2.40, respectively (Fig. 10). These high contents of calcium/silicon ratios show the considerable content of calcium hydroxide at the RCI. It is worth mentioning that

Fig. 9 Effects of silica fume on the calcium hydroxide percentage of the transition zone (adapted from Zayed [140])

Fig. 10 Calcium/silicon ratio with respect to the distance from the steel surface for 28 days of curing (adapted from Goudar et al. [139], OPC = ordinary Portland cement, PPC = Portland pozzolana cement, PSC = Portland slag cement)

as the distance from the rebar edge increases toward the matrix, the calcium/silicon ratio decreases, which indicates a lower amount of calcium hydroxide [139]. Clearly, their results emphasize that even the type of cement used in concrete can affect the RCI microstructure, followed by changing the RCI bond strength. Regarding different types of cement used in their tests, it can be clearly deduced that the contents of the calcium/silicon ratio for PPC and PSC concretes significantly reduced, which can be attributed to the improvement of the pozzolanic reaction and creation of more secondary CSH gel, which increases the RCI bonding [139]. To put it simply, they found that by decreasing the calcium/silicon ratio, the maximum bond strength increased. In this field, Horne et al. [146] used backscattered electron image analysis to confirm the calcium hydroxide layer

Fig. 11 A typical example of the results of the backscattered electron images procedure (for vertically cast steel at 28 days, w/c=0.49) (adapted from Horne et al. [146], Num-1 and Num-3 lines show 95% confidence intervals)

Fig. 12 Orientation index of calcium hydroxide of the RCI between steel rebar and cement paste (adapted from Yue and Shuguang [155])

around the rebar at RCI (Fig. 11). They reported that a larger amount of calcium hydroxide exists nearby both the steel (30%) and aggregate (20–25%), as compared with the bulk cement paste (12%) [146]. Additionally, the content of calcium hydroxide at RCI decreases as the w/c ratio increases, from around 30% for w/c ratio of 0.49 to 19% for w/c ratio of 0.70. Yue and Shuguang [155] defined the orientation index for measuring the content of calcium hydroxide at RCI for ordinary and expansive cement. They reported that the $\text{Ca}(\text{OH})_2$ in the bulk concrete matrix of ordinary and expansive paste cannot be oriented (Fig. 12), while considerable orientation index was obtained at RCI especially after 7 days curing. They also observed that the orientation indices of expansive paste at different hydration ages are lower as compared

with the ordinary paste (Fig. 12). This clearly shows that the microstructure of the expansive paste was developed as compared with ordinary cement paste [155].

As comprehensively reviewed in the present section, performing parallelly both RCI bond strength investigations and transition zone studies are necessary to accurately determine the effect of concrete composition on RCI characteristics. The present study proposes Fig. 13 as an efficient approach for studying the effect of new generations of concrete mixtures on RCI characteristics. Combining both macro and micro studying the RCI can help to accurately explain the efficiency of future generations of concrete mixtures. Hence, extensive experimental studies are necessary to interpret the current results summarized in Table 2 and Fig. 4.

4 Case study: concrete containing nanoparticles

To emphasize the importance and necessity of the discussed subject in the present study, nanoparticle-based concrete, denoted as “nano-concrete”, is considered in this section. Nano-concrete is a construction material that uses nanoparticles with a size of less than 500 nm [161]. Low electrical resistivity [162], self-sensing [163], self-monitoring capability [164], self-cleaning [165], self-healing [166], high ductility [167], self-control of cracks [168], reduction of shrinkage [169], thermal conductivity [170], and high mechanical performance (Table 3) are the main characteristics of mixtures containing nanoparticles. Several types of nanomaterials were used to improve the characteristics of concrete such as nano- SiO_2 , nanoclay, nano- Al_2O_3 ,

Fig. 13 Proposed approach for studying the effect of concrete composition on RCI by combining micro and macro studies

Table 3 Literature review on the mechanical strength of nano-concrete

Reference	Nanoparticle	Remarks
Bigley and Greenwood [188]	Amorphous nanosilica	Improved workability and strength of SCC
Li et al. [164, 185]	Nano-SiO ₂ and nano-Fe ₂ O ₃	Improved compressive strength (3% opt dosage for nano-Fe ₂ O ₃ and 10% for nano-SiO ₂)
Fan et al. [189]	Synthetic nano-ZrO ₂	Development in mechanical properties as a results of the pore filling and bridging action
Li et al. [190]	Nano-alumina	There is no clear trend for the increase of compressive strength (5% opt dosage at 7 days and no opt dosage for 28 days)
Li et al. [162]	Carbon nanotubes (CNTs)	Using treated or untreated CNTs in cement paste causes a noticeable improvement in compressive sensitivity
Mann [191]	Carbon nanotube	Improved compressive and flexural strengths
Sobolev et al. [192]	SiO ₂ nanoparticles	Improved compressive and flexural strengths
Sadrmomtazi et al. [193]	Nano-SiO ₂	Improved compressive (7% opt dosage)
Nazari et al. [186]	Al ₂ O ₃ nanoparticles	Improved flexural strength (1% opt dosage)
Nazari et al. [187]	TiO ₂ nanoparticles	Improved tensile splitting and flexural strengths of concrete along with a reduction in setting time (1% opt dosage)
Givi et al. [194]	SiO ₂ nanoparticles	Mechanical properties of mixtures containing SiO ₂ particles with average particle size of 15 nm are higher than those containing 80 nm particle size
Morsy et al. [195]	Nano-metakaolin	Tensile and compressive strength increased (1.5% opt dosage for 80 nm nanoparticles and 1.0% opt for 15 nm)
Morsy et al. [196]	Carbon nanotubes and nano-clays	Addition of 6% nano metakaolin increased compressive strength of mortar containing carbon nanotube (0.02% opt dosage)
Shekari et al. [197]	Nano-ZrO ₂ , nano-Fe ₃ O ₄ , nano TiO ₂ , and nano-Al ₂ O ₃	Improved compressive strength for all nanomaterials. For 1.5% nanoparticles, nano-Al ₂ O ₃ shows the highest compressive strength as compared with other nano-materials and reference
Heidari and Tavakoli [198]	Nano-SiO ₂ particles	An increase in compressive strength (mixture containing 10% ground ceramic powder and 1% nanoparticle have the highest compressive strength)
Morsy et al. [199]	Nano-metakaolin	15% nano-metakaolin considerably shows better residual compressive strength after high temperature (up to 800 °C)
Elkady et al. [200]	Nano-silica	Sonication is an efficient de-agglomeration method as it improved the compressive strength of concrete (up to 23%) by opt dosage of 1% nano silica
Oltulu and Şahin [201]	Nano-SiO ₂ , nano-Al ₂ O ₃ and nano-Fe ₂ O ₃	Addition of all oxide powders increased compressive strength of the mortars (opt dosage of 1.25% for nano-SiO ₂ , 1.25% for nano-Al ₂ O ₃ , 0.5% for nano-Fe ₂ O ₃)
Kartikeyan et al. [202]	Nano-silica	Improved compressive strength (opt dosage of 10%)
Hosseini et al. [203]	Nanoparticles and aminosilane	Aminosilane with nano-CaCO ₃ and nano-Al ₂ O ₃ particles causes lower mechanical characteristics as compared with nano-clay and nano-SiO ₂
Ferdiansyah et al. [204]	Nanocarbontubes	Mixtures containing nanocarbontubes along with 15% metakaolin showed higher strength as compared with normal mortar (1% opt dosage for silica fume- and metakaolin-contained mortar, 5% for rice husk- and fly ash-contained mortar)
Ghafari et al. [205]	Nano-silica	Dispersion of nanoparticles considerably affects the mechanical properties of nano-concrete

Table 3 (continued)

Reference	Nanoparticle	Remarks
Wang et al. [206]	Nano-silica and nano-calcium carbonate	Increased compressive strength of cement–silica fume–fly ash-based ultrahigh-strength concrete (UHSC, opt dosage of 1% for nano-silica and 2% for nano-calcium carbonate)
Sorathiya et al. [207]	Nano-TiO ₂	Improved compressive strength (opt dosage of 1%)

*“0%” denotes replacement percentages by weight of the powders or binders (cement + fillers or SCMs)

Fig. 14 TEM images of nano-particles used in the literature for studying RCI **(a)** Nano-silica

(Hashemi and MirzaeiMoghadam (2014) [208])

(b) SiO₂ nanoparticles

(Ismael et al. (2016) [210])

(c) Al₂O₃ nanoparticles

(Ismael et al. (2016) [210])

(d) Nano-silica particles

(Serag et al. (2017) [212, 213])

(e) Carbon Nanotubes

(Hassan et al. (2019) [216])

(f) Nano-clay de-agglomeration

(Hamed et al. (2019) [217])

nano-Fe₂O₃, carbon nanotubes, TiO₂ nanoparticles, etc. [171]. Extensive efforts were made to study the mechanical and durability properties of nano-concrete, which are summarized in some review papers [161, 172–181]. Previous studies only concentrated on compressive, tensile, and flexural strengths as the mechanical properties of nano-concrete. As mentioned in Table 3, general results indicate that nano-concrete has higher compressive strength as compared with NC. Nanoparticles fill the nanopores of cement grains (or binders). Moreover, due to the higher surface energy of nanoparticles, hydration products can deposit on their surfaces, causing nanoparticle to be a nucleation site for lattice growth [180]. This mechanism improves the cement hydration process [182]. Additionally, dispersion methods, well-scattering of particles, have a considerably high effect on these mechanisms [183]. For instance, Horszczaruk et al. [184] showed that effective mechanical performance can be obtained by using acetone solution as dispersants in mesoporous nano-silica-based cement mortar. Different optimum (opt) dosages were reported for different types of nanomaterials. For instance, Li et al. [164, 185] obtained 3% (bwt of powder) opt dosage for nano-Fe₂O₃ and 10% for nano-SiO₂. In this field, experimental results reported by Nazari et al.

[186, 187] shows 1% opt dosage for both Al₂O₃ and TiO₂ nanoparticles.

As illustrated before in Fig. 3, there is a growing tendency to use nanoparticles in concrete mixtures, so that 9% of the previous RCI studies (2009–2019) has been concentrated on bond properties of steel rebar embedded in nano-concrete. However, there is no specific review paper on the effect of nanoparticles on RCI bond strength. Hence, this section intends to provide a comprehensive analysis of the effect of nanoparticles on RCI.

4.1 Details of the studied references

Different types of nanoparticle were used to test the RCI bond strength of rebar embedded in nano-concrete including nano-silica (SiO₂ nanoparticles), nano-alumina (Al₂O₃ nanoparticles), ZnO nanoparticles, carbon nanotubes, and nano-clay. SEM and TEM images of them are illustrated in Fig. 14. Details of nanomaterials used in literature are summarized in Table 4. The average particle size of nanoparticles varies between 8 and 130 nm. Range of 50–240 m²/g was reported for the specific surface of these nanomaterials. Details of RCI bond tests conducted for each of these nanoparticles are presented in Table 5. The dosage range of nanoparticles added to the concrete

Table 4 Details of nanomaterials used in literature of RCI

References	Nanomaterial	Appearance	Density (g/cm ³)	PH	Viscosity	Average particle size	Percentage of silica in the solid phase (%)	Specific surface (m ² /g)
Hashemi and Mirzaei Moghadam [208]	Nano-silica	White liquid	1.403	9.1	Max 15	34 nm	99.70	70–100
Hashemi and Sedighi [209]	Nano-silica	White liquid	1.403	9.1	Max 15	34 nm	99.70	70–100
Ismael et al. [210]	Nano-silica	–	2.22	–	–	–	–	–
	Nano-aluminum	–	3.95	–	–	–	–	–
Hamed et al. [211]	Nano-clay	Off-white powder	–	–	–	0.13 µm	62.24	51.05
Serag et al. [212, 213]	Nano-silica	–	–	–	–	20–80 nm	99.17	–
Hawreen and Bogas [214]	CNTSS (carbon nanotube)	Suspension	2.1	–	–	> 50 nm	–	–
	CNTSL	Suspension	2.1	–	–	20–40 nm	–	–
	CNTPL	Powder	2.1	–	–	20–40 nm	–	–
	CNTCOOH	Powder	2.1	–	–	20–40 nm	–	–
	CNTOH	Powder	2.1	–	–	10–30 nm	–	–
Madadi et al. [215]	Nano-silica	Liquid	1.203–1.215	9.6–10.2	5.0	–	–	200–240
Hassan et al. [216]	Multi-walled carbon nanotubes	–	–	–	–	8–22 nm	–	–
Hamed et al. [217]	Nano-clay de-agglomeration	Off-white powder	–	–	–	–	61.24	–

Table 5 Summary of total results of literature for bond strength in nano-concrete (number of 92 pull-out specimens)

Refer- ences	Nanomaterial (wt% of powder)	Bond test	C (mm)	L (mm)	Con- fine- ment	Reinforcing bar (rebar)		Concrete composition			$\tau_{\max}$ (MPa)	$\frac{\tau_{\max}}{f_c}$		
						Type	d_b (mm)	Compressive strength	$\frac{w}{p}$	Powder type			Aggre- gate type	
														Size
Hashemi and Mirzaei Mogh- adam [208]	Nano-silica	Cube	67	150	No	Steel	16	Cube (100×100×100)	28.26	0.35	Cement + Sil- ica fume	Light- weight	8.85	1.0
	LWP0.56	0							31.03	0.35			8.99	1.02
	LWP0.56N1.5	1.5							32.67	0.35			9.27	1.05
	LWP0.56N3	3.0							29.56	0.35			8.11	1.0
	LWP1	0							26.45	0.35			10.44	1.29
	LWP1N1.5	1.5							27.88	0.35			9.27	1.14
	LWP1N3	3.0												
Hashemi and Sedighi [209]	Nano-silica	Cube	67	150	No	Steel	16	Cube (100×100×100)	75.5	0.30	Cement + Sil- ica fume	Normal	12.3	1.0
	HS-W	0							76.8	0.30			13.1	1.07
	HN-3-W	3							64.3	0.40			10.3	1.0
	LS-W	0							67.8	0.40			11.2	1.09
	LN3-W	3							72.3	0.30			11.8	1.0
	HS-H ₂ SO ₄	0							74.8	0.30			12.8	1.08
	HN-3-H ₂ SO ₄	3							60.6	0.40			10.0	1.0
	LS-H ₂ SO ₄	0							61.8	0.40			11.1	1.11
	LN3-H ₂ SO ₄	3												
	Nano-SiO ₂ , Nano-Al ₂ O ₃	Cylinder	45	50	No	Steel	10	Cube (100×100×100)	40.1	0.46	Cement + Limestone filler	Normal	19.22	1.0
Ismael et al. [210]	Reference	0				Ribbed			43.3	0.45			13.03	0.68
	Si2%	2				Ribbed			40.1	0.45			19.78	1.03
	Al2%	2				Ribbed			74.2	0.40			22.46	1.0
	Reference	0				Ribbed			74.1	0.40			27.99	1.25
	Si2%	2				Ribbed			72.7	0.40			22.56	1.004
	Al2%	2				Ribbed			79.1	0.40			29.15	1.0
	F0.5	0				Ribbed			78.5	0.40			15.76	0.54
	F0.5Al2%	2				Ribbed			40.1	0.46			3.15	1.0
	Reference	0				Plain			43.3	0.45			3.77	1.20
	Si2%	2				Plain			40.1	0.45			3.47	1.10
	Al2%	2				Plain			74.2	0.40			5.09	1.0
	Reference	0				Plain			74.1	0.40			6.78	1.33
	Si2%	2				Plain			72.7	0.40			6.86	1.35
	Al2%	2				Plain			79.1	0.40			5.27	1.0
	F0.5 + fibre	0				Plain			78.5	0.40			5.43	1.03
	F0.5Al2%+fibre	2				Plain								

Table 5 (continued)

Refer- ences	Nanomaterial (wt% of powder)	Bond test	C (mm)	L (mm)	Con- fine- ment	Reinforcing bar (rebar)		Concrete composition			$\tau_{\max}$ (MPa)	$\frac{(\tau_{\max})_{\text{Nano}}}{(\tau_{\max})_{\text{NC}}}$		
						Type	d_b (mm)	Compressive strength	$\frac{w}{p}$	Powder type			Aggre- gate type	
														Size
Hamed et al. [211]	Nano-clay	Cube (150×150×150)	69	75	No	Steel	12	Cube (100×100×100)	37.70	0.43	Cement	Normal	19.10	1.0
	SNC0-d12						12						22.02	1.15
	SNC5-d12						12						29.62	1.55
	SNC7.5-d12						12						27.06	1.42
	SNC10-d12						16						21.09	1.0
	SNC0-d16						16						22.55	1.07
	SNC5-d16						16						24.94	1.18
	SNC7.5-d16						16						23.83	1.13
	SNC10-d16						12	Cube (100×100×100)	41.78	0.43	Cement	Normal	21.33	1.0
	Nano-silica	Cube (150×150×150)	69	75	No	Steel	12		49.03	0.43			23.93	1.12
Serag et al. [212, 213]	NS0-d12						12		59.82	0.43			29.52	1.38
	NS1.5-d12						12		53.94	0.43			21.87	1.03
	NS3-d12						16		41.78	0.43			14.81	1.0
	NS4.5-d12						16		49.03	0.43			15.35	1.04
	NS0-d16						16		59.82	0.43			16.13	1.09
	NS1.5-d16						16		53.94	0.43			14.91	1.01
	NS3-d16						12	Cube (150×150×150)	47.5	0.55	Cement	Normal	14.80	1.0
	NS4.5-d16						16		52.1	0.55			16.90	1.14
	Carbon nanotubes	Cube (200×200×200)	94	100	No	Hot- rolled steel ribbed bars	12		51.6	0.55			16.10	1.09
	RC								57.5	0.55			16.20	1.09
Hawreen and Bogas [214]	CNTPLC								46.2	0.55			15.40	1.04
	CNTCOOHC								50.7	0.55			15.60	1.05
	CNTSSC													
	CNTSLC													
	CNTOHC													

Table 5 (continued)

Refer- ences	Nanomaterial (wt% of powder)	Bond test	C (mm)	L (mm)	Con- fine- ment	Reinforcing bar (rebar)		Concrete composition			$\tau_{\max}$ (MPa)	$\frac{(\tau_{\max})_{\text{Nano}}}{(\tau_{\max})_{\text{NC}}}$			
						Type	d_b (mm)	Compressive strength	$\frac{w}{p}$	Powder type			Aggre- gate type		
														Size	f_c (MPa)
Madadi et al. [215]	Nano-silica	Cylinder (100×150)	42	75	No	Steel	16	Cube (100×100×100)		Cement (32.5, 42.5, and 52.5) + Micro-silica	Normal				
	ONS0MSC32.5	0						30	0.50			6.71 1.0			
	ONS0MSC42.5	0						34	0.50			8.47 1.0			
	ONS0MSC52.5	0						24	0.50			4.67 1.0			
	2.88NS7MSC32.5	2.88						48	0.40			7.37 1.1			
	2.88NS7MSC42.5	2.88						48	0.40			8.30 0.98			
	2.88NS7MSC52.5	2.88						45	0.40			10.43 2.23			
	7NS2.88MSC32.5	7.19						36	0.40			6.67 0.99			
	7NS2.88MSC42.5	7.19						30	0.40			6.43 0.76			
	7NS2.88MSC52.5	7.19						27	0.40			6.05 1.30			
	5.03NS5.03MSC32.5	5.03						45	0.40			7.83 1.17			
	5.03NS5.03MSC42.5	5.03						34	0.40			6.49 0.77			
	5.03NS5.03MSC52.5	5.03						24	0.40			10.32 2.21			
	1.44NS8.63MSC32.5	1.44						47	0.40			8.88 1.32			
	1.44NS8.63MSC42.5	1.44						38	0.40			8.63 1.02			
	1.44NS8.63MSC52.5	1.44						36	0.40			7.06 1.51			
	10.07NS0MSC32.5	10.07						33	0.40			5.93 0.88			
	10.07NS0MSC42.5	10.07						30	0.40			6.57 0.78			
	10.07NS0MSC52.5	10.07						20	0.40			6.82 1.46			

Table 5 (continued)

Refer- ences	Nanomaterial (wt% of powder)	Bond test	C (mm)	L (mm)	Con- fine- ment	Reinforcing bar (rebar)		Concrete composition			$\tau_{\max}$ (MPa)	$\frac{(\tau_{\max})_{\text{Nano}}}{(\tau_{\max})_{\text{NC}}}$	
						Type	d_b (mm)	Compressive strength	$\frac{w}{p}$	Powder type			Aggre- gate type
Hassan et al. [216]	Carbon nanotubes	Cube		75	No	Steel		Cube		Cement			
	12 mm	0	69				12	(150×150×150)	29	0.49	20.06	1.0	
	0.01%12 mm	0.01	69				12		31.2	0.49	24.27	1.21	
	0.02%12 mm	0.02	69				12		33	0.49	25.73	1.28	
	0.03%12 mm	0.03	69				12		35	0.49	26.53	1.32	
	16 mm	0	67				16		29	0.49	17.98	1.0	
	0.01%16 mm	0.01	67				16		31.2	0.49	18.79	1.05	
	0.02%16 mm	0.02	67				16		33	0.49	21.21	1.18	
	0.03%16 mm	0.03	67				16		35	0.49	22.54	1.25	
Hamed et al. [217]	Nano-clay ^a	Cube		75	No	Steel		Cube		Cement			
	Co-d12	0	69				12	(100×100×100)	37.7	0.43	19.1	1.0	
	5%NC-d12-A	5	69				12		38.7	0.43	20.16	1.06	
	7.5%NC-d12-A	7.5	69				12		44.6	0.43	23.34	1.22	
	10%NC-d12-A	10	69				12		41.4	0.43	23.24	1.22	
	5%NC-d12-B	5	69				12		43.9	0.43	22.02	1.15	
	7.5%NC-d12-B	7.5	69				12		57.2	0.43	29.62	1.55	
	10%NC-d12-B	10	69				12		54	0.43	27.06	1.42	
	Co-d16	0	67				16		37.7	0.43	21.09	1.0	
	5%NC-d16-A	5	67				16		38.7	0.43	21.3	1.01	
	7.5%NC-d16-A	7.5	67				16		44.6	0.43	22.12	1.05	
	10%NC-d16-A	10	67				16		41.4	0.43	21.4	1.01	
	5%NC-d16-B	5	67				16		43.9	0.43	22.55	1.07	
7.5%NC-d16-B	7.5	67				16		57.2	0.43	24.94	1.18		
10%NC-d16-B	10	67				16		54	0.43	23.83	1.13		
Summary of data- base	Dosage: 0.01–10.07 wt% of cement				d_b : 10–16 mm			f_c : 20–79.1 MPa		$\frac{(\tau_{\max})_{\text{Nano}}}{(\tau_{\max})_{\text{NC}}}$: 0.54–2.23			

^aDifferent dispersion technique: A= Stirred by the wooden stick with water; and B= 5 min sonication

Fig. 15 Ratio of nano-concrete to normal concrete bond strength: **a** with respect to the dosage of nanomaterials; **b** with respect to the ratio of normalized bond strength

mixtures is 0.01–10.07% by weight of cement. Different specimen sizes were considered in the literature for bond including cube and cylindrical sizes. Rebar diameters of 10–16 mm were used in their tests. Concrete mixtures with compressive strength of 20–79.1 MPa were provided. Only steel rebars were tested in literature for RCI in nano-concrete. More information is mentioned in Table 5.

4.2 RCI bond strength in nano-concrete

Overall results of previous studies on RCI bond strength in nano-concrete is summarized in Table 5. The ratio of RCI bond strength in nano-concrete to that of NC with respect to the nanomaterials dosage is illustrated in Fig. 15a. Considerable deviation is observed between nano-concrete and NC. Results show that the majority of RCI bond strength in nano-concrete is higher than NC. However, scattered trend is observed for nano-silica (Fig. 15a). Equation (1) and current regulations cannot predict and consider these observations. Increasing RCI bond strength as compared with the NC can be attributed to the higher compressive strength of nano-concrete than NC [185, 192, 218–220]. Nanoparticles not only act as nano-filler

to improve the microstructure but also act as an activator to accelerate pozzolanic reactions [221]. As reported by Morsy et al. [195], by uniformly dispersing the nanoparticles in the mixture, high surface energy of nanoparticles causes the sedimentation of the hydrate products of cement on the nanoparticles, and grow to generate conglomeration containing the nanoparticles as the nucleus. This nucleus develops and accelerates cement hydration reactions of C_3S due to the highly reactive surface of nanoparticles [222, 223]. However, compressive strength of concrete is not the only aspect affected by nanoparticles. In order to confirm this hypothesis, normalized RC bond strength by compressive strength of mixtures (τ/f_c) is illustrated in Fig. 15b for both NC and nano-concrete, which is a common way for ignoring effect of concrete compressive strength on RCI bond strength [21, 48]. Results indicate that considerable deviation exists between $\tau_{\text{nano}}/\tau_{\text{NC}}$ from the ratio $(\tau/f_c)_{\text{nano}}/(\tau/f_c)_{\text{NC}}$, especially for nano-clay, carbon nanotubes, and nano-silica (Fig. 15b). However, good correlation exists for nano-alumina. Despite the current challenging observations, there is no specific investigation to discuss and explain these results. This is the main intention of the present review paper to highlight this research gap. Hence, based on the proposed approach presented in Fig. 13, extensive experimental studies are necessary to be performed for transition zone characteristics at RCI.

5 Conclusions

A critical review study was performed in the present study on the effect of the concrete composition on RCI bond strength. Different concrete types were studied as compared with NC. Potential scenarios were also explained. Besides, the present review study highlighted current research gaps to be filled by future experimental studies, in the field of the transition zone at RCI, along with RCI bond tests. An efficient experimental approach was also introduced to practically study new types of concrete compositions. This approach mainly emphasizes on the importance of considering both RCI bond strength and transitions zone for new generations of concrete mixtures. Finally, nano-concrete was considered as a case study to illustrate the importance of the proposed approach and current considerable research gaps. Overall results indicate that it is essential for common regulations to consider new generations of concrete and their influences on RCI bond strength.

Future studies are needed to consider the effect of concrete composition variations on RCI bond strength. Moreover, future works are necessary to investigate the effect of supplementary cementitious materials and fillers on the RCI microstructure. Upcoming studies may

help design codes and regulations to define appropriate modifications and adjustments in RCI bond equations (or development length). This is crucial in steel-congested areas, such as beam–column joint and shear wall, where RCI is in a critical situation and extra attention is needed.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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