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Corresponding Author: Mr. Nikola Tošic, MSc Civil Engineering

Corresponding Author's Institution: University of Belgrade Faculty of Civil Engineering

First Author: Nikola Tošić, MSc Civil Engineering

Order of Authors: Nikola Tošić, MSc Civil Engineering; Snežana Marinković, PhD Civil Engineering; Ivan Ignjatović, PhD Civil Engineering

Abstract: A comprehensive database of recycled aggregate concrete and companion natural aggregate concrete beams' flexural and shear strength was compiled from 217 experimental results. Strict criteria were applied to determine the failure type. Sub-databases were formed with beams failing in flexure and shear with and without stirrups. On each sub-database the applicability of Eurocode 2 provisions for flexural and shear strength to recycled aggregate concrete beams was tested. The results show that flexural and shear strength of recycled aggregate concrete beams without stirrups is successfully predicted by Eurocode 2. As for beams with stirrups, further research and experimental results are necessary.

**Highlights_R1**

## Highlights:

- database of experimental results on recycled aggregate concrete beams compiled
- database filtered by different parameters—concrete strength, anchorage, etc.
- database analyzed to identify clear failure types~~ – ~~—flexural or shear
- sub-databases formed for flexural and shear failure (with and without stirrup)
- applicability of Eurocode 2 provisions to recycled aggregate concrete beams tested

# A database on flexural and shear strength of reinforced recycled aggregate concrete beams and comparison to Eurocode 2 predictions

N. Tošić[a,*], S. Marinković[a], I. Ignjatović[a]

[a] *University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia*

* Corresponding author. Tel.: +381 11 3218 547; fax: +381 11 3370 253.
E-mail address: ntosic@imk.grf.bg.ac.rs
Postal address: Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia

S.Marinković
E-mail address: sneska@imk.grf.bg.ac.rs
I.Ignjatović
E-mail address: ivani@imk.grf.bg.ac.rs

# ABSTRACT

A comprehensive database of recycled aggregate concrete and companion natural aggregate concrete beams' flexural and shear strength was compiled from 217 experimental results. Strict criteria were applied to determine the failure type. Sub-databases were formed with beams failing in flexure~~,~~ and shear with and without stirrups. On each sub-database the applicability of Eurocode 2 provisions for flexural and shear strength to recycled aggregate concrete beams was tested. The results show that flexural and shear strength of recycled aggregate concrete beams without stirrups is successfully predicted ~~using~~ by Eurocode 2. ~~For~~ As for beams with stirrups, further research and ~~more~~ experimental results are necessary.

**Keywords:**

recycled aggregate concrete; reinforced concrete; beams; database; flexural strength; shear strength; Eurocode 2

# 1. Introduction

## ~~1.1. Background~~

The construction industry today faces urgent calls to reform. The current rate of consumption of natural resources, waste generation and greenhouse gas emissions is unsustainable. On the one hand, new concrete requires the use of natural river or crushed stone aggregates, up to 15 billion tons annually worldwide [1]. On the other hand, old concrete structures are demolished and construction and demolition (C&D) waste is generated in large quantities, around 850 million tons in the EU annually [2].

It is not surprising that alternatives are being sought out. One solution that solves both problems simultaneously is recycling of concrete waste. Through a process that usually involves multi-stage crushing, eliminating impurities and sieving, a new aggregate is produced called recycled concrete aggregate (RCA). When this new aggregate is used to make concrete, with complete or partial replacement of natural aggregate, this concrete is called recycled aggregate concrete (RAC).

Recycled concrete aggregate and recycled aggregate concrete have been studied for several decades [3]. At the material level, practically all important characteristics of RCA and RAC have been studied, from short-term and long-term mechanical properties to durability [4–8]. The main characteristic that distinguishes RCA from natural aggregate is the certain quantity of cement paste that remains attached to the aggregates after crushing. This residual cement paste is the reason for higher water absorption of RCA compared with natural aggregates, especially in the case of fine RCA [9,10]. Beside the empirical observations about the influence of higher RCA water absorption on RAC properties, there have also been deeper, fundamental studies that demonstrated how the moisture state and water absorption of RCA influence the evolution of cement hydration [11]. The high water absorption of fine RCA has led to them mostly being avoided when producing RAC. However, even for coarse RCA the situation isn't much better as they make up only 1% of aggregates being used in structural concrete production worldwide [12].

This doesn't mean that research into the structural application of RAC has been lacking. Besides investigations of short-term flexural and shear performance of reinforced RAC beams, which is studied in this paper, there has been significant research on various other topics such as semi-precast RAC elements [13], shaking-table and pushover analyses of complete RAC frame structures [14,15] and long-term behavior of RAC beams [16]. Important literature also exists on the ecological and economic viability of RCA production and use [17–19].

Despite all of this, coordinated efforts by national and international institutions and organizations to codify the design procedures for RAC structural members have been lacking. Code provisions for material properties of RAC have been successfully tested and proven to be applicable [20,21] but these results cannot simply be extrapolated onto structural members. With the exception of China and its Technical Code on the Application of Recycled Concrete [22], neither European nor American concrete or standardization institutes have integrated provisions for the design of RAC structural members into their respective codes [23,24], even though researchers have attempted to demonstrate design procedures of RAC members according to them [25]. Besides natural aggregate concrete (NAC), only high-strength and lightweight aggregate concretes have been dealt with in their codes. Consequently, practicing engineers are faced with uncertainties in the rare situations when they have the opportunity to design structural RAC members.

### ~~*1.2. Research outline*~~

In the present paper, results on short-term flexural and shear behavior of RAC beams were gathered from available literature. Strict selection criteria were applied to determine the failure type, flexure or shear. A comprehensive database was compiled with three sub-databases: beams failing in flexure, in shear without and with stirrups. These selected results can be considered to represent well-executed experiments and clear failure types with as little shear-flexure interaction as possible. The compilation of such a database has been missing from existing literature and is critical for any design formula verification and calibration.

As a second part of this study, EN 1992-1-1:2004 (Eurocode 2 or EC2) [23] provisions for predicting flexural and shear strength were tested on RAC beams by calculating the ratio of test-to-predicted flexural and shear strengths. This ratio was called the “model factor” $\gamma$, as it represents the uncertainty and variability introduced into calculations by the model itself and by its appropriateness. This is separate from the uncertainties arising from loads and material properties, covered in design by the partial safety factors which were removed and characteristic values of material properties were replaced with mean values. This approach is, in essence, the same as that proposed by EN 1990:2002 (Eurocode – Basis of structural design) in Annex D—Design assisted by testing, [26].

The accuracy and precision of EC2 provisions was assessed using qualitative and quantitative analyses. In this study, accuracy is understood as the closeness of the model factor's mean value to 1.0 and precision is determined by the value of the model factor's coefficient of variation (CoV) i.e. scatter.

## 2. Database formation

### *2.1. Selection of studies*

The first step in this research was the collection of all available studies on shear and flexural strength of RAC beams. A review of existing literature yielded 16 studies [27–42] carried out in the period from 2001 to 2015 with a total of 217 experimental results. All of the studies were comparative tests of RAC and NAC beams. The replacement ratios of natural aggregate by coarse RCA, chosen for this study, were 0, 50 and 100% i.e. NAC, RAC50 and RAC100 concretes. In studies [32,33,35] the replacement ratio of 63.5% was assigned to RAC50 and the replacement ratio of 74.3% was assigned to RAC100 concrete.

Before compiling any database, rigorous selection criteria had to be established by which results would be tested. Since the aim of the study was to test the applicability of EC2 [23] flexural and shear strength predictions on RAC beams, the selection criteria had to ensure that only well-executed experiments and unambiguous results entered the database.

Only slender beams were analyzed since the test results on non-slender RAC beams are scarce. An initial screening was performed and any beams with a shear span-to-effective depth ratio smaller than 2.4 were eliminated. This value was chosen as critical so that a comparison with other databases could be performed [43,44]. This eliminated 17 results. Since EC2 prescribes different formulas for concrete classes greater than C50/60 and since high-strength RAC is not very common, only concretes with strengths smaller than 63 MPa were considered. This eliminated another 3 results. If the beams had stirrups then the minimum transverse reinforcement ratio was checked according to the EC2 limit:

$$\rho_w \geq 0.08\sqrt{f_c}/f_{yw} \tag{1}$$

where: $\rho_w$ – transverse reinforcement ratio

$f_c$ – 28-day concrete compressive strength on a Ø150/300mm cylinder (MPa)

$f_{yw}$ – transverse reinforcement yield strength (MPa)

This criterion eliminated another 3 results. Finally, 194 experimental results on NAC, RAC50, and RAC100 beams were left. Data were collected on beam geometry (width, depth, and effective depth), shear span-to-effective depth ratio, longitudinal and transverse reinforcement ratios and yield strength, concrete properties (percentage of RCA, maximum aggregate size, and compressive strength) and beam shear and flexural strengths. The data were then entered into an Excel spreadsheet that can be found in Appendix A.

### *2.2. Anchorage and shear-flexure interaction checks*

Although practically all of the studies claim to be testing either flexural or shear strength of beams, this cannot be trusted at face value. It is not uncommon for researches investigating shear strength to report a flexural failure of beams or vice versa. This means that the experimental setup and failure load for each beam have to be checked for anchorage failure and shear-flexure interaction.

To check against anchorage failure, the following condition must be satisfied:

$$\beta_{lb} = l_{b,req}/l_{b,prov} \leq 1 \tag{2}$$

where $l_{b,req}$ and $l_{b,prov}$ are the required and provided anchorage lengths (in mm) and $\beta_{lb}$ is the anchorage criterion. The required anchorage length was calculated according to section 8.4 of EC2 as:

$$l_{b,req} = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 l_{b,rqd} = 0.7 \cdot \frac{\emptyset}{4} \cdot \frac{\sigma_s}{2.25\,\eta_1\eta_2 f_{ct}} = 0.7 \cdot \frac{\emptyset}{9} \cdot \frac{\sigma_s}{f_{ct}} \tag{3}$$

where: $\alpha_1$- $\alpha_5$ – coefficients taking into account the shape of the bars, concrete cover, confinement by transverse reinforcement (welded and not welded to longitudinal reinforcement) and confinement by transverse pressure

$\varnothing$ – maximum diameter of longitudinal reinforcement (mm)

$\sigma_s$ – stress in longitudinal reinforcement at start of anchorage length (MPa)

$\eta_1$–$\eta_2$ – coefficients taking into account the bond condition and reinforcement diameter

$f_{ct}$ – 28-day concrete axial tensile strength (MPa)

While in some studies the bars had hooks and in others they were straight, all of the studies used steel support plates and consequently introduced large transverse pressures at the supports. Because of this the product $\alpha_1\alpha_2\alpha_3\alpha_4\alpha_5$ was taken as the minimum allowed value of 0.7 in all cases. All the studies had good bond conditions and bars with diameters smaller than 32 mm so the product $\eta_1\eta_2$ was equal to 1. The concrete tensile strength was calculated from compressive strength according to the formula given in Table 3.1 of EC2:

$$f_{ct} = 0.3 \cdot (f_c)^{2/3} \tag{4}$$

As for the stress in the longitudinal reinforcement, the calculation depended on whether the beam had stirrups or not since the mechanical models are different. In the case of beams with stirrups, the usual truss model was adopted and the stress calculated according to clause 6.2.3(7) of EC2:

$$\sigma_s = \frac{0.5 \cdot V_{R,test} \cdot \cot\theta}{A_{sl}} = \frac{1.25 \cdot V_{R,test}}{A_{sl}} \tag{5}$$

where: $V_{R,test}$ – experimental value of shear strength (N)

$A_{sl}$ – longitudinal reinforcement area (mm$^2$)

$\theta$ – angle of concrete compression strut inclination

When calculating Eq. (5) the angle $\theta$ was conservatively taken as the minimum value of 21.8º according to EC2. Mechanically, $\theta$ represents the angle of the concrete compression strut inclination in the truss model; in principle, it depends on the amount of stirrups. Hence, adopting $\theta$ = 21.8º in Eq. (8) is a conservative and simplistic assumption.

In the case of beams without stirrups, the load transfer mechanism is different so another model was necessary. For this purpose the provision given in Model Code 2010 (MC2010), equation (7.3-18) was adopted [45]:

$$\sigma_s = \frac{V_{R,test}}{A_{sl}} \tag{6}$$

It should be noted that in Eqs. (5) and (6) a simpler and more conservative assumption would have been to assume yielding of the longitudinal reinforcement, i.e. $\sigma_s = f_{yl}$. Nonetheless, ~~As~~ as can be seen from Appendix A, all 194 results satisfy the anchorage criterion.

In the case of shear-flexure interaction however, the situation is a little more complicated. Since the aim of the study was to analyze EC2 predictions of shear and flexural strength on RAC beams, the database had to be filtered for results that exemplified true and clear shear or flexural failures. A similar approach was taken in [43,44] where a check for flexural failures was performed on beams that were stated to have failed in shear. The check performed in [43,44] ~~these studies~~ consisted of calculating the test-to-predicted flexural strength ratio and checking if it is smaller than 1.1. If so, the beam was deemed to have failed in shear since it did not surpass its flexural strength by more than 10%.

However, using this approach, some flexural failures can be classified as shear and some situations in which the failure type is unclear, can be classified as either one. Consider, for example, a beam with a test-to-predicted flexural strength ratio equal to 1.05 and a test-to-predicted shear strength ratio equal to 0.65. Using this criterion, the beam would be classified as failing in shear, though it most likely failed in flexure. Another problematic situation would be a beam with both test-to-predicted strength ratios equal to 1.05. Again, it would be classified as a shear failure, even though it is actually very difficult to determine a clear failure type in this situation.

~~This approach however, disregards the fact that in some cases the test-to-predicted shear strength ratio can be equal or even lower than the test-to-predicted flexural strength ratio (e.g. both equal to 1.05) and still the beam would be classified as failing in shear.~~

In order to overcome this problem, a slightly different approach was formulated in the current study. First, the test-to-predicted flexural and shear strength ratios, $\beta_{fl}$ and $\beta_{sh}$ respectively, were calculated. When choosing according to which model to calculate the predicted values, care had to be taken to select the most accurate and physically meaningful models.

For flexural strength, the standard procedure given in ~~both EC2 and~~ MC2010 was thought to be satisfactory. For the concrete stress-strain relation the parabola-rectangle diagram was chosen whereas for the reinforcement steel stress-strain relation the idealized bi-linear diagram with a horizontal top branch was selected. The predicted flexural strength was calculated as:

$$M_{R,pred} = A_{sl} f_{yl} d \left(1 - 0.513 \frac{A_{sl} f_{yl}}{b d f_c}\right) \tag{7}$$

where: $M_{R,pred}$ – predicted value of flexural strength (Nm)

$f_{yl}$ – longitudinal reinforcement yield stress (MPa)

$d$ – cross-section effective depth (mm)

$b$ – cross-section width (mm)

For shear strength, MC2010 was chosen, specifically the level III approximation [45]. It was chosen as the physically most meaningful and justifiable model, based on the Modified compression field theory (MCFT). MC2010 defines shear strength as:

$$V_{R,pred} = V_{R,c}, \tag{8}$$

for beams without stirrups and for beams with stirrups greater than the minimum defined by Eq. (1) as:

$$V_{R,pred} = \begin{cases} V_{R,c}, + V_{R,s} & for \quad V_{R,c}, + V_{R,s} < V_{R,max} \\ \max\left(V_{R,c}; V_{R,s}\right) \leq V_{R,max} & for \quad V_{R,c}, + V_{R,s} \geq V_{R,max} \end{cases} \tag{9}$$

where: $V_{R,pred}$ – predicted value of shear strength (N)

$V_{R,c}$ – shear strength attributed to concrete (N)

$V_{R,s}$ – shear strength provided by stirrups (N)

$V_{R,max}$ – maximum allowed shear strength (N)

The shear strengths defined in Eq. (8,9) were calculated according to the following expressions:

$$V_{R,c} = k_v \sqrt{f_c} z b_w \tag{10}$$

$$V_{R,s} = \frac{A_{sw}}{s} z f_{yw} \cot\theta \tag{11}$$

$$V_{R,max} = k_\varepsilon \eta_{fc} f_c z b_w \sin\theta \cos\theta \tag{12}$$

where: *z* – inner lever arm = 0.9·d (mm)

$b_w$ – cross-section width or web width for I, L and T sections (mm)

$A_{sw}$ – transverse reinforcement area (mm$^2$)

*s* – transverse reinforcement spacing (mm)

The remaining coefficients and parameters were determined from the following equations:

$$\eta_{fc} = \left(\frac{30}{f_c}\right)^{1/3} \leq 1.0 \tag{13}$$

$$k_\varepsilon = \frac{1}{1.2 + 55\varepsilon_1} \leq 0.65 \tag{14}$$

$$\varepsilon_1 = \varepsilon_x + (\varepsilon_x + 0.002)\cot^2\theta \tag{15}$$

$$\varepsilon_x = \frac{V_{E,test}\left[\frac{d}{z}\left(\frac{a}{d} - 1\right) + 1\right]}{2 E_s A_{sl}} \tag{16}$$

$$\theta = 20° + 10000\varepsilon_x \tag{17}$$

$$k_v = \begin{cases} = \dfrac{0.4}{1 + 1500\varepsilon_x} \cdot \dfrac{1300}{1000 + k_{dg} z} & if \;\; \rho_w = 0 \\ = \dfrac{0.4}{1 + 1500\varepsilon_x} \cdot (1 - \dfrac{V_{E,test}}{V_{R,max,pred}}) \geq 0 & if \;\; \rho_w \geq 0.08\sqrt{f_c}/f_{yw} \end{cases} \tag{18}$$

$$k_{dg} = \frac{32}{16 + d_g} \geq 0.75 \tag{19}$$

where: $\varepsilon_x$ – longitudinal strain at mid-depth of beam (mm/mm)

$E_s$ – reinforcement steel modulus of elasticity (N/mm$^2$)

$d_g$ – maximum aggregate size (mm)

The test-to-predicted flexural and shear strength ratios were then calculated as:

$$\beta_{fl} = M_{R,test}/M_{R,pred} \tag{20}$$

$$\beta_{sh} = V_{R,test}/V_{R,pred} \tag{21}$$

as seen in columns 20 and 25 in Appendix A. The next step was to determine how the failure type can be identified with as much certainty as possible. Nominally, a test-to-predicted strength ratio greater than 1 points to a failure type. However, situations where both ratios are greater than 1 or smaller than 1 are also possible. It is clear that what points to a failure type isn't the absolute value of a test-to-predicted strength ratio but rather the difference between the two. The only outstanding question is then the selection of the critical value of this difference in reference to which failure types would be identified. The ratios should be sufficiently apart to guarantee that there is as little shear-flexure interaction as possible.

One approach to this problem would be defining a joint probability distribution of the difference $\Delta = \beta_{sh} - \beta_{fl}$ and operating with it. These calculations can be further complicated depending on the correlation between the variables and their marginal probability distributions. Instead, in this study, an empirical approach was chosen. First, a critical value, $\Delta_{cr}$, was chosen on the basis of experience. Secondly, the complete analysis was carried out using this criterion. Finally, the robustness and validity of the analysis and conclusions were tested by carrying out a sensitivity analysis of the critical value $\Delta_{cr}$.

From previous studies [38,46], it was found that the CoVs of $\beta_{fl}$ and $\beta_{sh}$, calculated according to different codes, are in the range of 0.05–0.15 and 0.20–0.30 respectively. ~~In this study~~Using these values as a reference point, the critical value $\Delta_{cr}$ ~~$= \beta_{sh} - \beta_{fl}$~~ was chosen as 0.35 (= $\text{CoV}_{\text{shear}}$ + $\text{CoV}_{\text{flexure}}$ = 0.25 + 0.10).

After calculating $\Delta_{cr}$ for each beam in the database the results were sorted into three sub-databases. If $\Delta_{cr} \geq 0.35$ and the beam had stirrups, the result was assigned to database Shear S and if it had no stirrups it was assigned to database Shear NS. If $\Delta_{cr} \leq -0.35$ the results were assigned to database Flexure. If $-0.35 \leq \Delta_{cr} \leq 0.35$ the result was left out of all databases. In this way, out of the original 194 results, 49 were assigned to database Flexure, 69 to Shear NS and 25 to Shear S. This means that 51 beams were excluded from all databases since according to the selected criteria it was not possible to determine whether the failure was shear or flexural.

For a more detailed presentation of the experimental results, Figs. 1–4 are given. In each of the figures, the number of beams $n$ is plotted versus a certain parameter—concrete compressive strength $f_c$, longitudinal reinforcement ratio $\rho_l$, beam effective depth $d$, and shear span-to-effective depth ratio $a/d$, respectively. Each parameter is divided into classes and the number of beams in each class is plotted, given separately for beams assigned to a database (Flexure, Shear NS, or Shear S) and for beams unassigned to any sub-database.

From Fig. 1 it can be seen that concrete compressive strengths in the range of 30–45 MPa comprise 72% of the original database. Also interestingly, most of the results on higher compressive strengths (>55 MPa) remained unassigned to any sub-database.

Figure 2 shows that longitudinal reinforcement ratios 0.5–2% make up 64% of the original database. However, there is a spike in the number of beams with a 2.5–3% longitudinal ratio (15% of the results) and all of them were assigned to a sub-database.

In Fig. 3, the number of beams is plotted versus the beams' effective depth and 92% of the results are with $d < 400$ mm. Importantly, the highest number of unassigned results is for beams with $d < 250$ mm, while all of the beams with $d > 400$ mm were assigned to sub-databases.

Finally, from Fig. 4 an almost uniform distribution of shear span-to-effective depth ratios between 2.4 and 4.4 can be seen. The largest number of unassigned results is in the 2.4–3.2 range.

In order to further expand the number of results, other databases available in literature were analyzed. The ACI-DAfStb database of shear strength of NAC beams contains 744 results of shear strength of slender beams without stirrups and 87 results on beams with stirrups [43,44]. Applying the criteria described in this section 507 results were assigned to database Shear NS and 37 to database Shear S.

In total, this amounts to 49 results in database Flexure (18 NAC, 14 RAC50, and 17 RAC100 beams), 576 results in Shear NS database (530 NAC, 24 RAC50, and 22 RAC100) and 62 results in Shear S (45 NAC, 8 RAC50, and 9 RAC100).

## 3. Eurocode 2 flexural and shear strength predictions for RAC beams

### *3.1. Flexural strength*

In this section the predictive capability of EC2 provisions for flexural strength of RAC beams was tested. For all the results in database Flexure the EC2 predictions were calculated. For concrete, a parabola-rectangle stress-strain diagram was chosen and for reinforcement steel, a bi-linear stress-strain diagram with a horizontal top branch. Since the EC2 provisions for flexural strength are identical to those of MC2010, ~~The ~~the predicted flexural strength was calculated according to Eq. (7) given in the previous section.

The database Flexure along with relevant data and the model factor $\gamma_{fl}$ is given in Table 1 and the statistical descriptors are given in Table 2. The mean values for all three samples (NAC, RAC50, and RAC100) are very close to 1, below 1.1, and the CoVs are satisfactorily low as well. This is to be expected as the analytical model for flexural failure is well-established and physically meaningful.

The next step was to visually assess the results, plotting the model factor values against relevant parameters, Figs. ~~1~~5–~~3~~7. In all of the figures horizontal lines were plotted representing the 5–95 percentile interval around the mean value for NAC beams ($\mu \pm 1.645 \cdot \sigma$) for easier assessment of the fit between RAC and NAC beams. As expected for flexure, this 5–95% interval is narrow and practically all the results fit within it. ~~What is also important is that there is no correlation of~~Moreover, no correlation emerges between the model factor ~~to ~~and any of the parameters—concrete compressive strength, longitudinal reinforcement ratio or cross-section effective depth. This means that the model's predictive capability is equal in the complete range of the parameters' values.

The initial visual inspection pointed to an excellent agreement between RAC and NAC beams, so further calculations were performed to quantify this observation. The statistical descriptors given in Table 2 can be used for statistical tests and comparisons of RAC and NAC beams. The usual procedure in these cases is to carry out the so-called *t*-test and compare the means of different samples.

When dealing with relatively small sample sizes, as in this case, the *t*-test requires the tested samples to be normally distributed [47]. To determine this, the Kolmogorov-Smirnov goodness-of-fit test was carried out. This is a non-parametric test that quantifies the distance between an empirical distribution function of the sample and the cumulative distributive function of the Normal distribution. In the case of NAC beams the following hypotheses were tested:

*Null hypothesis $H_0$:* The distribution of $\gamma_{fl,NAC}$ is Normal with $\mu = 1.064$ and $\sigma = 0.092$

*Alternate hypothesis $H_1$:* $\gamma_{fl,NAC}$ has a different distribution

*Level of significance:* $\alpha = 0.05$

RAC50 and RAC100 beams were tested in the same way for their descriptors as given in Table 2. The test statistic of the Kolmogorov-Smirnov test is the maximum difference between the empirical and hypothesized ~~distribution~~ distributions and it is compared to a critical value depending on the significance level and sample size. If the test statistic is smaller than the critical value, the null hypothesis should be retained. The test statistics were 0.118 for NAC, 0.261 for RAC50, and 0.245 for RAC100 beams and the critical values were 0.309, 0.349, and 0.318, respectively. This means that at the significance level $\alpha = 0.05$ (the probability that a test will reject a null hypothesis that is actually true) the null hypothesis should be retained for all three concretes.

The final step was to perform the *t*-test and see whether the means of $\gamma_{fl}$ for RAC50 and RAC100 were significantly different from the mean of $\gamma_{fl}$ for NAC beams. Both for RAC50 and RAC100 the following hypotheses were tested:

*Null hypothesis $H_0$:* $\mu_{NAC} = \mu_{RAC50/100}$

*Alternate hypothesis $H_1$:* $\mu_{NAC} \neq \mu_{RAC50/100}$

*Level of significance:* $\alpha = 0.05$

The *t*-test uses the sample means and variances ($\sigma^2$) to calculate a test statistic *t* that follows the Student's *T* distribution (hence the name, *t*-test). The test statistic and the cumulative distribution function are used to calculate the so-called *p*-value which, if smaller than 0.05 (the significance level), points to a significant difference between the samples, i.e. the null hypothesis should be rejected.

The calculated *p*-values were 0.734 for the NAC-RAC50 comparison and 0.524 for the NAC-RAC100 comparison. This means that there is no significant difference between the NAC and RAC samples at the 0.05 significance level. More concretely, this means that EC2 predictions of flexural strength are equally precise and accurate for NAC, RAC50, and RAC100. Flexural strength of RAC beams can be calculated using the existing provisions without any alterations.

### *3.2. Shear strength of slender beams without stirrups*

In this section the predictive capability of Eurocode 2 provisions for shear strength of slender RAC beams without stirrups was tested. For all the results in database Shear NS the Eurocode 2 predicted values of shear strength were calculated according to the following equation:

$$V_{R,c} = 0.18k(100\rho_l f_c)^{1/3} b_w d \tag{22}$$

where the longitudinal reinforcement ratio is limited to 2% and *k* is the size effect coefficient:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \tag{23}$$

The shear strength calculated according to Eq. (22) was compared with the maximum allowed value:

$$V_{R,max} = 0.5 b_w d f_c \left[0.6(1 - \frac{f_c}{250})\right] \tag{24}$$

and the minimum of the forces was taken as the predicted value $V_{R,pred}$ and the shear model factor, i.e. the test-to-predicted shear strength ratio $\gamma_{sh}$ was calculated.

The selected values from studies [27–42] that entered the database Shear NS along with relevant data and $\gamma_{sh}$ are given in Table 3 and the statistical descriptors are given in Table 4. The 507 results from [43] that entered the database are not repeated in Table 3. The mean values for all three samples are very similar and close to 1.

As a first step, Figs. ~~4~~8–~~7~~ 11 present the model factor $\gamma_{sh}$ in relation to concrete compressive strength, longitudinal reinforcement ratio, cross-section effective depth, and shear span-to-effective depth ratio, respectively. As for flexure, the 5–95 percentile lines were drawn in relation to the $\gamma_{sh}$ mean value for NAC beams.

Figure ~~4~~ 8 shows practically no correlation between $\gamma_{sh}$ and concrete compressive strength which means that this parameter is well captured by the current model. All of the NAC values above the 95% line are results from the ACI-DAfStb database. Looking at Figs. ~~5~~9–~~7~~ 11 these outliers can be easily identified. They are beams with a very small effective depth, a very large reinforcement ratio and a relatively low shear span-to-effective depth ratio. It is possible that for these beams the size effect coefficient $k$ is inadequate and also the limit of 2% for the longitudinal reinforcement ratio imposed by Eq. (22).

What is more important is that all but one RAC results lie within the 5–95% interval meaning that even though a relatively large range of parameters has been studied on RAC beams, they agree with the existing model very well.

As in section 3.1 this visual analysis was followed up by a statistical one. Again the Kolmogorov-Smirnov normality test was carried out to check whether $\gamma_{sh}$ for the NAC, RAC50, and RAC100 samples follows the Normal distribution. The test statistics were 0.175 for NAC, 0.163 for RAC50, and 0.229 for RAC100 and the critical values were 0.062, 0.269, and 0.275, respectively. This means that at the 0.05 significance level the null hypothesis should be retained in the case of RAC50 and RAC100 samples but rejected in the case of NAC beams, i.e. the RAC50 and RAC100 samples are normally distributed whereas the NAC sample is not.

The condition for carrying out the *t*-test is that the samples are normally distributed only when the sample sizes are small (e.g. smaller than 40–50). The Central Limit Theorem states that the average of a large number of independent random variables is approximately normally distributed around the true population mean [47]. With this in mind, although the NAC sample wasn't normally distributed, the *t*-test was carried out as in the previous section to test whether the means of $\gamma_{sh}$ for RAC50 and RAC100 samples were equal to that of the NAC sample.

The calculated *p*-values were 0.377 for the NAC-RAC50 comparison and 0.640 for the NAC-RAC100 comparison. This means that there is no significant difference between the NAC and RAC samples at the 0.05 significance level. As in the case of flexural strength, EC2 predictions for shear strength of beams without stirrups are equally precise and accurate for all concretes. Equation (22) can be used for RAC beams without stirrups without alterations.

### *3.3. Shear strength of slender beams with stirrups*

The last analyzed case was the EC2 provisions for shear strength of slender RAC beams with stirrups. For all the results in database Shear S the EC2 predicted values of shear strength were calculated according to Eq. (11), section 6.2.3 of EC2. Contrary to MC2010, for predictions according to EC2 the angle $\theta$ wasn't calculated but rather it was measured from the photos given in studies [27–42] as the inclination of the critical crack at beam mid-depth. However, its value was restricted to the interval 21.8º–45º as given in the same section.

For beams with stirrups EC2 takes the concrete contribution to shear strength into account through this variable inclination of the struts, i.e. the angle $\theta$. ~~Because EC2 ignores the concrete contribution to shear strength when stirrups are provided~~However, ~~cases~~ situations can arise ~~where~~ in which the shear strength without stirrups $V_{R,c}$ is greater than the shear strength with stirrups $V_{R,s}$. Without going into discussion whether there exist relevant design situations where this can arise, in this study both values were calculated and compared. The larger of the two was then compared to the maximum allowed value given by:

$$V_{R,max} = \frac{0.6zbf_c}{\cot\theta + \tan\theta} \tag{25}$$

and the minimum of these was taken as the predicted value $V_{R,pred}$ and the shear model factor $\gamma_{sh}$ was calculated.

As in the previous section, only the 25 values from studies [27–42] that entered the database Shear S along with relevant data and $\gamma_{sh}$ are given in Table 5 and the statistical descriptors are given in Table 6. The 37 results from [44] that entered the database are not repeated in Table 6.

One very important thing to note is that in 10 out of the 25 results from studies [27–42] the shear strength without stirrups $V_{R,c}$ was larger than the shear strength with stirrups $V_{R,s}$. This is mainly due to the fact that most of those results were beams reinforced with a transverse reinforcement ratio just above the minimum value of $0.08f_c^{0.5}/f_{yw}$. These are obviously beams in which, mechanically, $\theta$ would be lower than 21.8º, though this is not allowed by EC2; in other words, the concrete contribution is greater than is allowed for by the code.~~the concrete contribution to shear strength cannot be neglected~~.

This fact is responsible for a large discrepancy between the statistical descriptors of NAC versus RAC50 and RAC100 beams since the majority of NAC results were added from [44] and in those experiments the transverse reinforcement ratios were generally larger. The aforementioned problem is clear in Table 5 where it can be seen that the values of $\gamma_{sh}$ are very similar for all the concretes i.e. when only RAC and companion NAC beams are analyzed.

In Figs. ~~8~~12–~~11~~ 15 the model factor $\gamma_{sh}$ is plotted in relation to concrete compressive strength, unit stirrup stress, cross-section effective depth and shear span-to-effective depth ratio, respectively. As previously, the 5–95 percentile lines were drawn in relation to the $\gamma_{sh}$ mean value for NAC beams.

From all the figures a significant upward shift can be seen in the RAC50 and RAC100 results as discussed previously. Perhaps most notably on Figure ~~9~~13, the largest values of $\gamma_{sh}$ are clearly for beams with lower unit stirrup stresses.

Even though the difference between NAC and RAC beams is obvious from Table 6, for the purpose of methodological consistency the same statistical tests were carried out. The result of the Kolmogorov-Smirnov normality test was 0.178 for NAC, 0.102 for RAC50, and 0.152 for RAC100 and the critical values 0.189, 0.409, and 0.409, respectively. All three samples were normally distributed. The *t*-test was performed as in the previous sections to test whether the means of $\gamma_{sh}$ for RAC50 and RAC100 samples are equal to that of the NAC sample.

The calculated *p*-values were 0.000 for the NAC-RAC50 comparison and 0.009 for the NAC-RAC100 comparison. This means that there is a significant difference between the NAC and RAC samples at the 0.05 significance level and that the null hypothesis of equal means should be rejected. Initially this would suggest that Eq. (11) is not appropriate for RAC beams. However, the discussion in this section rather points to the fact that Eq. (11) is equally inadequate for NAC and RAC beams when they are reinforced with close to minimum transverse reinforcement. Preferably, more studies should be carried out on RAC and companion NAC beams with transverse reinforcement ratios larger than the minimum value.

### *3.4. Sensitivity analysis*

All of the discussion based on the analyses in the previous sections and all of the conclusion drawn from it are dependent on the analyzed databases. They in turn depend primarily on the selection criterion $\Delta_{cr}$, the difference between the test-to-predicted values of shear and flexural strength. In section 2.2 an argument was proposed why the value $\Delta_{cr}$ = 0.35 was chosen. After the analyses it can be seen from the CoVs in Tables 2, 4 and 6 that this choice was adequate. However, it can't be stated with certainty that different results wouldn't have been obtained with different samples.

In order to test to the robustness of the conclusions from previous sections, a short sensitivity analysis was carried out. Two additional scenarios are proposed:

a) $\Delta_{cr}$ = 0.25
b) $\Delta_{cr}$ = 0.45

With these criteria, formation of new databases Flexure, Shear NS and Shear S was performed. Table 7 presents the results. The number of results in each sample and statistical descriptors are given. In most cases the number of results in each database doesn't vary significantly i.e. it is not sensitive to the criterion $\Delta_{cr}$. Differences exist for NAC beams in database Shear NS and for RAC100 beams in database Shear S. In the former case the number of results increases or decreases by approximately 80–90 which is around 20% of the initial database. This sample is sensitive to changes in the criterion $\Delta_{cr}$ which is to be expected for beams without stirrups. What is important also is that the CoV remains relatively stable around 25%. In the case of RAC100 beams in database Shear S the significant change in mean values is due to the fact that the sample size decreases to only 3 results in the case of $\Delta_{cr}$ = 0.45.

The same statistical tests were carried out for the new databases and the only case where there was a change in the results was the NAC-RAC50 comparison in database Shear NS where a *p*-value of 0.034 was obtained with $\Delta_{\mathrm{cr}}$ = 0.25. In this case these two samples are significantly different. Since this is the case with a more relaxed selection criteria (i.e. the test-to-predicted strength ratios can be closer) this results could point to different shear-flexure interaction in RAC beams compared to NAC beams. Further investigation of this topic is not within the scope of this study.

Besides this, the fact that the mean values and CoVs generally don't change significantly for different selection criteria means that the conclusion reached in section 3 are robust and valid for the current state of knowledge of flexural and shear strength of RAC beams.

## 4. Conclusions

As with any database, the formation of the one presented in this paper is also subject to bias arising from availability of literature and criteria according to which results are selected. Consequently, all the results from the previous analyses are dependent upon the extensiveness and comprehensiveness of the database. This is why it is important to be transparent about the database creation and analysis process when discussing results and making conclusions.

In this paper, 217 experimental results on RAC and companion NAC beams' flexural and shear strength were gathered from 16 studies. Results were filtered by compressive strength, shear span-to-effective depth ratio and transverse reinforcement ratio, leaving 194 results. To increase the number of results, already existing databases of NAC beams' shear strengths were added from literature. Within these results, failure types were identified using strict criteria and finally, on each failure type the applicability of Eurocode 2 predictions of flexural and shear strength to RAC beams were tested.

Having this in mind, for the databases created and analyzed in this paper the following conclusions can be drawn:

1. There exist in literature, sufficient experimental results on RAC and companion NAC beams for the creation of a comprehensive database of flexural and shear strengths with 194 results.
2. The failure types (flexural or shear) nominally tested in the studies aren't always achieved in the experiment and criteria must be applied to determine the failure type. This can be done using Model Code 2010 provisions and comparing the difference between the test-to-predicted shear and flexural strength ratios. Using these criteria, out of 194 results, 49 were identified as flexural failure, 69 as shear failure without stirrups and 25 as shear failure with stirrups while for 51 results the failure type could not be clearly identified.
3. Eurocode 2 predictions of flexural strength are accurate and precise with a mean value of test-to-predicted strength ratio of 1.064 for NAC, 1.079 for RAC50, and 1.091 for RAC100 beams. The CoVs are 8.64%, 14.36%, and 13.24% respectively. Using the statistical *t*-test it was shown that these three samples show no significant difference between them.

Flexural strength of RAC beams can be calculated using the existing provisions without any alterations.

4. Eurocode 2 predictions of shear strength for beams without stirrups are accurate but less precise compared to flexural strength. The mean value of test-to-predicted strength ratio is 1.030 for NAC, 1.060 for RAC50, and 1.054 for RAC100 beams while the CoVs are 27.03%, 14.25%, and 22.07% respectively. Using the statistical *t*-test it was shown that these three samples show no significant difference between them. Shear strength of RAC beams without stirrups can be calculated using the existing provisions without any alterations.
5. Eurocode 2 predictions of shear strength for beams with stirrups are both inaccurate and imprecise. The mean value of test-to-predicted strength ratio is 1.346 for NAC, 1.861 for RAC50, and 1.682 for RAC100 beams while the CoVs are 25.03%, 15.34%, and 20.71% respectively. Using the statistical *t*-test it was shown that these three samples are significantly different. This was because most of the experiments on RAC beams were carried out applying close to minimum transverse reinforcement ratios and for this type of beams Eurocode 2 predictions are equally inaccurate and imprecise for both RAC and NAC beams. The difference between NAC and RAC beams arose only when other results on NAC beams from literature were added, with high transverse reinforcement ratios. More experiments on RAC beams with larger than minimum transverse reinforcement ratios should be carried out in order to draw a final conclusion.
6. A sensitivity analysis by selection criteria variation showed that the database of flexural strength is insensitive to criteria variation whereas the databases of shear strengths with and without stirrups are somewhat sensitive. For beams without stirrups this can be explained by a large scatter of the test-to-predicted strength ratio whereas for beams with stirrups the reason is the small number of results on RAC beams.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version.

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Figure ~~11~~15. Model factor for Eurocode 2 predictions of shear strength for beams with stirrups compared to shear span-to-effective depth ratio

Table 1. Eurocode 2 predictions of flexural strength for 49 selected beams

| Study | Specimen | RCA (%) | $b_w$ (mm) | $d$ (mm) | $\rho_l$ (%) | $f_{yl}$ (MPa) | $f_c$ (MPa) | $M_{E,test}$ (kNm) | $M_{R,pred}$ (kNm) | $\gamma_{fl}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| [27] | V45-03-WB | 0 | 150 | 160 | 1.06 | 331 | 57.0 | 15.0 | 13.6 | 1.10 |
| | VEX45-03-WB | | 150 | 160 | 1.06 | 331 | 55.3 | 15.3 | 13.6 | 1.13 |
| | V-01-10WB | | 150 | 160 | 0.59 | 331 | 30.6 | 8.0 | 8.0 | 1.00 |
| | V-01-10DB | | 150 | 160 | 0.59 | 331 | 32.5 | 9.1 | 8.0 | 1.13 |
| [30] | CL-Av | | 200 | 304 | 1.99 | 420 | 37.1 | 142.7 | 165.1 | 0.86 |
| | CG-Av | | 200 | 304 | 1.99 | 420 | 33.8 | 139.1 | 162.4 | 0.86 |
| [34] | BSF4-A0 | | 400 | 525 | 2.34 | 380 | 26.9 | 878.9 | 813.8 | 1.08 |
| [35] | NAC1a | | 200 | 268 | 0.28 | 640 | 35.0 | 28.4 | 25.2 | 1.13 |
| | NAC2a | | 200 | 263 | 1.46 | 550 | 35.0 | 108.6 | 97.5 | 1.11 |
| | NAC3a | | 200 | 244 | 2.54 | 550 | 35.0 | 137.6 | 134.8 | 1.02 |
| [38] | F0-1a | | 150 | 200 | 1.3 | 572 | 38.6 | 42.6 | 41.3 | 1.03 |
| | F0-1b | | 150 | 200 | 1.3 | 572 | 38.6 | 43.1 | 41.3 | 1.04 |
| | F0-2a | | 150 | 200 | 1.3 | 572 | 46.5 | 43.8 | 42.1 | 1.04 |
| | F0-2b | | 150 | 200 | 1.3 | 572 | 46.5 | 43.8 | 42.1 | 1.04 |
| [39] | N0-0.5 | | 135 | 230 | 0.5 | 377 | 38.6 | 15.9 | 13.3 | 1.20 |
| | N0-1.0 | | 135 | 230 | 1 | 408 | 38.6 | 28.2 | 23.8 | 1.19 |
| | N0-1.5 | | 135 | 230 | 1.5 | 389 | 38.6 | 36.9 | 33.6 | 1.10 |
| | N0-1.8 | | 135 | 230 | 1.8 | 410 | 38.6 | 52.8 | 48.1 | 1.10 |
| [35] | RAC50-1a | 50 | 200 | 268 | 0.28 | 640 | 35.4 | 27.0 | 25.2 | 1.07 |
| | RAC50-2a | | 200 | 263 | 1.46 | 550 | 35.4 | 110.6 | 97.6 | 1.13 |
| | RAC50-3a | | 200 | 244 | 2.54 | 550 | 35.4 | 160.4 | 135.2 | 1.19 |
| [38] | F50-1a | | 150 | 200 | 1.3 | 572 | 40.0 | 41.8 | 41.5 | 1.01 |
| | F50-1b | | 150 | 200 | 1.3 | 572 | 40.0 | 43.1 | 41.5 | 1.04 |
| | F50-2a | | 150 | 200 | 1.3 | 572 | 39.3 | 41.3 | 41.4 | 1.00 |
| | F50-2b | | 150 | 200 | 1.3 | 572 | 39.3 | 41.3 | 41.4 | 1.00 |
| [39] | N50-0.5 | | 135 | 230 | 0.5 | 377 | 29.0 | 13.6 | 13.2 | 1.03 |
| | N50-1.0 | | 135 | 230 | 1 | 408 | 29.0 | 24.4 | 23.4 | 1.04 |
| | N50-1.5 | | 135 | 230 | 1.5 | 389 | 29.0 | 32.8 | 32.8 | 1.00 |
| | N50-1.8 | | 135 | 230 | 1.8 | 410 | 29.0 | 50.5 | 46.4 | 1.09 |
| [30] | EM-Min | 63.5 | 200 | 304 | 0.49 | 420 | 41.6 | 46.0 | 29.5 | 1.56 |
| | EM-Av | | 200 | 304 | 1.99 | 420 | 41.6 | 149.2 | 168.1 | 0.89 |
| | EM-Max | | 200 | 304 | 3.26 | 420 | 41.6 | 221.9 | 208.7 | 1.06 |
| [30] | EV-Min | 74.3 | 200 | 304 | 0.49 | 420 | 49.1 | 46.7 | 29.6 | 1.58 |
| | EV-Av | | 200 | 304 | 1.99 | 420 | 49.1 | 150.2 | 171.9 | 0.87 |
| | EV-Max | | 200 | 304 | 3.26 | 420 | 49.1 | 225.2 | 215.1 | 1.05 |
| [27] | CR45-03-WB | 100 | 150 | 160 | 1.06 | 331 | 46.5 | 14.8 | 13.5 | 1.10 |
| | CREX45-03-WB | | 150 | 160 | 1.06 | 331 | 46.6 | 15.1 | 13.5 | 1.12 |
| | CR45-01-10WB | | 150 | 160 | 0.59 | 331 | 30.4 | 8.5 | 8.0 | 1.06 |
| | CR45-01-10DB | | 150 | 160 | 0.59 | 331 | 28.4 | 8.9 | 8.0 | 1.11 |
| | CR60-01-10WB | | 150 | 160 | 0.59 | 331 | 34.5 | 9.3 | 8.1 | 1.16 |
| | CR60-01-10DB | | 150 | 160 | 0.59 | 331 | 31.8 | 9.5 | 8.0 | 1.18 |
| [34] | BSF4-A100 | | 400 | 525 | 2.34 | 380 | 26.9 | 817.6 | 813.8 | 1.00 |
| [35] | RAC100-1a | | 200 | 268 | 0.28 | 640 | 34.0 | 26.8 | 25.2 | 1.07 |
| | RAC100-2a | | 200 | 263 | 1.46 | 550 | 34.0 | 105.4 | 97.1 | 1.09 |
| | RAC100-3a | | 200 | 244 | 2.54 | 550 | 34.0 | 142.6 | 133.7 | 1.07 |
| [38] | F100-1a | | 150 | 200 | 1.3 | 572 | 43.8 | 41.7 | 41.9 | 1.00 |
| | F100-1b | | 150 | 200 | 1.3 | 572 | 43.8 | 41.7 | 41.9 | 1.00 |
| | F100-2a | | 150 | 200 | 1.3 | 572 | 38.5 | 44.1 | 41.3 | 1.07 |
| | F100-2b | | 150 | 200 | 1.3 | 572 | 38.5 | 42.5 | 41.3 | 1.03 |

Table 2. Statistical descriptors of model factors for Eurocode 2 predictions of beams' flexural strength

| Concrete | Sample size, n | Mean, $\mu$ | Standard deviation, $\sigma$ | CoV (%) | Results outside the 5–95% range |
|---|---|---|---|---|---|
| NAC | 18 | 1.064 | 0.092 | 8.64 | 2 |
| RAC50 | 14 | 1.079 | 0.155 | 14.36 | 2 |
| RAC100 | 17 | 1.091 | 0.144 | 13.24 | 2 |

**Table 3_R1**

Table 3. Eurocode 2 predictions of shear strength for 69 selected beams without stirrups

| Study | Specimen | RCA (%) | $b_w$ (mm) | $d$ (mm) | $a/d$ | $\rho_l$ (%) | $f_c$ (MPa) | $V_{E,test}$ (kN) | $V_{R,pred}$ (kN) | $\gamma_{sh}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| [26] | HC-1 | 0 | 200 | 303 | 3.3 | 2.98 | 41.9 | 100.5 | 86.5 | 1.16 |
| [28] | V0CC |  | 200 | 303 | 3.3 | 2.98 | 40.2 | 88.9 | 85.3 | 1.04 |
| [31] | CL-M |  | 200 | 309 | 2.6 | 1.62 | 38.8 | 92.8 | 79.8 | 1.16 |
|  | CG-2.7 |  | 200 | 309 | 2.6 | 1.62 | 34.4 | 150.0 | 76.7 | 1.96 |
| [32] | NANAC-H2.5 |  | 200 | 360 | 2.5 | 1.61 | 24.7 | 90.7 | 77.2 | 1.17 |
|  | NANAC-H3.25 |  | 200 | 360 | 3.25 | 1.61 | 24.7 | 71.1 | 77.2 | 0.92 |
|  | NANAC-L2.5 |  | 200 | 360 | 2.5 | 0.53 | 24.7 | 66.2 | 53.3 | 1.24 |
|  | NANAC-M2.5 |  | 200 | 360 | 2.5 | 0.83 | 24.7 | 72.0 | 61.9 | 1.16 |
| [36] | NAC1b |  | 200 | 235 | 4.2 | 4.09 | 30.8 | 106.3 | 64.2 | 1.65 |
| [37] | NA-S2 |  | 200 | 300 | 2.5 | 1.94 | 31.8 | 75.5 | 77.5 | 0.97 |
|  | NA-M2 |  | 200 | 450 | 2.5 | 1.93 | 31.8 | 106.9 | 106.4 | 1.00 |
|  | NA-L2 |  | 200 | 600 | 2.5 | 1.94 | 31.8 | 125.9 | 134.5 | 0.94 |
|  | NA-M3 |  | 300 | 450 | 2.5 | 2.00 | 31.8 | 156.7 | 161.5 | 0.97 |
|  | NA-L4 |  | 400 | 600 | 2.5 | 1.94 | 31.8 | 256.4 | 269.0 | 0.95 |
| [40] | NAC NS-6 1 |  | 300 | 375 | 3.2 | 2.03 | 37.3 | 143.2 | 147.5 | 0.97 |
|  | NAC NS-8 1 |  | 300 | 375 | 3.2 | 2.71 | 37.3 | 173.5 | 147.5 | 1.18 |
|  | NAC NS-4 2 |  | 300 | 400 | 3 | 1.27 | 34.2 | 129.9 | 129.6 | 1.00 |
|  | NAC NS-6 2 |  | 300 | 375 | 3.2 | 2.03 | 34.2 | 167.0 | 143.3 | 1.17 |
|  | NAC NS-8 2 |  | 300 | 375 | 3.2 | 2.71 | 34.2 | 170.8 | 143.3 | 1.19 |
| [38] | S0-1a |  | 150 | 200 | 3.8 | 1.30 | 32.6 | 31.1 | 37.7 | 0.83 |
|  | S0-1b |  | 150 | 200 | 3.8 | 1.30 | 32.6 | 36.9 | 37.7 | 0.98 |
|  | S0-2a |  | 150 | 200 | 3.8 | 1.30 | 50.3 | 40.4 | 43.5 | 0.93 |
|  | S0-2b |  | 150 | 200 | 3.8 | 1.30 | 50.3 | 42.3 | 43.5 | 0.97 |
| [26] | HR50-1 | 50 | 200 | 303 | 3.3 | 2.98 | 41.3 | 89.0 | 86.1 | 1.03 |
| [28] | V0RC |  | 200 | 303 | 3.3 | 2.98 | 39.7 | 90.6 | 85.0 | 1.07 |
| [32] | RARAC50-H2.5 |  | 200 | 360 | 2.5 | 1.61 | 24.1 | 87.9 | 76.6 | 1.15 |
|  | RARAC50-H3.25 |  | 200 | 360 | 3.25 | 1.61 | 24.1 | 71.6 | 76.6 | 0.93 |
|  | RARAC50-M2.5 |  | 200 | 360 | 2.5 | 0.83 | 24.1 | 67.1 | 61.4 | 1.09 |
| [36] | RAC50-1b |  | 200 | 235 | 4.2 | 4.09 | 33.4 | 91.8 | 66.0 | 1.39 |
| [37] | RH-S2 |  | 200 | 300 | 2.5 | 1.94 | 32.6 | 60.6 | 78.1 | 0.78 |
|  | RH-M2 |  | 200 | 450 | 2.5 | 1.93 | 32.6 | 108.9 | 107.3 | 1.01 |
|  | RH-L2 |  | 200 | 600 | 2.5 | 1.94 | 32.6 | 126.1 | 135.6 | 0.93 |
|  | RH-M3 |  | 300 | 450 | 2.5 | 2.00 | 32.6 | 154.2 | 162.9 | 0.95 |
|  | RH-L4 |  | 400 | 600 | 2.5 | 1.94 | 32.6 | 261.5 | 271.3 | 0.96 |
| [40] | RAC50 NS-6 1 |  | 300 | 375 | 3.2 | 2.03 | 32.1 | 151.3 | 140.3 | 1.08 |
|  | RAC50 NS-8 1 |  | 300 | 375 | 3.2 | 2.71 | 32.1 | 171.8 | 140.3 | 1.22 |
|  | RAC50 NS-6 2 |  | 300 | 375 | 3.2 | 2.03 | 35.5 | 148.6 | 145.1 | 1.02 |
|  | RAC50 NS-8 2 |  | 300 | 375 | 3.2 | 2.71 | 35.5 | 168.7 | 145.1 | 1.16 |
| [38] | S50-1a |  | 150 | 200 | 3.8 | 1.30 | 43.6 | 44.0 | 41.5 | 1.06 |
|  | S50-1b |  | 150 | 200 | 3.8 | 1.30 | 43.6 | 39.1 | 41.5 | 0.94 |
|  | S50-2a |  | 150 | 200 | 3.8 | 1.30 | 40.2 | 43.7 | 40.4 | 1.08 |
|  | S50-2b |  | 150 | 200 | 3.8 | 1.30 | 40.2 | 41.2 | 40.4 | 1.02 |
| [33] | EM-4 | 63.5 | 200 | 305 | 3.9 | 2.46 | 41.6 | 83.2 | 86.7 | 0.96 |
|  | EM-L |  | 200 | 201 | 2.7 | 1.99 | 41.6 | 89.3 | 63.0 | 1.42 |
|  | EM-2.7 |  | 200 | 309 | 2.6 | 1.62 | 41.6 | 103.9 | 81.7 | 1.27 |
|  | EM-H |  | 200 | 381 | 2.7 | 1.83 | 41.6 | 99.5 | 100.2 | 0.99 |
|  | EM-VH |  | 200 | 476 | 2.7 | 1.68 | 41.6 | 104.6 | 116.3 | 0.90 |
| [33] | EV-4 | 74.3 | 200 | 305 | 3.9 | 2.46 | 49.1 | 105.6 | 91.7 | 1.15 |
|  | EV-L |  | 200 | 201 | 2.6 | 1.99 | 49.1 | 122.6 | 66.6 | 1.84 |
|  | EV-H |  | 200 | 381 | 2.7 | 1.83 | 49.1 | 111.7 | 105.9 | 1.05 |
|  | EV-VH |  | 200 | 476 | 2.7 | 1.68 | 49.1 | 119.6 | 122.9 | 0.97 |
| [25] | R3.0-N | 100 | 170 | 270 | 3 | 1.10 | 31.2 | 55.1 | 50.0 | 1.10 |
| [26] | HR100-1 |  | 200 | 303 | 3.3 | 2.98 | 39.8 | 84.0 | 85.0 | 0.99 |
| [32] | RARAC100-H2.5 |  | 200 | 360 | 2.5 | 1.61 | 22.6 | 84.8 | 75.0 | 1.13 |
|  | RAC100-M2.5 |  | 200 | 360 | 2.5 | 0.83 | 22.6 | 70.1 | 60.1 | 1.17 |
| [36] | RAC1000-1b |  | 200 | 235 | 4.2 | 4.09 | 34.5 | 104.8 | 66.7 | 1.57 |
| [37] | RF-S2 |  | 200 | 300 | 2.5 | 1.94 | 34.9 | 72.9 | 79.9 | 0.91 |
|  | RF-M2 |  | 200 | 450 | 2.5 | 1.93 | 34.9 | 96.4 | 109.8 | 0.88 |
|  | RF-L2 |  | 200 | 600 | 2.5 | 1.94 | 34.9 | 125.1 | 138.8 | 0.90 |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | RF-M3 | 300 | 450 | 2.5 | 2.00 | 34.9 | 159.8 | 166.6 | 0.96 |
|  | RF-L4 | 400 | 600 | 2.5 | 1.94 | 34.9 | 256.6 | 277.5 | 0.92 |
| [40] | RAC100 NS-6 1 | 300 | 375 | 3.2 | 2.03 | 30.0 | 143.2 | 137.2 | 1.04 |
|  | RAC100 NS-8 1 | 300 | 375 | 3.2 | 2.71 | 30.0 | 131.4 | 137.2 | 0.96 |
|  | RAC100 NS-6 2 | 300 | 375 | 3.2 | 2.03 | 34.1 | 124.1 | 143.2 | 0.87 |
|  | RAC100 NS-8 2 | 300 | 375 | 3.2 | 2.71 | 34.1 | 140.3 | 143.2 | 0.98 |
| [38] | S100-1a | 150 | 200 | 3.8 | 1.30 | 41.4 | 36.4 | 40.8 | 0.89 |
|  | S100-1b | 150 | 200 | 3.8 | 1.30 | 41.4 | 38.0 | 40.8 | 0.93 |
|  | S100-2a | 150 | 200 | 3.8 | 1.30 | 35.7 | 39.9 | 38.8 | 1.03 |
|  | S100-2b | 150 | 200 | 3.8 | 1.30 | 35.7 | 36.1 | 38.8 | 0.93 |

Table 4. Statistical descriptors of model factors for Eurocode 2 predictions of shear strength for beams without stirrups

| Concrete | Sample size, n | Mean, $\mu$ | Standard deviation, $\sigma$ | CoV (%) | Results outside the 5–95% range |
|---|---|---|---|---|---|
| NAC | 530 | 1.030 | 0.279 | 27.03 | 75 |
| RAC50 | 24 | 1.060 | 0.151 | 14.25 | 0 |
| RAC100 | 22 | 1.054 | 0.233 | 22.07 | 2 |

Table 5. Eurocode 2 predictions of shear strength for 25 selected beams with stirrups

| Study | Specimen | RCA (%) | $b_w$ (mm) | $d$ (mm) | $a/d$ | $A_{sw}$ (mm$^2$) | $s$ (mm) | $f_{yw}$ (mm$^2$) | $\theta$ (°) | $V_{E,test}$ (kN) | $V_{R,pred}$ (kN) | $\gamma_{sh}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [26] | HC-2 | 0 | 200 | 303 | 3.3 | 57 | 130 | 544 | 19 | 213.0 | 161.3 | 1.32 |
|  | HC-3 |  | 200 | 303 | 3.3 | 57 | 170 | 544 | 30 | 177.0 | 86.5 | 2.05 |
|  | HC-4 |  | 200 | 303 | 3.3 | 57 | 240 | 544 | 28 | 187.5 | 86.5 | 2.17 |
| [28] | V24CC |  | 200 | 303 | 3.3 | 57 | 240 | 500 | 22 | 128.0 | 84.6 | 1.51 |
|  | V17CC |  | 200 | 303 | 3.3 | 57 | 170 | 500 | 24 | 150.8 | 101.9 | 1.48 |
|  | V13CC |  | 200 | 303 | 3.3 | 57 | 130 | 500 | 26 | 190.3 | 121.6 | 1.56 |
| [29] | BNN-Ib2 |  | 200 | 250 | 3.2 | 57 | 100 | 234 | 30 | 115.5 | 68.0 | 1.70 |
| [36] | NAC3b |  | 200 | 235 | 4.2 | 57 | 150 | 300 | 21 | 159.9 | 64.2 | 2.49 |
| [26] | HR50-2 | 50 | 200 | 303 | 3.3 | 57 | 130 | 544 | 28 | 220.0 | 121.4 | 1.81 |
|  | HR50-3 |  | 200 | 303 | 3.3 | 57 | 170 | 544 | 22 | 176.0 | 122.1 | 1.44 |
|  | HR50-4 |  | 200 | 303 | 3.3 | 57 | 240 | 544 | 21 | 164.0 | 87.4 | 1.88 |
| [28] | V24RC |  | 200 | 303 | 3.3 | 57 | 240 | 500 | 25 | 164.3 | 84.7 | 1.94 |
|  | V17RC |  | 200 | 303 | 3.3 | 57 | 170 | 500 | 35 | 177.0 | 86.2 | 2.05 |
|  | V13RC |  | 200 | 303 | 3.3 | 57 | 130 | 500 | 21 | 233.6 | 148.3 | 1.58 |
| [36] | RAC50-3b |  | 200 | 235 | 4.2 | 57 | 150 | 300 | 21 | 156.9 | 66.0 | 2.38 |
| [31] | EM-6S-D | 63.5 | 200 | 301 | 2.7 | 157 | 200 | 530 | 31 | 341.0 | 187.7 | 1.82 |
| [31] | EV-3S-R | 74.3 | 200 | 301 | 2.7 | 101 | 200 | 530 | 27 | 235.0 | 141.6 | 1.66 |
|  | EV-6S-D |  | 200 | 301 | 2.7 | 157 | 200 | 530 | 28 | 327.0 | 212.1 | 1.54 |
| [26] | HR100-2 | 100 | 200 | 303 | 3.3 | 57 | 130 | 544 | 22 | 189.5 | 159.7 | 1.19 |
|  | HR100-3 |  | 200 | 303 | 3.3 | 57 | 170 | 544 | 24 | 163.0 | 110.8 | 1.47 |
|  | HR100-4 |  | 200 | 303 | 3.3 | 101 | 240 | 544 | 29 | 168.0 | 112.6 | 1.49 |
| [29] | ORN-Ib2 |  | 200 | 250 | 3.2 | 57 | 100 | 234 | 26 | 118.0 | 66.2 | 1.78 |
|  | BRN-Ib2 |  | 200 | 250 | 3.2 | 57 | 100 | 234 | 26 | 120.5 | 65.7 | 1.83 |
|  | GRN-Ib2 |  | 200 | 250 | 3.2 | 57 | 100 | 234 | 26 | 116.5 | 67.8 | 1.72 |
| [36] | RAC100-3b |  | 200 | 235 | 4.2 | 57 | 150 | 300 | 21 | 163.4 | 66.7 | 2.45 |

Table 6. Statistical descriptors of model factors for Eurocode 2 predictions of shear strength for beams with stirrups

| Concrete | Sample size, n | Mean, $\mu$ | Standard deviation, $\sigma$ | CoV (%) | Results outside the 5–95% range |
|---|---|---|---|---|---|
| NAC | 45 | 1.346 | 0.337 | 25.03 | 4 |
| RAC50 | 8 | 1.861 | 0.286 | 15.34 | 3 |
| RAC100 | 9 | 1.682 | 0.348 | 20.71 | 1 |

**Table 7**

Table 7. Statistical descriptors of model factors for Eurocode 2 predictions of beam's flexural and shear strength for different database selection criteria

| Database | Concrete | $\Delta_{cr}$ = 0.25 | | | $\Delta_{cr}$ = 0.45 | | |
|---|---|---|---|---|---|---|---|
| | | n | $\mu$ | CoV (%) | n | $\mu$ | CoV (%) |
| Flexure | NAC | 23 | 1.070 | 7.95 | 14 | 1.086 | 5.63 |
| | RAC50 | 14 | 1.079 | 14.36 | 14 | 1.079 | 14.36 |
| | RAC100 | 23 | 1.090 | 11.50 | 15 | 1.088 | 14.17 |
| Shear NS | NAC | 595 | 1.117 | 25.50 | 429 | 1.177 | 26.32 |
| | RAC50 | 27 | 1.048 | 14.29 | 21 | 1.079 | 13.25 |
| | RAC100 | 27 | 1.034 | 21.35 | 18 | 1.075 | 23.20 |
| Shear S | NAC | 50 | 1.348 | 24.67 | 38 | 1.375 | 25.23 |
| | RAC50 | 8 | 1.861 | 15.34 | 7 | 1.868 | 16.49 |
| | RAC100 | 12 | 1.683 | 18.72 | 3 | 1.966 | 24.91 |

Figure 1_R1

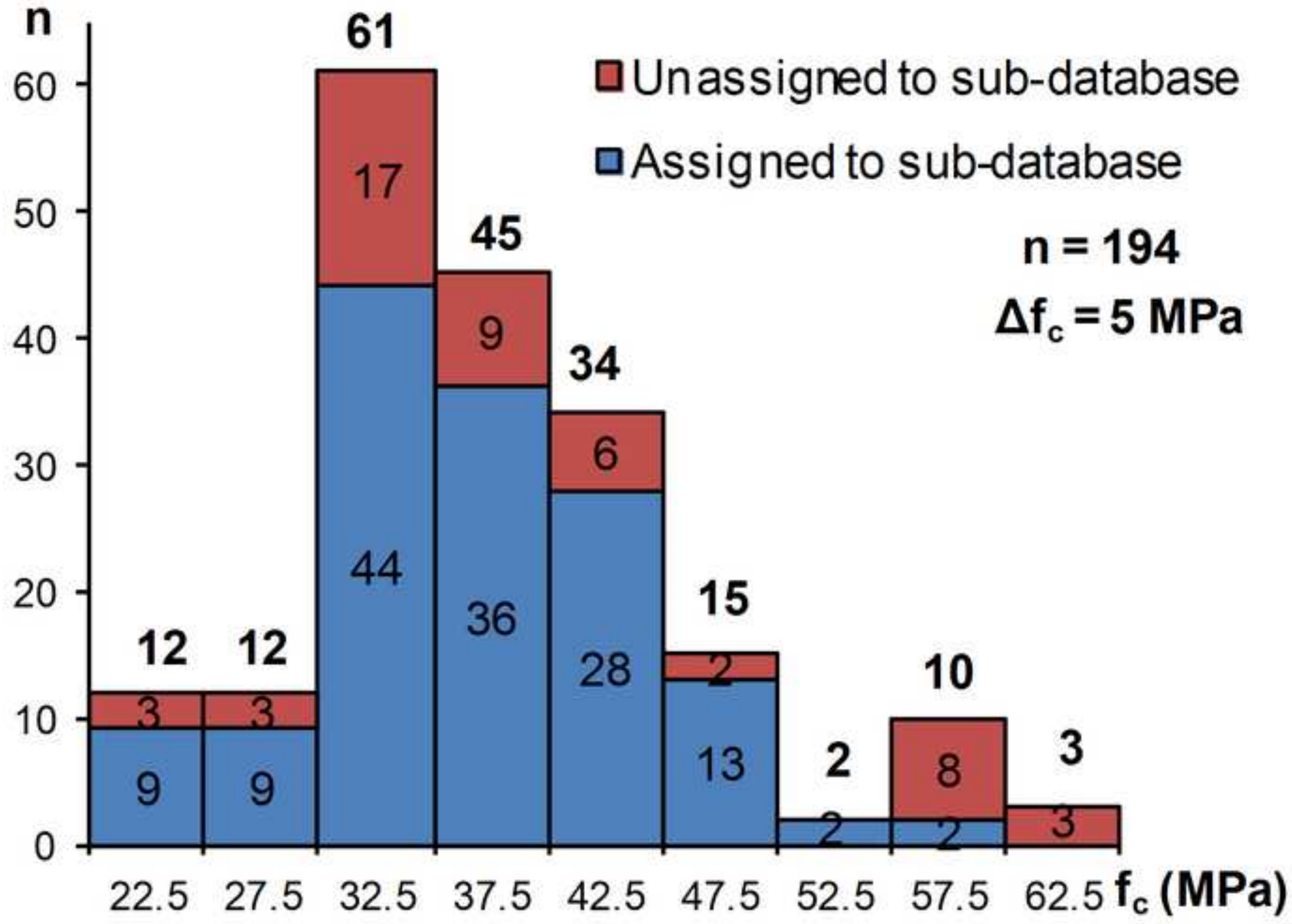
n
60
50
40
30
20
10
0
61
45
34
12
12
15
2
10
3
17
44
9
36
6
28
3
9
3
9
2
13
2
8
2
3
🟥 Unassigned to sub-database
🟦 Assigned to sub-database
n = 194
$\Delta f_c = 5$ MPa
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
$f_c$ (MPa)

**Figure 2_R1**

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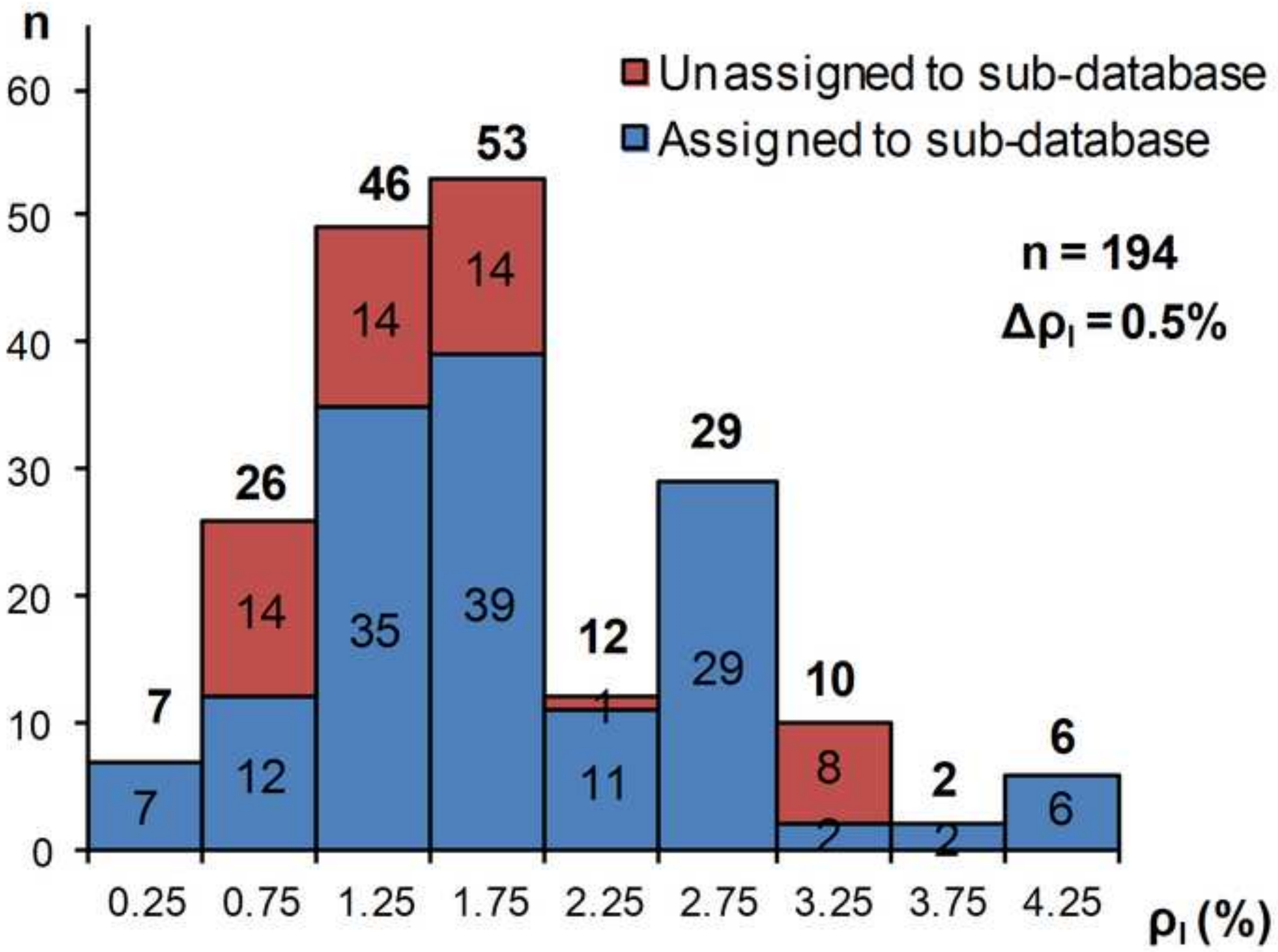

Figure 3_R1

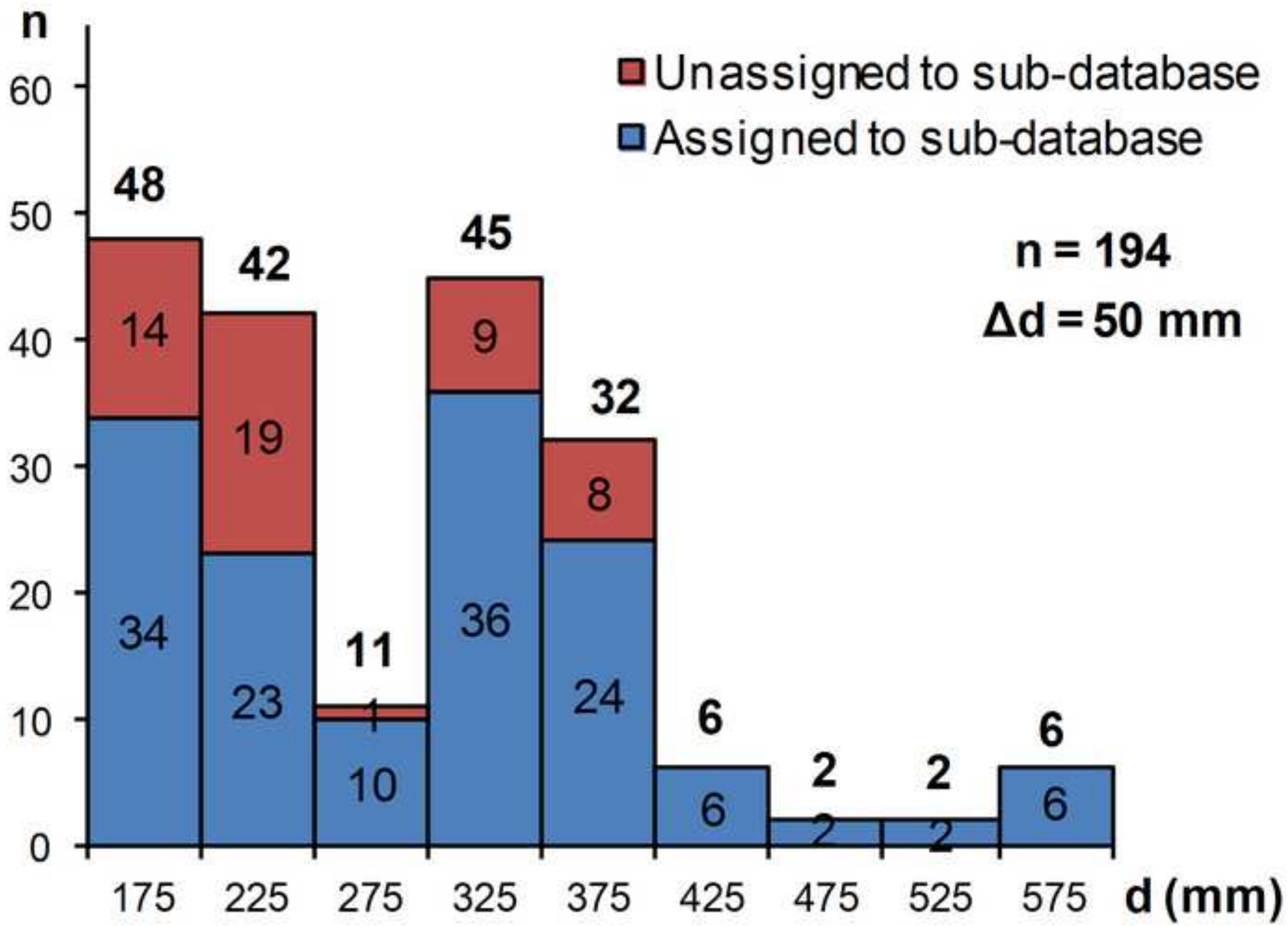
n
60
50
40
30
20
10
0
🟥 Unassigned to sub-database
🟦 Assigned to sub-database
48
14
34
42
19
23
11
1
10
45
9
36
32
8
24
6
6
2
2
2
2
6
6
n = 194
Δd = 50 mm
175
225
275
325
375
425
475
525
575
d (mm)

Figure 4_R1

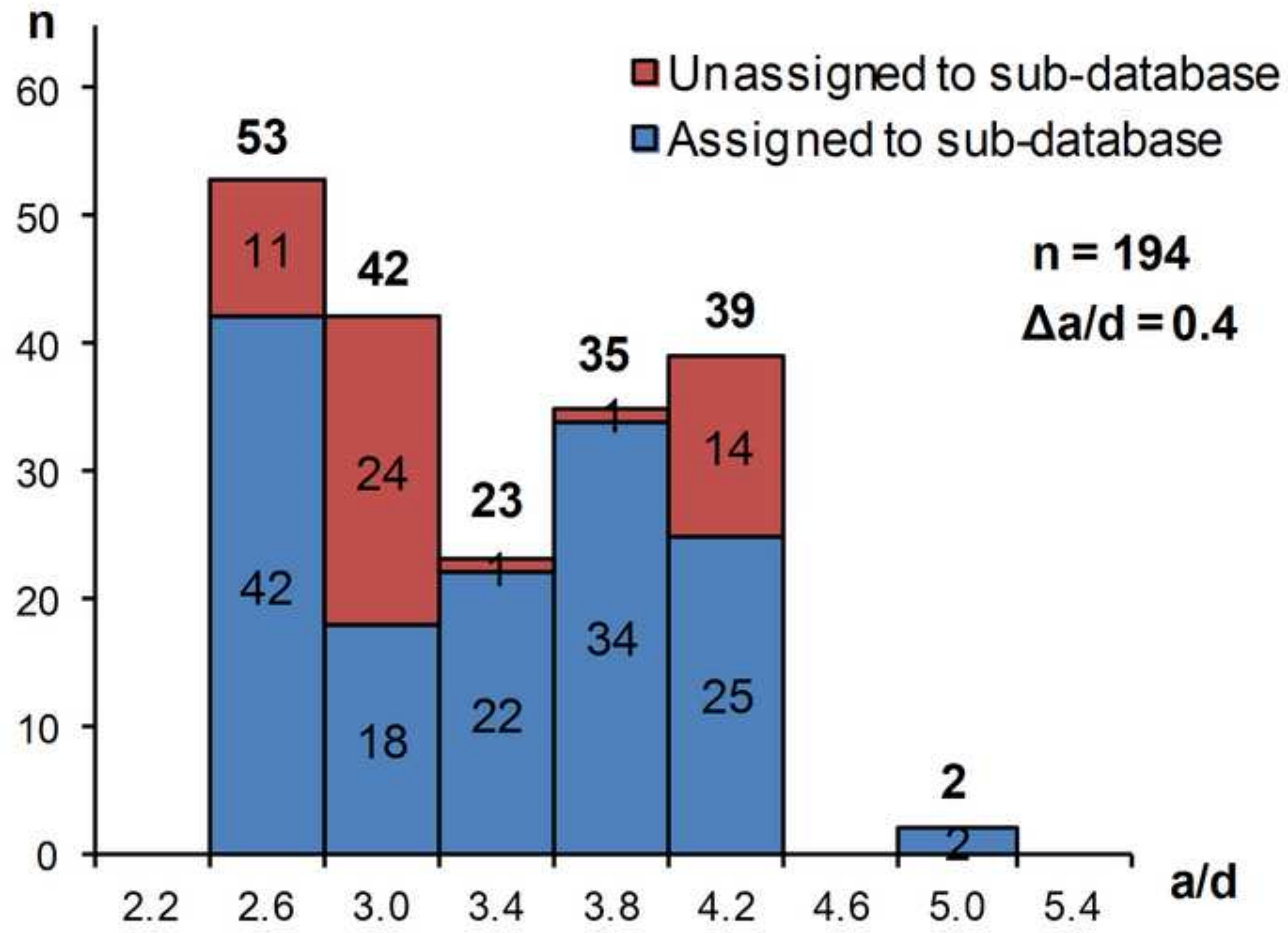
n
60
50
40
30
20
10
0
🟥 Unassigned to sub-database
🟦 Assigned to sub-database
53
11
42
42
24
18
23
1
22
35
1
34
39
14
25
2
2
n = 194
Δa/d = 0.4
2.2
2.6
3.0
3.4
3.8
4.2
4.6
5.0
5.4
a/d

**Figure 5_R1**

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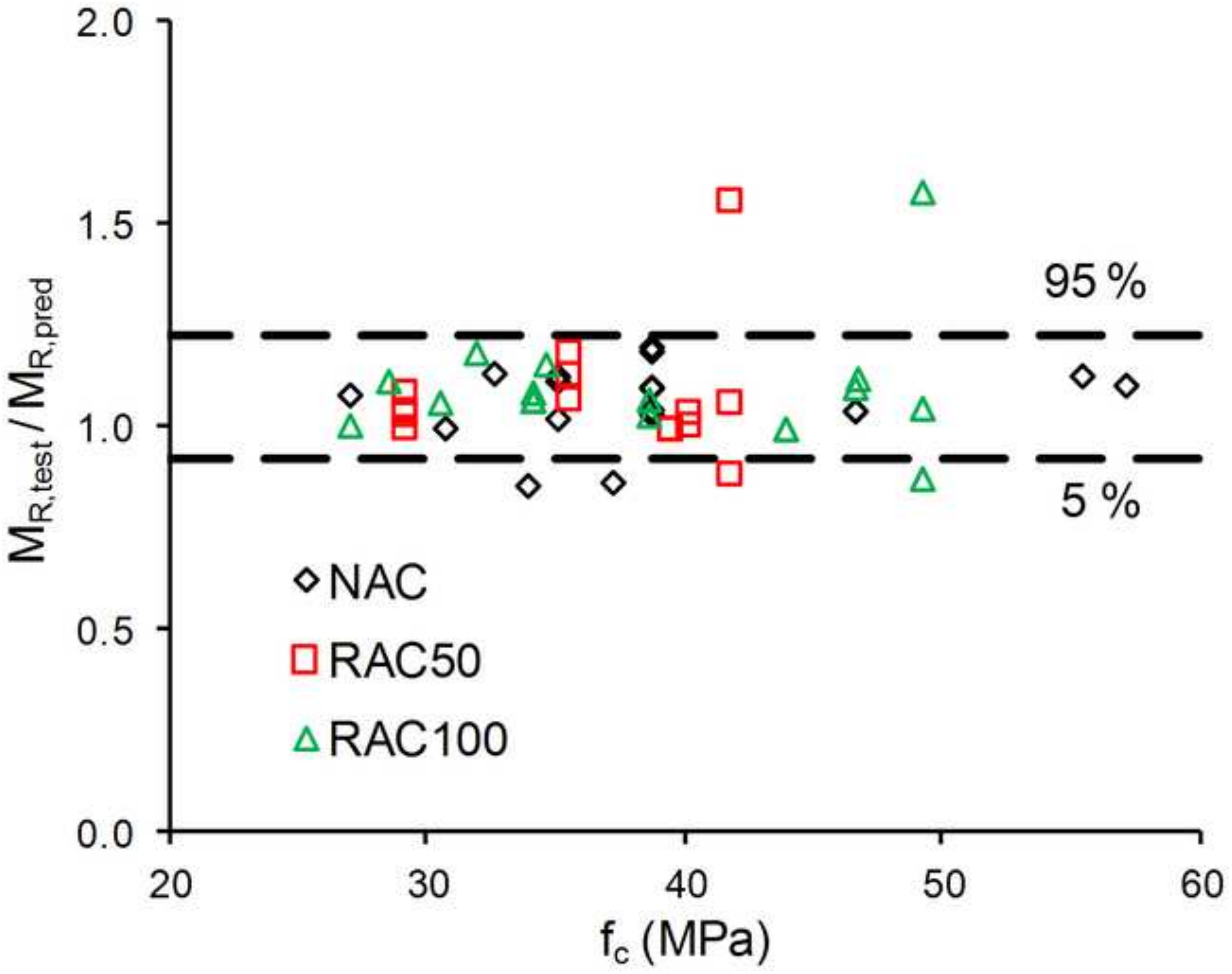

Figure 6_R1

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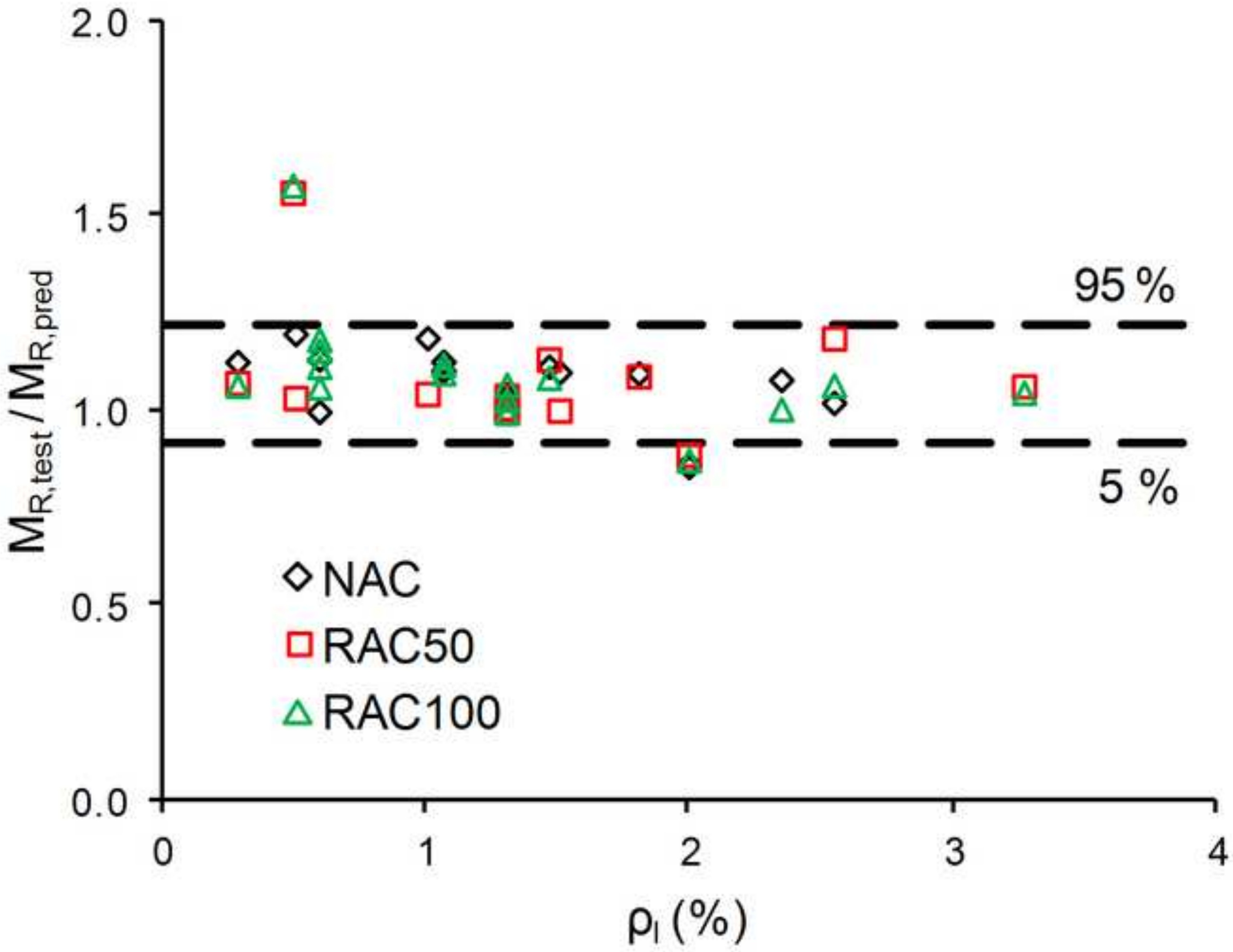

Figure 7_R1

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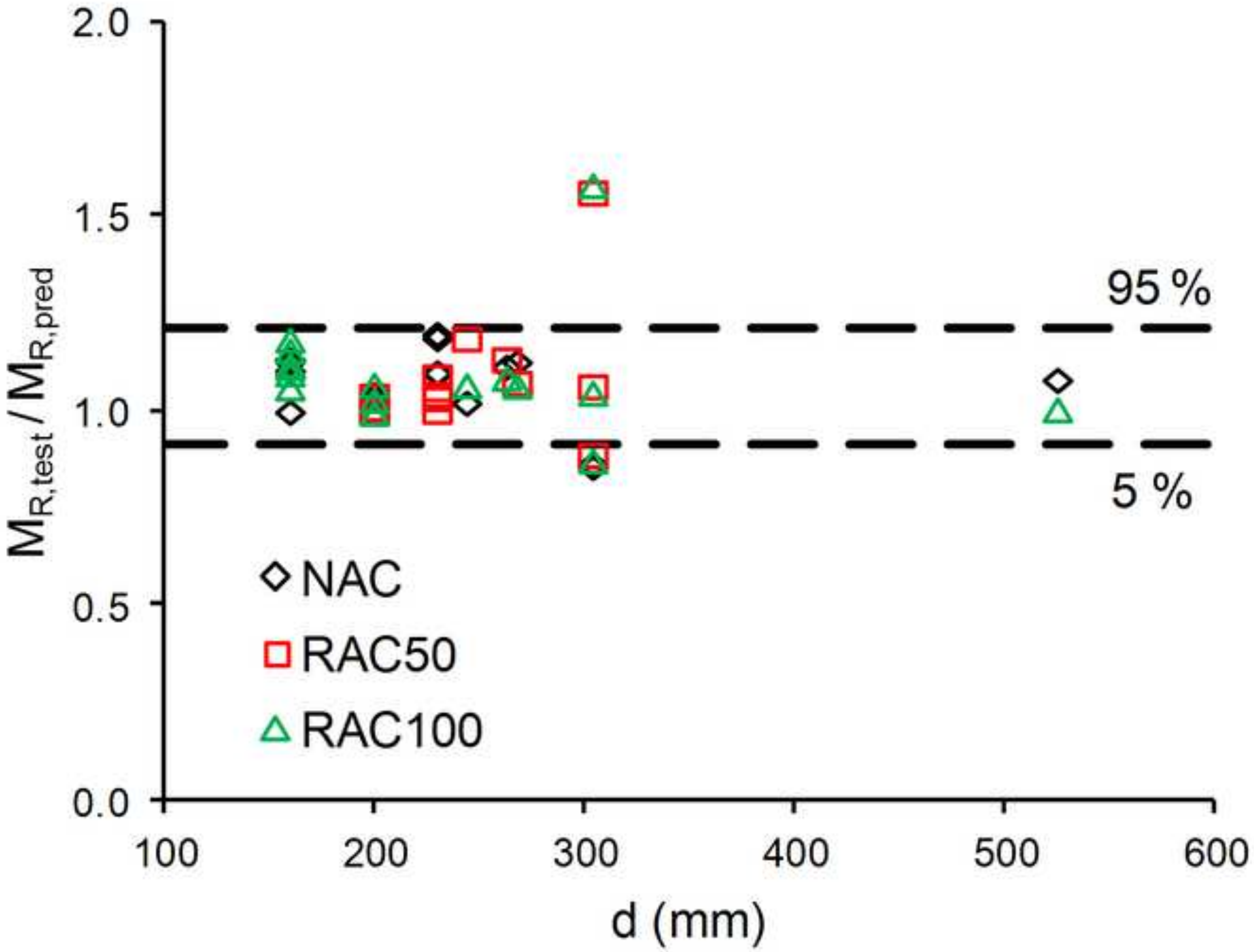

**Figure 8_R1**

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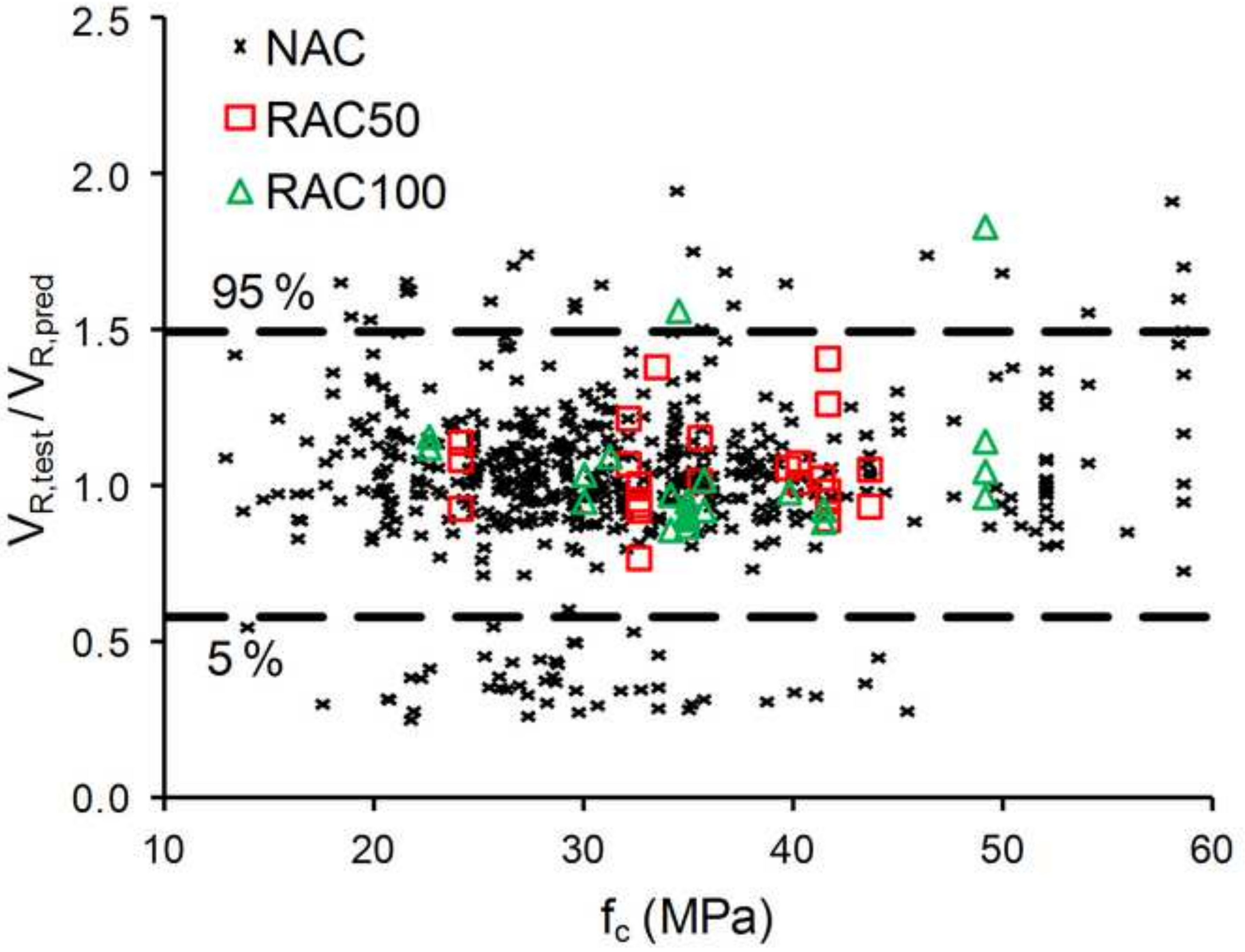

**Figure 9_R1**

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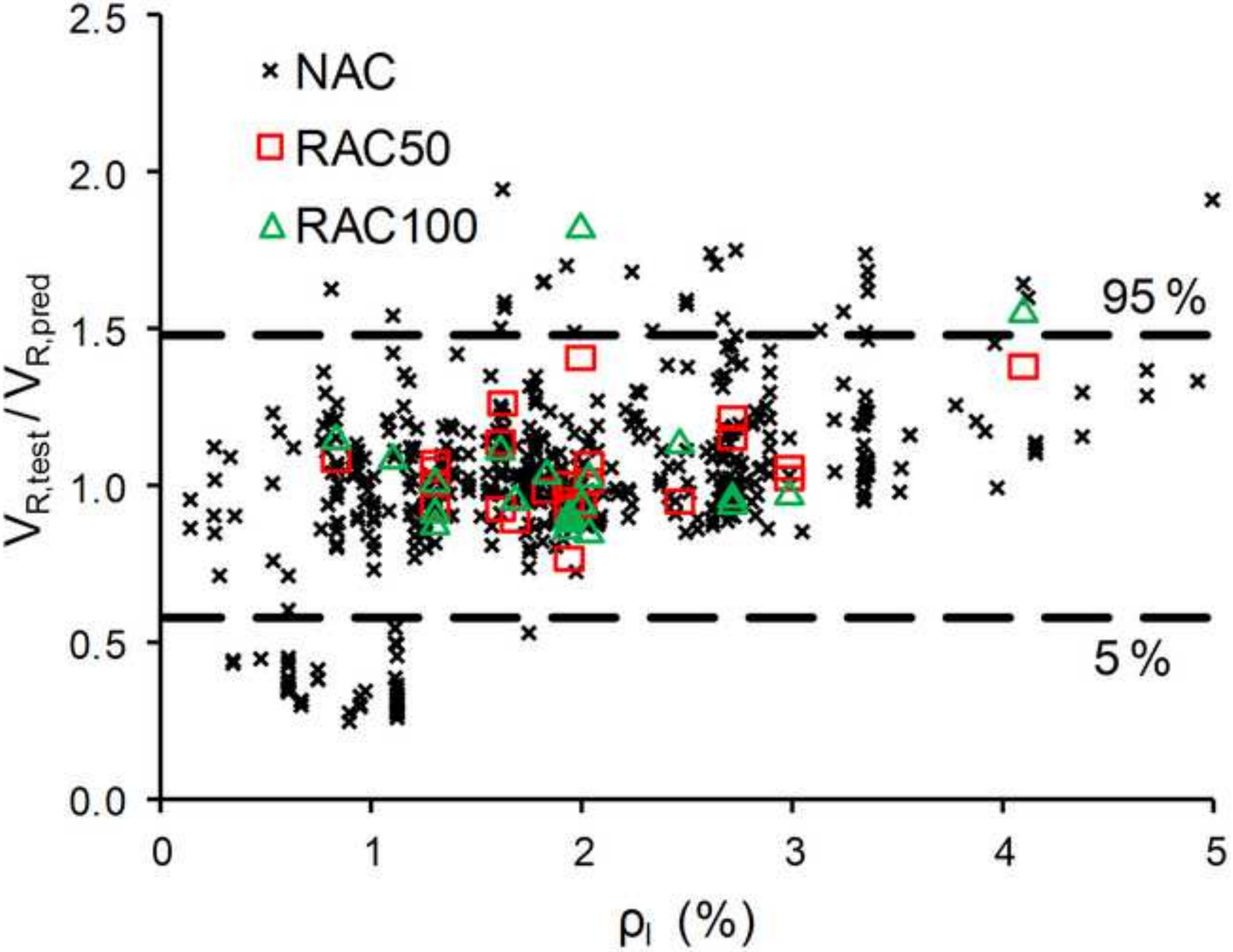

Figure 10_R1

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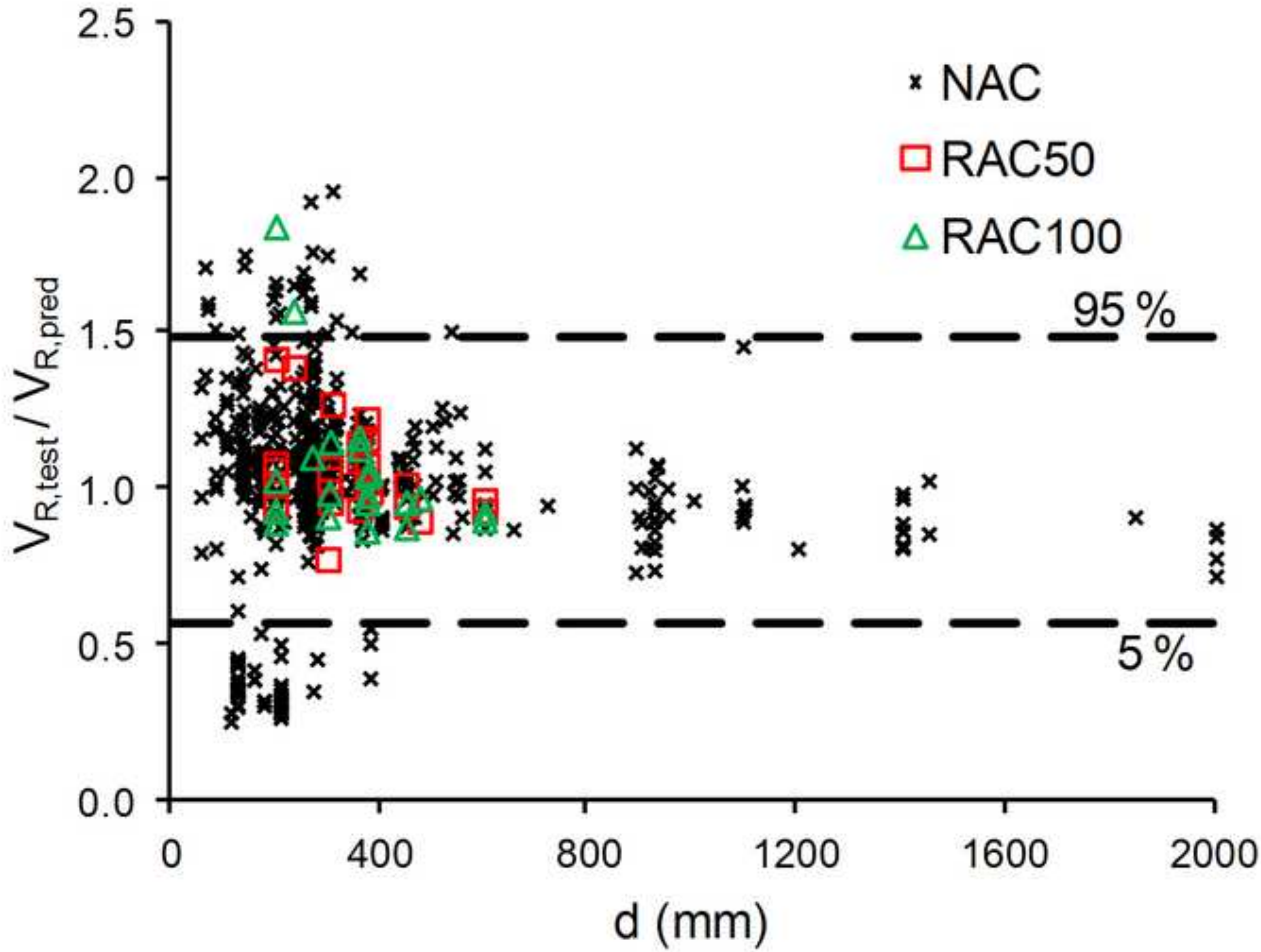

**Figure 11_R1**

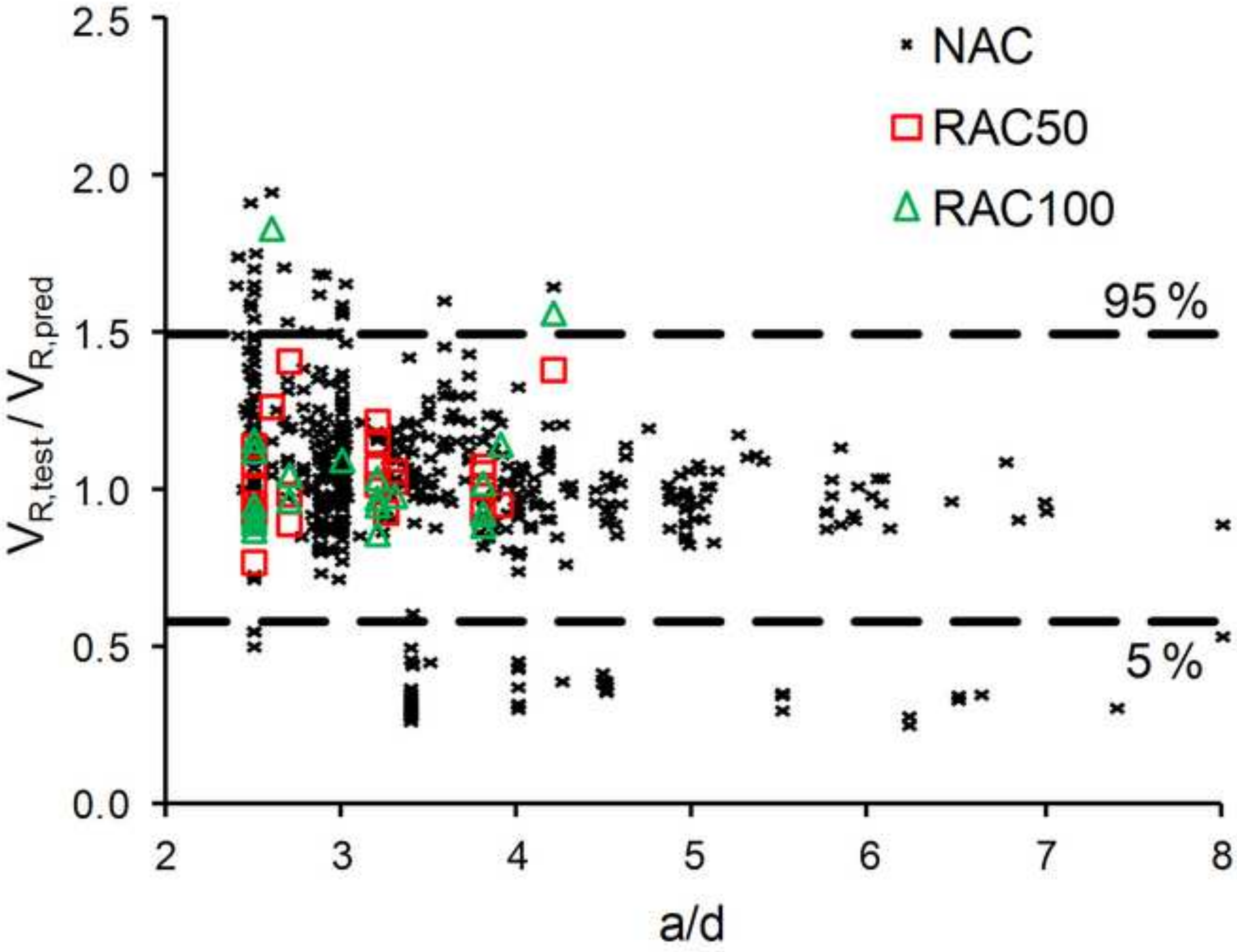
2.5
2.0
1.5
1.0
0.5
0.0
$V_{R,test} / V_{R,pred}$
2
3
4
5
6
7
8
a/d
× NAC
□ RAC50
△ RAC100
95 %
5 %

Figure 12_R1

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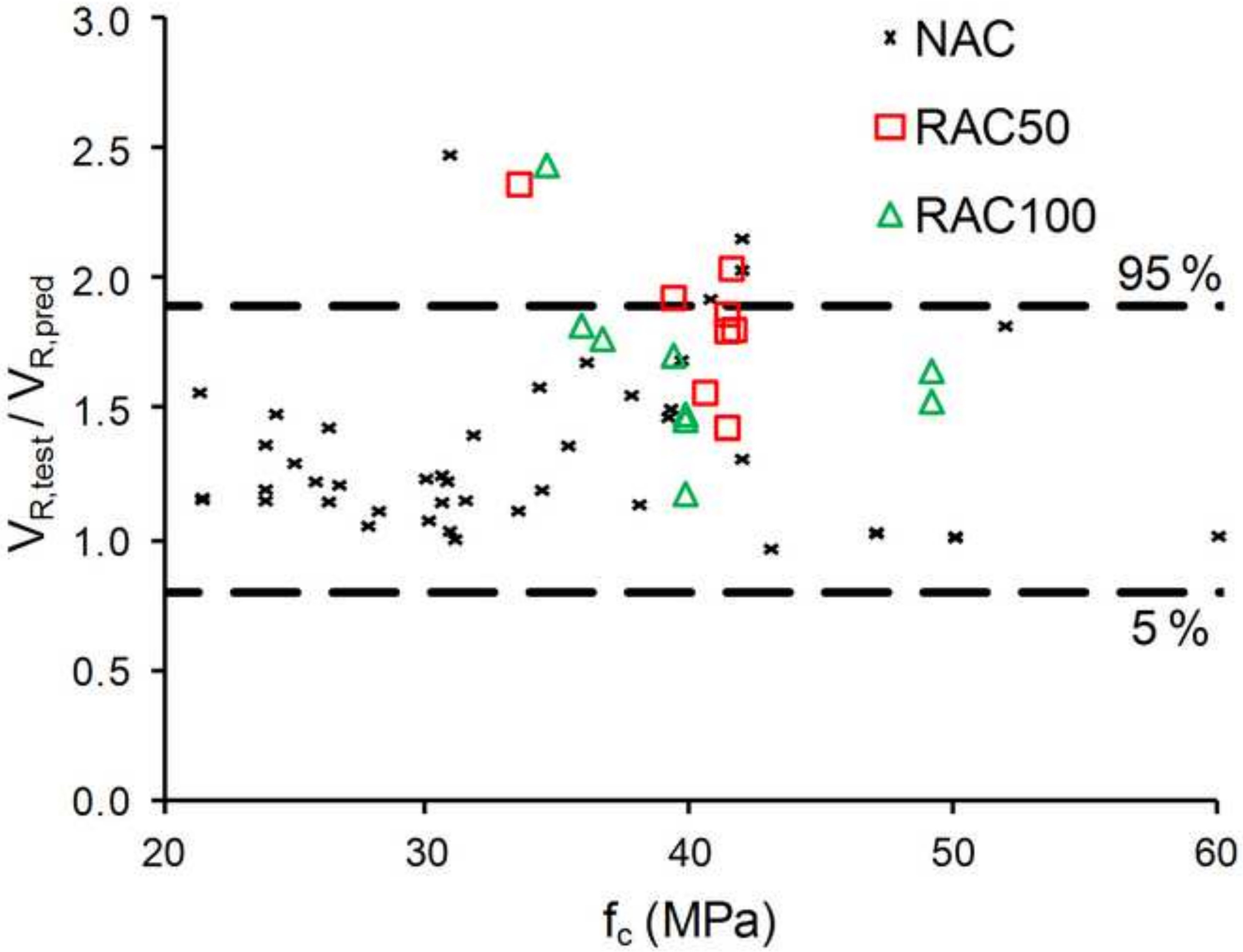

**Figure 13_R1**

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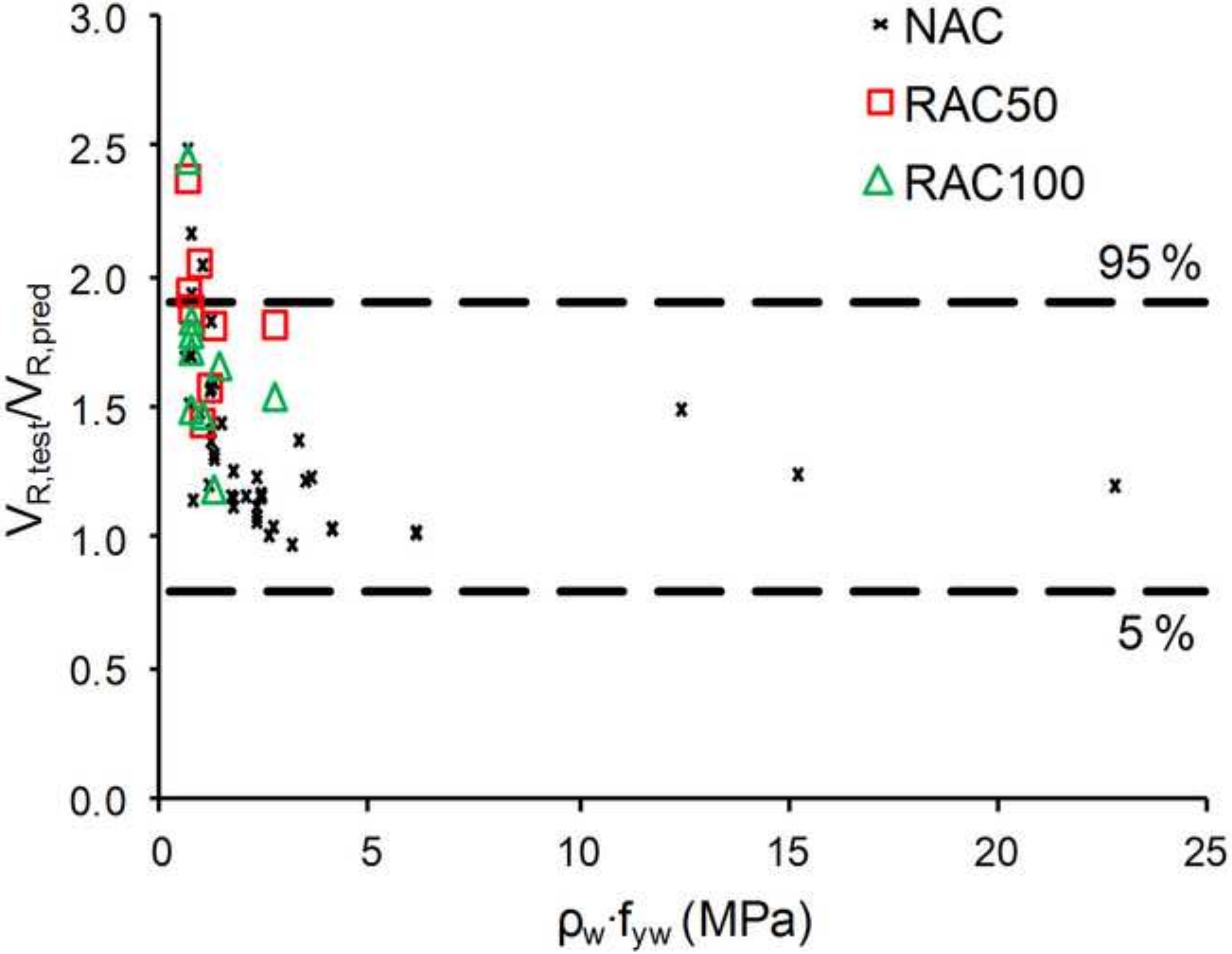

Figure 14_R1

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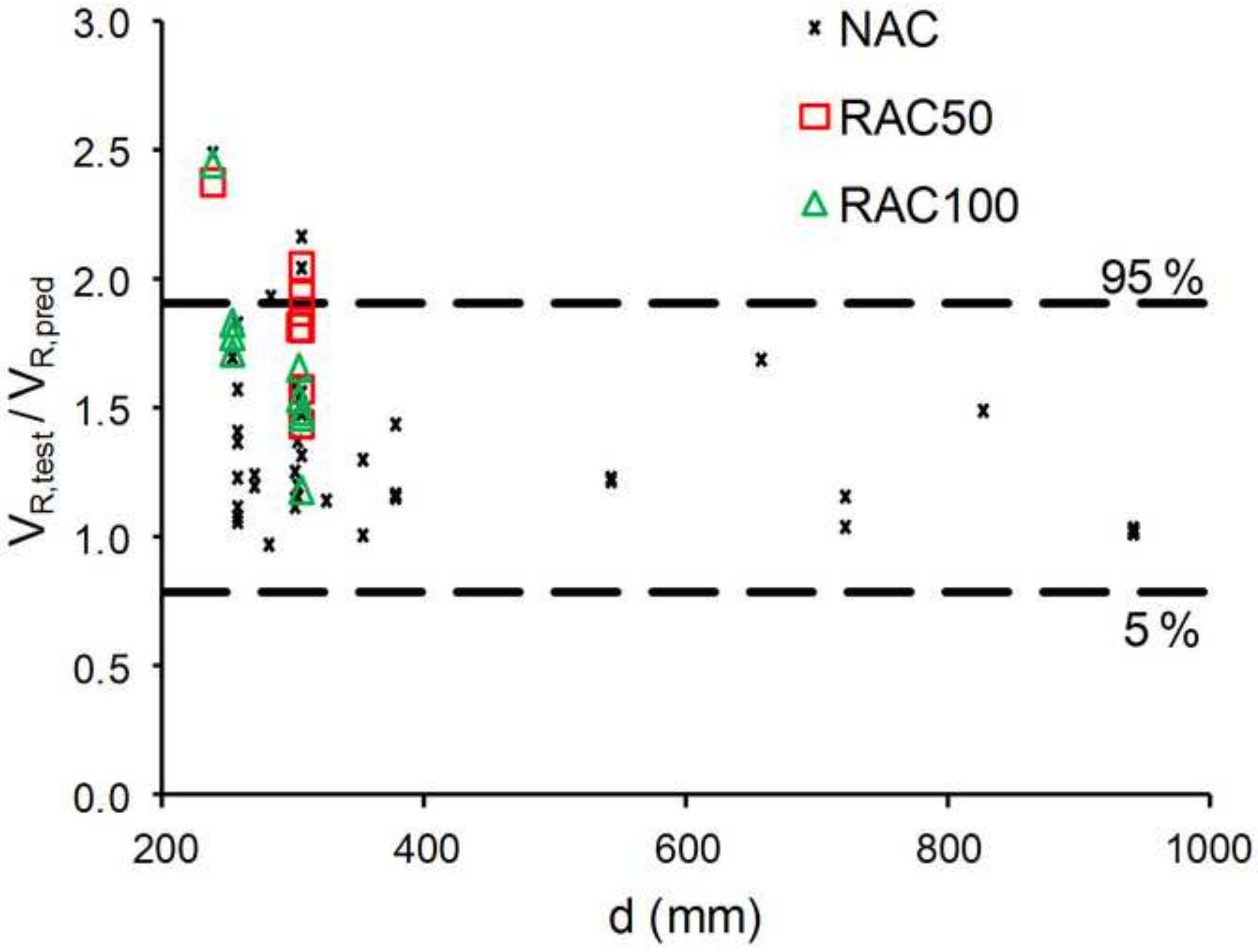

Figure 15_R1

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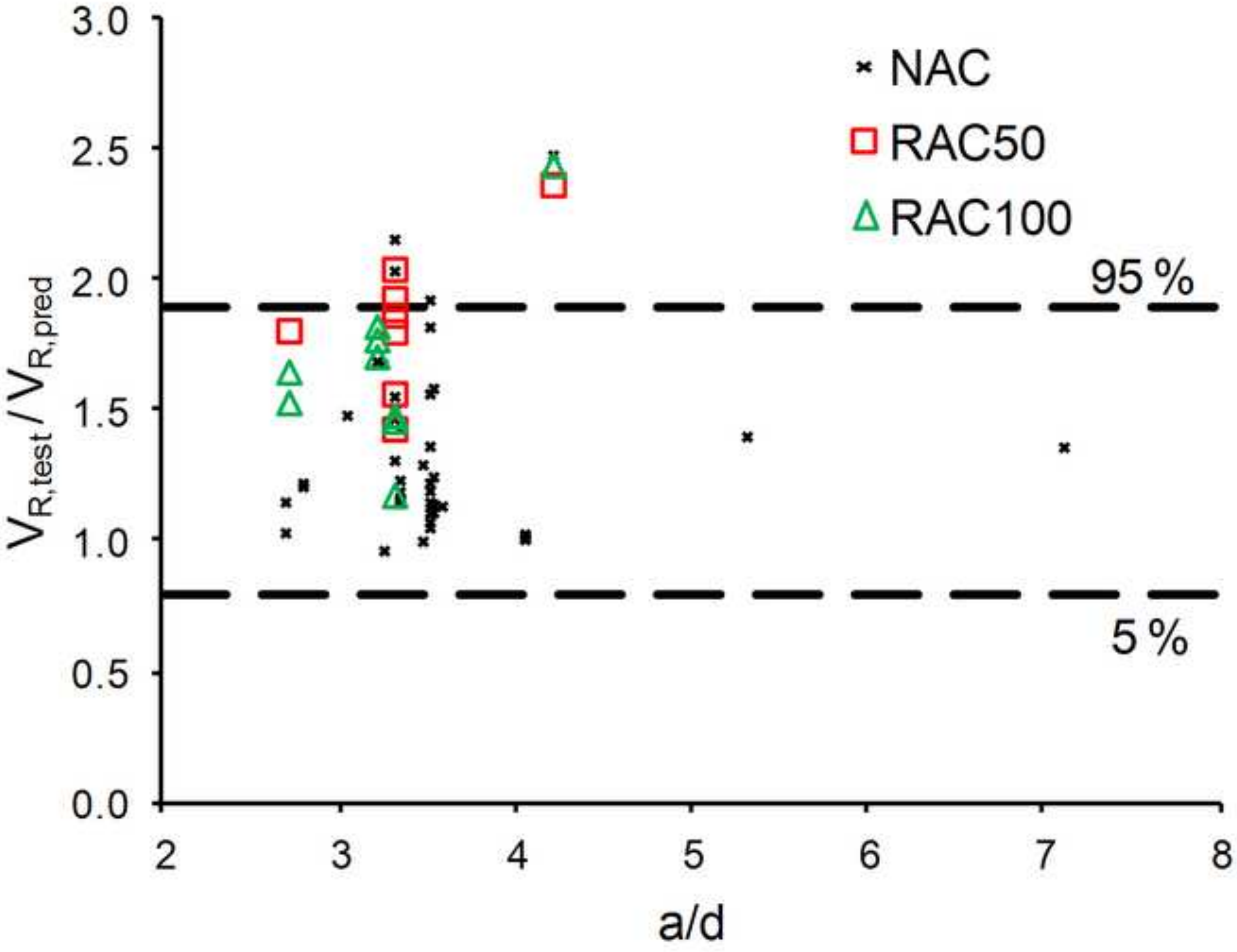

# Appendix A - Supplementary material

| Study information | | Aggregate information | | Section properties | | | Loading and reinforcement | | | Material properties | | | Test results | | Anchorage check | | | Bending check | | Shear check | | | | | Database selection | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| Author | Specimen | coarse RCA (%) | $d_{max}$ (mm) | b (mm) | h (mm) | d (mm) | a/d | $\rho_l$ (%) | $\rho_w$ (%) | $f_{yl}$ (MPa) | $f_{yw}$ (MPa) | $f_c$ (MPa) | $V_{R,test}$ (kN) | $M_{R,test}$ (kNm) | $l_{b,prov}$ (mm) | $l_{b,req}$ (mm) | $\beta_{lb}$ (-) | $M_{R,pred}$ (kNm) | $\beta_{fl}$ (-) | $V_{R,c}$ (kN) | $V_{R,s}$ (kN) | $V_{R,pred}$ (kN) | $V_{R,max}$ (kN) | $\beta_{sh}$(-) | $\Delta\beta = \beta_{sh}-\beta_{fl}$ | Database $\Delta_{cr}$=0.35 |
| Han et al. (2001) | R3.0-N | 100 | 25 | 170 | 300 | 270 | 3.0 | 1.1 | – | 430 | - | 31.2 | 55.1 | 44.6 | 150 | 37.1 | 0.25 | 54.1 | 0.83 | 44.7 | 0.0 | 44.7 | 298.6 | 1.23 | 0.41 | Shear NS |
| Han et al. (2001) | R4.0-N | 100 | 25 | 170 | 300 | 270 | 4.0 | 1.1 | – | 430 | - | 31.9 | 50.9 | 55.0 | 150 | 33.8 | 0.23 | 54.2 | 1.02 | 39.8 | 0.0 | 39.8 | 323.3 | 1.28 | 0.26 | None |
| Etxeberria (2004) | HR50-1 | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | – | 500 | - | 41.34 | 89 | 89.0 | 225 | 34.2 | 0.15 | 222.9 | 0.40 | 92.5 | 0.0 | 92.5 | 402.0 | 0.96 | 0.56 | Shear NS |
| Etxeberria (2004) | HR50-2 | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/13) 0.22 | 500 | 544 | 41.34 | 220 | 220.0 | 225 | 105.7 | 0.47 | 222.9 | 0.99 | 31.1 | 110.4 | 141.5 | 506.1 | 1.55 | 0.57 | Shear S |
| Etxeberria (2004) | HR50-3 | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/17) 0.17 | 500 | 544 | 41.34 | 176 | 176.0 | 225 | 84.5 | 0.38 | 222.9 | 0.79 | 39.4 | 91.8 | 131.2 | 473.7 | 1.34 | 0.55 | Shear S |
| Etxeberria (2004) | HR50-4 | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/24) 0.12 | 500 | 544 | 41.34 | 164 | 164.0 | 225 | 78.8 | 0.35 | 222.9 | 0.74 | 42.1 | 66.6 | 108.7 | 464.3 | 1.51 | 0.77 | Shear S |
| Etxeberria (2004) | HR100-1 | 100 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | – | 500 | - | 39.75 | 84 | 84.0 | 225 | 33.1 | 0.15 | 220.9 | 0.38 | 92.7 | 0.0 | 92.7 | 387.4 | 0.91 | 0.53 | Shear NS |
| Etxeberria (2004) | HR100-2 | 100 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/13) 0.22 | 500 | 544 | 39.75 | 189.5 | 189.5 | 225 | 93.4 | 0.42 | 220.9 | 0.86 | 35.3 | 117.0 | 152.2 | 471.4 | 1.24 | 0.39 | Shear S |
| Etxeberria (2004) | HR100-3 | 100 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/17) 0.17 | 500 | 544 | 39.75 | 163 | 163.0 | 225 | 80.4 | 0.36 | 220.9 | 0.74 | 41.0 | 94.2 | 135.2 | 451.6 | 1.21 | 0.47 | Shear S |
| Etxeberria (2004) | HR100-4 | 100 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/24) 0.12 | 500 | 544 | 39.75 | 168 | 168.0 | 225 | 82.8 | 0.37 | 220.9 | 0.76 | 39.8 | 66.1 | 105.9 | 455.4 | 1.59 | 0.83 | Shear S |
| Etxeberria (2004) | HC-1 | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | – | 500 | - | 41.9 | 100.5 | 100.5 | 225 | 38.3 | 0.17 | 223.6 | 0.45 | 88.7 | 0.0 | 88.7 | 415.7 | 1.13 | 0.68 | Shear NS |
| Etxeberria (2004) | HC-2 | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/13) 0.22 | 500 | 544 | 41.9 | 213 | 213.0 | 225 | 101.4 | 0.45 | 223.6 | 0.95 | 32.7 | 111.8 | 144.6 | 505.6 | 1.47 | 0.52 | Shear S |
| Etxeberria (2004) | HC-3 | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/17) 0.17 | 500 | 544 | 41.9 | 177 | 177.0 | 225 | 84.3 | 0.37 | 223.6 | 0.79 | 39.7 | 91.7 | 131.3 | 478.7 | 1.35 | 0.56 | Shear S |
| Etxeberria (2004) | HC-4 | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/24) 0.12 | 500 | 544 | 41.9 | 187.5 | 187.5 | 225 | 89.3 | 0.40 | 223.6 | 0.84 | 37.4 | 63.6 | 101.1 | 486.8 | 1.86 | 1.02 | Shear S |
| Sato et al. (2004) | CR45-03-WB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 46.5 | 21.0 | 14.8 | 300 | 21.5 | 0.07 | 13.5 | 1.10 | 29.4 | 0.0 | 29.4 | 208.1 | 0.72 | -0.38 | Flexural |
| Sato et al. (2004) | CR60-03-WB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 32.9 | 21.7 | 15.3 | 300 | 28.0 | 0.09 | 13.3 | 1.15 | 24.3 | 0.0 | 24.3 | 166.9 | 0.90 | -0.26 | None |
| Sato et al. (2004) | CREX45-03-WB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 46.6 | 21.4 | 15.1 | 300 | 21.9 | 0.07 | 13.5 | 1.12 | 29.1 | 0.0 | 29.1 | 209.7 | 0.74 | -0.38 | Flexural |
| Sato et al. (2004) | CR45-01-10WB | 100 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 30.4 | 12.1 | 8.5 | 300 | 22.7 | 0.08 | 8.0 | 1.06 | 24.2 | 0.0 | 24.2 | 155.4 | 0.50 | -0.56 | Flexural |
| Sato et al. (2004) | CR45-01-10DB | 100 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 28.4 | 12.6 | 8.9 | 300 | 24.9 | 0.08 | 8.0 | 1.11 | 22.8 | 0.0 | 22.8 | 147.8 | 0.56 | -0.56 | Flexural |
| Sato et al. (2004) | CR60-01-10WB | 100 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 34.5 | 13.2 | 9.3 | 300 | 22.8 | 0.08 | 8.1 | 1.16 | 24.5 | 0.0 | 24.5 | 173.7 | 0.54 | -0.61 | Flexural |
| Sato et al. (2004) | CR60-01-10DB | 100 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 31.8 | 13.5 | 9.5 | 300 | 24.6 | 0.08 | 8.0 | 1.18 | 23.2 | 0.0 | 23.2 | 165.5 | 0.58 | -0.60 | Flexural |
| Sato et al. (2004) | CR45-01-13WB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 30.4 | 19.7 | 13.9 | 300 | 26.9 | 0.09 | 13.2 | 1.05 | 24.6 | 0.0 | 24.6 | 153.9 | 0.80 | -0.25 | None |
| Sato et al. (2004) | CR45-01-13DB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 28.4 | 20.0 | 14.1 | 300 | 28.5 | 0.10 | 13.1 | 1.07 | 23.6 | 0.0 | 23.6 | 145.0 | 0.85 | -0.23 | None |
| Sato et al. (2004) | CR60-01-13WB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 34.5 | 20.0 | 14.1 | 300 | 25.0 | 0.08 | 13.3 | 1.06 | 26.0 | 0.0 | 26.0 | 168.2 | 0.77 | -0.29 | None |
| Sato et al. (2004) | CR60-01-13DB | 100 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 31.8 | 21.4 | 15.1 | 300 | 28.3 | 0.09 | 13.2 | 1.14 | 24.0 | 0.0 | 24.0 | 162.5 | 0.89 | -0.25 | None |
| Sato et al. (2004) | CR45-01-16WB | 100 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 30.4 | 27.3 | 19.2 | 300 | 29.3 | 0.10 | 19.9 | 0.97 | 25.9 | 0.0 | 25.9 | 150.0 | 1.05 | 0.09 | None |
| Sato et al. (2004) | CR45-01-16DB | 100 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 28.4 | 27.7 | 19.5 | 300 | 31.2 | 0.10 | 19.7 | 0.99 | 24.8 | 0.0 | 24.8 | 141.3 | 1.12 | 0.13 | None |
| Sato et al. (2004) | CR60-01-16WB | 100 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 34.5 | 28.3 | 19.9 | 300 | 27.9 | 0.09 | 20.1 | 0.99 | 27.1 | 0.0 | 27.1 | 164.8 | 1.04 | 0.06 | None |
| Sato et al. (2004) | CR60-01-16DB | 100 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 31.8 | 31.1 | 21.9 | 300 | 32.5 | 0.11 | 20.0 | 1.10 | 24.6 | 0.0 | 24.6 | 160.5 | 1.26 | 0.17 | None |
| Sato et al. (2004) | V45-03-WB | 0 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 57 | 21.3 | 15.0 | 300 | 19.1 | 0.06 | 13.6 | 1.10 | 32.3 | 0.0 | 32.3 | 239.3 | 0.66 | -0.44 | Flexural |
| Sato et al. (2004) | V60-03-WB | 0 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 40.2 | 22.4 | 15.8 | 300 | 25.3 | 0.08 | 13.4 | 1.18 | 26.3 | 0.0 | 26.3 | 192.6 | 0.85 | -0.33 | None |
| Sato et al. (2004) | VEX45-03-WB | 0 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 55.3 | 21.7 | 15.3 | 300 | 19.8 | 0.07 | 13.6 | 1.13 | 31.5 | 0.0 | 31.5 | 235.9 | 0.69 | -0.44 | Flexural |
| Sato et al. (2004) | V-01-10WB | 0 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 30.6 | 11.4 | 8.0 | 300 | 21.3 | 0.07 | 8.0 | 1.00 | 25.1 | 0.0 | 25.1 | 153.4 | 0.45 | -0.55 | Flexural |
| Sato et al. (2004) | V-01-10DB | 0 | | 150 | 200 | 160 | 4.4 | 0.59 | – | 331 | - | 32.5 | 12.9 | 9.1 | 300 | 23.2 | 0.08 | 8.0 | 1.13 | 24.0 | 0.0 | 24.0 | 165.8 | 0.54 | -0.59 | Flexural |
| Sato et al. (2004) | V-01-13WB | 0 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 30.6 | 19.5 | 13.7 | 300 | 26.4 | 0.09 | 13.2 | 1.04 | 24.9 | 0.0 | 24.9 | 154.0 | 0.78 | -0.26 | None |
| Sato et al. (2004) | V-01-13DB | 0 | | 150 | 200 | 160 | 4.4 | 1.06 | – | 331 | - | 32.5 | 19.9 | 14.0 | 300 | 25.9 | 0.09 | 13.2 | 1.06 | 25.4 | 0.0 | 25.4 | 161.3 | 0.78 | -0.27 | None |
| Sato et al. (2004) | V-01-16WB | 0 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 30.6 | 27.6 | 19.4 | 300 | 29.5 | 0.10 | 19.9 | 0.98 | 25.8 | 0.0 | 25.8 | 151.1 | 1.07 | 0.09 | None |
| Sato et al. (2004) | V-01-16DB | 0 | | 150 | 200 | 160 | 4.4 | 1.65 | – | 342 | - | 32.5 | 27.7 | 19.5 | 300 | 28.5 | 0.09 | 20.0 | 0.97 | 26.6 | 0.0 | 26.6 | 157.5 | 1.04 | 0.07 | None |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V0RC | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | – | 571 | - | 39.7 | 90.6 | 90.6 | 178 | 35.8 | 0.20 | 243.6 | 0.37 | 90.0 | 0.0 | 90.0 | 392.7 | 1.01 | 0.63 | Shear NS |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V24RC | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/24) 0.12 | 571 | 500 | 39.3 | 164.3 | 164.3 | 178 | 81.6 | 0.46 | 242.9 | 0.68 | 40.2 | 61.2 | 101.4 | 449.2 | 1.62 | 0.94 | Shear S |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V17RC | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/17) 0.17 | 571 | 500 | 41.5 | 177 | 177.0 | 178 | 84.8 | 0.48 | 246.6 | 0.72 | 39.3 | 84.2 | 123.6 | 475.7 | 1.43 | 0.71 | Shear S |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V13RC | 50 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/13) 0.22 | 571 | 500 | 40.5 | 233.6 | 233.6 | 178 | 113.7 | 0.64 | 245.0 | 0.95 | 28.4 | 98.9 | 127.3 | 508.5 | 1.83 | 0.88 | Shear S |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V0CC | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | – | 571 | - | 40.2 | 88.9 | 88.9 | 178 | 34.8 | 0.20 | 244.5 | 0.36 | 91.2 | 0.0 | 91.2 | 394.5 | 0.97 | 0.61 | Shear NS |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V24CC | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/24) 0.12 | 571 | 500 | 39.2 | 128 | 128.0 | 178 | 63.7 | 0.36 | 242.7 | 0.53 | 50.0 | 65.9 | 115.9 | 420.1 | 1.10 | 0.58 | Shear S |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V17CC | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/17) 0.17 | 571 | 500 | 39.1 | 150.8 | 150.8 | 178 | 75.2 | 0.42 | 242.6 | 0.62 | 43.4 | 88.7 | 132.1 | 437.3 | 1.14 | 0.52 | Shear S |
| Gonzalez-Fonteboa and Martinez-Abella (2007) | V13CC | 0 | 25 | 200 | 350 | 303 | 3.3 | 2.98 | (Φ6/13) 0.22 | 571 | 500 | 37.7 | 190.3 | 190.3 | 178 | 97.2 | 0.55 | 240.0 | 0.79 | 33.4 | 107.3 | 140.7 | 455.6 | 1.35 | 0.56 | Shear S |
| Ajdukiewicz and Kliszczewicz (2007) | ORN-lb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 34.6 | 64 | 51.2 | 90 | 52.1 | 0.58 | 51.1 | 1.00 | 32.2 | 48.4 | 80.6 | 384.6 | 0.79 | -0.21 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ORN-mb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 56.4 | 78 | 62.4 | 90 | 45.8 | 0.51 | 52.5 | 1.19 | 37.3 | 43.9 | 81.3 | 566.5 | 0.96 | -0.23 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GRN-lb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 40.1 | 81.5 | 65.2 | 90 | 60.1 | 0.67 | 51.6 | 1.26 | 29.1 | 42.9 | 72.0 | 457.4 | 1.13 | -0.13 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GRN-mb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 60.2 | 68 | 54.4 | 90 | 38.3 | 0.43 | 52.6 | 1.03 | 43.1 | 47.1 | 90.2 | 567.0 | 0.75 | -0.28 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BRN-lb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 35.3 | 75 | 60.0 | 90 | 60.2 | 0.67 | 51.2 | 1.17 | 28.7 | 44.8 | 73.6 | 409.5 | 1.02 | -0.15 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BRN-mb1 | 100 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 57.6 | 71.5 | 57.2 | 90 | 41.4 | 0.46 | 52.5 | 1.09 | 40.5 | 45.9 | 86.4 | 559.2 | 0.83 | -0.26 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ORN-lb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 36.6 | 118 | 94.4 | 90 | 52.0 | 0.58 | 81.0 | 1.17 | 27.5 | 47.6 | 75.1 | 403.8 | 1.57 | 0.41 | Shear S |
| Ajdukiewicz and Kliszczewicz (2007) | ORN-mb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 58.3 | 118.5 | 94.8 | 90 | 38.3 | 0.43 | 84.4 | 1.12 | 38.4 | 47.5 | 85.9 | 551.5 | 1.38 | 0.26 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GRN-lb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 39.3 | 116.5 | 93.2 | 90 | 49.0 | 0.54 | 81.6 | 1.14 | 29.4 | 47.9 | 77.2 | 421.8 | 1.51 | 0.37 | Shear S |

| Study information | | Aggregate information | | Section properties | | | Loading and reinforcement | | | Material properties | | | Test results | | Anchorage check | | | Bending check | | Shear check | | | | | Database selection | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| Author | Specimen | coarse RCA (%) | $d_{max}$ (mm) | b (mm) | h (mm) | d (mm) | a/d | $\rho_l$ (%) | $\rho_w$ (%) | $f_{yl}$ (MPa) | $f_{yw}$ (MPa) | $f_c$ (MPa) | $V_{R,test}$ (kN) | $M_{R,test}$ (kNm) | $l_{b,prov}$ (mm) | $l_{b,req}$ (mm) | $\beta_{lb}$ (-) | $M_{R,pred}$ (kNm) | $\beta_{fl}$ (-) | $V_{R,c}$ (kN) | $V_{R,s}$ (kN) | $V_{R,pred}$ (kN) | $V_{R,max}$ (kN) | $\beta_{sh}$(-) | $\Delta\beta = \beta_{sh}-\beta_{fl}$ | Database $\Delta_{cr}$=0.35 |
| Ajdukiewicz and Kliszczewicz (2007) | GRN-mb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 59.6 | 118.5 | 94.8 | 90 | 37.8 | 0.42 | 84.5 | 1.12 | 38.9 | 47.5 | 86.5 | 559.7 | 1.37 | 0.25 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BRN-lb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 35.8 | 120.5 | 96.4 | 90 | 53.9 | 0.60 | 80.8 | 1.19 | 26.5 | 47.1 | 73.6 | 400.5 | 1.64 | 0.44 | Shear S |
| Ajdukiewicz and Kliszczewicz (2007) | BRN-mb2 | 100 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 59.6 | 119 | 95.2 | 90 | 37.9 | 0.42 | 84.5 | 1.13 | 38.8 | 47.4 | 86.2 | 560.4 | 1.38 | 0.25 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ONN-lb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 37.7 | 64.5 | 51.6 | 90 | 49.6 | 0.55 | 51.4 | 1.00 | 33.8 | 48.2 | 82.0 | 408.2 | 0.79 | -0.22 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ONN-mb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 57.9 | 80 | 64.0 | 90 | 46.2 | 0.51 | 52.5 | 1.22 | 37.2 | 43.3 | 80.5 | 581.0 | 0.99 | -0.22 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GNN-lb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 39.8 | 78 | 62.4 | 90 | 57.8 | 0.64 | 51.6 | 1.21 | 30.1 | 43.9 | 74.0 | 449.0 | 1.05 | -0.16 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GNN-mb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 58.3 | 70 | 56.0 | 90 | 40.2 | 0.45 | 52.5 | 1.07 | 41.4 | 46.4 | 87.8 | 560.0 | 0.80 | -0.27 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BNN-lb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 40.1 | 75.5 | 60.4 | 90 | 55.7 | 0.62 | 51.6 | 1.17 | 31.0 | 44.7 | 75.7 | 446.8 | 1.00 | -0.17 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BNN-mb1 | 0 | 16 | 200 | 300 | 250 | 3.2 | 0.9 | (Φ6/10) 0.28 | 483 | 234.1 | 61.8 | 73 | 58.4 | 90 | 40.4 | 0.45 | 52.7 | 1.11 | 41.5 | 45.5 | 87.0 | 589.9 | 0.84 | -0.27 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ONN-lb2 | 0 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 38.2 | 113.5 | 90.8 | 90 | 48.6 | 0.54 | 81.4 | 1.12 | 29.4 | 48.5 | 77.9 | 410.5 | 1.46 | 0.34 | None |
| Ajdukiewicz and Kliszczewicz (2007) | ONN-mb2 | 0 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 59.1 | 117 | 93.6 | 90 | 37.5 | 0.42 | 84.5 | 1.11 | 39.1 | 47.8 | 86.9 | 554.3 | 1.35 | 0.24 | None |
| Ajdukiewicz and Kliszczewicz (2007) | GNN-lb2 | 0 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 38.7 | 108.5 | 86.8 | 90 | 46.1 | 0.51 | 81.5 | 1.06 | 30.9 | 49.4 | 80.4 | 408.3 | 1.35 | 0.29 | None |
| Ajdukiewicz and Kliszczewicz (2007) | BNN-lb2 | 0 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 39.6 | 115.5 | 92.4 | 90 | 48.3 | 0.54 | 81.7 | 1.13 | 29.8 | 48.1 | 77.8 | 422.8 | 1.48 | 0.35 | Shear S |
| Ajdukiewicz and Kliszczewicz (2007) | BNN-mb2 | 0 | 16 | 200 | 300 | 250 | 3.2 | 1.6 | (Φ6/10) 0.28 | 448 | 234.1 | 60.8 | 119 | 95.2 | 90 | 37.4 | 0.42 | 84.6 | 1.12 | 39.3 | 47.4 | 86.8 | 567.9 | 1.37 | 0.25 | None |
| Fathifazl et al. (2009) | EM-Min | 63.5 | 19 | 200 | | 304 | 2.6 | 0.49 | (Φ10/20) 0.39 | 420 | 450 | 41.6 | 57.5 | 46.0 | 200 | 52.1 | 0.26 | 29.5 | 1.56 | 36.9 | 131.4 | 168.3 | 587.3 | 0.34 | -1.22 | Flexural |
| Fathifazl et al. (2009) | EM-Av | 63.5 | 19 | 200 | | 304 | 2.7 | 1.99 | (Φ15/20) 0.88 | 420 | 450 | 41.6 | 184.5 | 149.2 | 200 | 82.3 | 0.41 | 168.1 | 0.89 | 38.7 | 404.7 | 443.3 | 477.5 | 0.42 | -0.47 | Flexural |
| Fathifazl et al. (2009) | EM-Max | 63.5 | 19 | 200 | | 304 | 2.6 | 3.26 | (Φ15/10) 1.77 | 420 | 450 | 41.6 | 279.7 | 221.9 | 200 | 95.2 | 0.48 | 208.7 | 1.06 | 25.5 | 770.4 | 496.7 | 496.7 | 0.56 | -0.50 | Flexural |
| Fathifazl et al. (2009) | EM-CMP | 63.5 | 19 | 200 | | 304 | 2.7 | 3.31 | (Φ810) 1.01 | 420 | 530 | 41.6 | 305.5 | 246.1 | 200 | 102.4 | 0.51 | 208.7 | 1.18 | 22.2 | 247.5 | 269.7 | 512.6 | 1.13 | -0.05 | None |
| Fathifazl et al. (2009) | EV-Min | 74.3 | 19 | 200 | | 304 | 2.6 | 0.49 | (Φ10/20) 0.39 | 420 | 450 | 49.1 | 58.4 | 46.7 | 200 | 47.4 | 0.24 | 29.6 | 1.58 | 40.1 | 130.2 | 170.3 | 658.8 | 0.34 | -1.24 | Flexural |
| Fathifazl et al. (2009) | EV-Av | 74.3 | 19 | 200 | | 304 | 2.7 | 1.99 | (Φ15/20) 0.88 | 420 | 450 | 49.1 | 185.7 | 150.2 | 200 | 74.2 | 0.37 | 171.9 | 0.87 | 44.5 | 403.7 | 448.2 | 534.3 | 0.41 | -0.46 | Flexural |
| Fathifazl et al. (2009) | EV-Max | 74.3 | 19 | 200 | | 304 | 2.6 | 3.26 | (Φ15/10) 1.77 | 420 | 450 | 49.1 | 283.8 | 225.2 | 200 | 86.5 | 0.43 | 215.1 | 1.05 | 30.8 | 766.0 | 557.2 | 557.2 | 0.51 | -0.54 | Flexural |
| Fathifazl et al. (2009) | EV-CMP | 74.3 | 19 | 200 | | 304 | 2.7 | 3.31 | (Φ810) 1.01 | 420 | 530 | 49.1 | 305.0 | 245.7 | 200 | 91.6 | 0.46 | 215.1 | 1.14 | 27.9 | 247.7 | 275.5 | 572.2 | 1.11 | -0.04 | None |
| Fathifazl et al. (2009) | CL-Av | 0 | 19 | 200 | | 304 | 2.6 | 1.99 | (Φ15/20) 0.88 | 420 | 450 | 37.1 | 178.5 | 142.7 | 200 | 86.0 | 0.43 | 165.1 | 0.86 | 36.1 | 410.9 | 410.9 | 436.8 | 0.43 | -0.43 | Flexural |
| Fathifazl et al. (2009) | CL-CMP | 0 | 19 | 200 | | 304 | 2.7 | 3.33 | (Φ810) 1.01 | 420 | 530 | 37.1 | 283.3 | 229.1 | 200 | 101.9 | 0.51 | 203.6 | 1.13 | 21.1 | 254.8 | 275.9 | 464.7 | 1.03 | -0.10 | None |
| Fathifazl et al. (2009) | CG-Av | 0 | 19 | 200 | | 304 | 2.6 | 1.99 | (Φ15/20) 0.88 | 420 | 450 | 33.8 | 175.3 | 139.1 | 200 | 89.8 | 0.45 | 162.4 | 0.86 | 33.6 | 414.4 | 407.5 | 407.5 | 0.43 | -0.43 | Flexural |
| Fathifazl et al. (2009) | CG-CMP | 0 | 19 | 200 | | 304 | 2.7 | 3.33 | (Φ810) 1.01 | 420 | 530 | 33.8 | 281.2 | 226.5 | 200 | 107.6 | 0.54 | 199.0 | 1.14 | 18.4 | 256.0 | 274.4 | 435.2 | 1.02 | -0.11 | None |
| Fathifazl et al. (2010) | EM-3S-R | 63.5 | 19 | 200 | 375 | 306 | 2.6 | 2.46 | (Φ8/20) 0.25 | 420 | 530 | 41.6 | 172 | 136.8 | 200 | 61.7 | 0.31 | 168.8 | 0.81 | 42.2 | 140.6 | 182.8 | 468.7 | 0.94 | 0.13 | None |
| Fathifazl et al. (2010) | EM-6S-R | 63.5 | 19 | 200 | 375 | 306 | 2.6 | 3.2 | (Φ8/10) 0.5 | 420 | 530 | 41.6 | 308 | 245.0 | 200 | 84.9 | 0.42 | 209.9 | 1.17 | 22.3 | 250.1 | 272.4 | 514.6 | 1.13 | -0.04 | None |
| Fathifazl et al. (2010) | EM-6S-D | 63.5 | 19 | 200 | 385 | 301 | 2.7 | 4 | (Φ10/20) 0.5 | 420 | 530 | 41.6 | 341 | 277.1 | 200 | 76.4 | 0.38 | 241.2 | 1.15 | 17.8 | 197.4 | 215.1 | 496.1 | 1.59 | 0.44 | Shear S |
| Fathifazl et al. (2010) | EV-3S-R | 74.3 | 19 | 200 | 385 | 301 | 2.7 | 2.46 | (Φ8/20) 0.25 | 420 | 530 | 49.1 | 235 | 191.0 | 200 | 76.7 | 0.38 | 167.0 | 1.14 | 34.0 | 120.5 | 154.5 | 573.8 | 1.52 | 0.38 | Shear S |
| Fathifazl et al. (2010) | EV-6S-R | 74.3 | 19 | 200 | 385 | 301 | 2.7 | 3.2 | (Φ8/10) 0.5 | 420 | 530 | 49.1 | 308 | 250.3 | 200 | 77.3 | 0.39 | 209.3 | 1.20 | 26.6 | 240.2 | 266.9 | 575.1 | 1.15 | -0.04 | None |
| Fathifazl et al. (2010) | EV-6S-D | 74.3 | 19 | 200 | 385 | 301 | 2.7 | 4 | (Φ10/20) 0.5 | 420 | 530 | 49.1 | 327 | 265.8 | 200 | 65.6 | 0.33 | 250.9 | 1.06 | 25.5 | 200.6 | 226.1 | 547.2 | 1.45 | 0.39 | Shear S |
| Fathifazl et al. (2010) | CL-M | 0 | 19 | 200 | 375 | 309 | 2.6 | 1.62 | – | 420 | - | 38.8 | 92.8 | 74.6 | 200 | 41.9 | 0.21 | 118.2 | 0.63 | 74.8 | 0.0 | 74.8 | 427.8 | 1.24 | 0.61 | Shear NS |
| Fathifazl et al. (2010) | CG-2.7 | 0 | 19 | 200 | 375 | 309 | 2.6 | 1.62 | – | 420 | - | 34.4 | 150 | 120.5 | 200 | 73.4 | 0.37 | 116.7 | 1.03 | 54.4 | 0.0 | 54.4 | 451.1 | 2.76 | 1.73 | Shear NS |
| Fathifazl et al. (2010) | CL-6S-R | 0 | 19 | 200 | 385 | 309 | 2.6 | 3.2 | (Φ8/10) 0.5 | 420 | 530 | 38.8 | 287 | 230.6 | 200 | 82.1 | 0.41 | 211.0 | 1.09 | 23.1 | 260.9 | 284.0 | 484.1 | 1.01 | -0.08 | None |
| Fathifazl et al. (2010) | CG-6S-R | 0 | 19 | 200 | 385 | 309 | 2.6 | 3.2 | (Φ8/10) 0.5 | 420 | 530 | 34.4 | 284 | 228.2 | 200 | 88.0 | 0.44 | 205.1 | 1.11 | 19.5 | 261.9 | 281.4 | 445.3 | 1.01 | -0.10 | None |
| Choi et al. (2010) | RARAC50-H2.5 | 50 | 25 | 200 | 400 | 360 | 2.5 | 1.61 | – | 500 | - | 24.1 | 87.9 | 79.1 | 200 | 51.8 | 0.26 | 172.8 | 0.46 | 76.7 | 0.0 | 76.7 | 319.0 | 1.15 | 0.69 | Shear NS |
| Choi et al. (2010) | RARAC50-H3.25 | 50 | 25 | 200 | 400 | 360 | 3.3 | 1.61 | – | 500 | - | 24.1 | 71.6 | 83.8 | 200 | 42.2 | 0.21 | 172.8 | 0.48 | 74.5 | 0.0 | 74.5 | 323.7 | 0.96 | 0.48 | Shear NS |
| Choi et al. (2010) | RARAC50-L2.5 | 50 | 25 | 200 | 400 | 360 | 2.5 | 0.53 | – | 500 | - | 24.1 | 57.8 | 52.0 | 200 | 103.5 | 0.52 | 64.8 | 0.80 | 54.1 | 0.0 | 54.1 | 381.9 | 1.07 | 0.27 | None |
| Choi et al. (2010) | RARAC50-M2.5 | 50 | 25 | 200 | 400 | 360 | 2.5 | 0.83 | – | 500 | - | 24.1 | 67.1 | 60.4 | 200 | 76.8 | 0.38 | 98.0 | 0.62 | 63.8 | 0.0 | 63.8 | 350.6 | 1.05 | 0.44 | Shear NS |
| Choi et al. (2010) | RARAC100-H2.5 | 100 | 25 | 200 | 400 | 360 | 2.5 | 1.61 | – | 500 | - | 22.6 | 84.8 | 76.3 | 200 | 52.2 | 0.26 | 170.5 | 0.45 | 75.4 | 0.0 | 75.4 | 296.9 | 1.13 | 0.68 | Shear NS |
| Choi et al. (2010) | RARAC100-H3.25 | 100 | 25 | 200 | 400 | 360 | 3.3 | 1.61 | – | 500 | - | 22.6 | 57.8 | 67.6 | 200 | 35.6 | 0.18 | 170.5 | 0.40 | 78.8 | 0.0 | 78.8 | 290.3 | 0.73 | 0.34 | None |
| Choi et al. (2010) | RARAC100-L2.5 | 100 | 25 | 200 | 400 | 360 | 2.5 | 0.53 | – | 500 | - | 22.6 | 59.8 | 53.8 | 200 | 111.8 | 0.56 | 64.5 | 0.83 | 51.3 | 0.0 | 51.3 | 361.8 | 1.17 | 0.33 | None |
| Choi et al. (2010) | RAC100-M2.5 | 100 | 25 | 200 | 400 | 360 | 2.5 | 0.83 | – | 500 | - | 22.6 | 70.1 | 63.1 | 200 | 83.7 | 0.42 | 97.4 | 0.65 | 60.4 | 0.0 | 60.4 | 332.7 | 1.16 | 0.51 | Shear NS |
| Choi et al. (2010) | NANAC-H2.5 | 0 | 25 | 200 | 400 | 360 | 2.5 | 1.61 | – | 500 | - | 24.7 | 90.7 | 81.6 | 200 | 52.6 | 0.26 | 173.7 | 0.47 | 76.6 | 0.0 | 76.6 | 329.2 | 1.18 | 0.71 | Shear NS |
| Choi et al. (2010) | NANAC-H3.25 | 0 | 25 | 200 | 400 | 360 | 3.3 | 1.61 | – | 500 | - | 24.7 | 71.1 | 83.2 | 200 | 41.2 | 0.21 | 173.7 | 0.48 | 75.7 | 0.0 | 75.7 | 331.2 | 0.94 | 0.46 | Shear NS |
| Choi et al. (2010) | NANAC-L2.5 | 0 | 25 | 200 | 400 | 360 | 2.5 | 0.53 | – | 500 | - | 24.7 | 66.2 | 59.6 | 200 | 116.7 | 0.58 | 64.9 | 0.92 | 50.4 | 0.0 | 50.4 | 408.0 | 1.31 | 0.40 | Shear NS |
| Choi et al. (2010) | NANAC-M2.5 | 0 | 25 | 200 | 400 | 360 | 2.5 | 0.83 | – | 500 | - | 24.7 | 72 | 64.8 | 200 | 81.0 | 0.41 | 98.3 | 0.66 | 62.2 | 0.0 | 62.2 | 366.3 | 1.16 | 0.50 | Shear NS |
| Fathifazl et al. (2011) | EM-4 | 63.5 | 19 | 200 | | 305 | 3.9 | 2.46 | – | 420 | - | 41.6 | 83.2 | 99.0 | 200 | 23.9 | 0.12 | 167.7 | 0.59 | 80.2 | 0.0 | 80.2 | 432.3 | 1.04 | 0.45 | Shear NS |
| Fathifazl et al. (2011) | EM-L | 63.5 | 19 | 200 | 250 | 201 | 2.7 | 1.99 | – | 420 | - | 41.6 | 89.3 | 48.5 | 200 | 48.2 | 0.24 | 60.6 | 0.80 | 48.4 | 0.0 | 48.4 | 309.2 | 1.85 | 1.05 | Shear NS |
| Fathifazl et al. (2011) | EM-2.7 | 63.5 | 19 | 200 | 375 | 309 | 2.6 | 1.62 | – | 420 | - | 41.6 | 103.9 | 83.5 | 200 | 44.8 | 0.22 | 119.0 | 0.70 | 73.3 | 0.0 | 73.3 | 461.2 | 1.42 | 0.72 | Shear NS |
| Fathifazl et al. (2011) | EM-H | 63.5 | 19 | 200 | 450 | 381 | 2.7 | 1.83 | – | 420 | - | 41.6 | 99.5 | 102.4 | 200 | 30.8 | 0.15 | 202.0 | 0.51 | 100.9 | 0.0 | 100.9 | 524.8 | 0.99 | 0.48 | Shear NS |
| Fathifazl et al. (2011) | EM-VH | 63.5 | 19 | 200 | 550 | 476 | 2.7 | 1.68 | – | 420 | - | 41.6 | 104.6 | 134.4 | 200 | 28.2 | 0.14 | 291.9 | 0.46 | 123.3 | 0.0 | 123.3 | 643.7 | 0.85 | 0.39 | Shear NS |
| Fathifazl et al. (2011) | EV-4 | 74.3 | 19 | 200 | | 305 | 3.9 | 2.46 | – | 420 | - | 49.1 | 105.6 | 125.6 | 200 | 27.2 | 0.14 | 171.4 | 0.73 | 77.6 | 0.0 | 77.6 | 512.5 | 1.36 | 0.63 | Shear NS |
| Fathifazl et al. (2011) | EV-L | 74.3 | 19 | 200 | 250 | 201 | 2.6 | 1.99 | – | 420 | - | 49.1 | 122.6 | 64.1 | 200 | 59.3 | 0.30 | 61.6 | 1.04 | 44.9 | 0.0 | 44.9 | 374.5 | 2.73 | 1.69 | Shear NS |
| Fathifazl et al. (2011) | EV-H | 74.3 | 19 | 200 | 450 | 381 | 2.7 | 1.83 | – | 420 | - | 49.1 | 111.7 | 114.9 | 200 | 31.0 | 0.15 | 205.2 | 0.56 | 104.2 | 0.0 | 104.2 | 601.5 | 1.07 | 0.51 | Shear NS |
| Fathifazl et al. (2011) | EV-VH | 74.3 | 19 | 200 | 550 | 476 | 2.7 | 1.68 | – | 420 | - | 49.1 | 119.6 | 153.7 | 200 | 28.9 | 0.14 | 296.1 | 0.52 | 126.6 | 0.0 | 126.6 | 739.8 | 0.94 | 0.43 | Shear NS |
| Choi et al. (2012) | BSF4-A100 | 100 | 25 | 400 | 600 | 525 | 5.1 | 2.34 | (Φ10/10) 0.39 | 380 | 483 | 26.9 | 302.82 | 817.6 | 200 | 55.6 | 0.28 | 813.8 | 1.00 | 131.3 | 669.9 | 801.2 | 1184.5 | 0.38 | -0.63 | Flexural |
| Choi et al. (2012) | BSF4-A0 | 0 | 25 | 400 | 600 | 525 | 5.1 | 2.34 | (Φ10/10) 0.39 | 380 | 483 | 26.9 | 325.51 | 878.9 | 200 | 59.8 | 0.30 | 813.8 | 1.08 | 123.8 | 653.1 | 776.9 | 1209.4 | 0.42 | -0.66 | Flexural |

| Study information | | Aggregate information | | Section properties | | | Loading and reinforcement | | | Material properties | | | Test results | | Anchorage check | | | Bending check | | Shear check | | | | | Database selection | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| Author | Specimen | coarse RCA (%) | $d_{max}$ (mm) | b (mm) | h (mm) | d (mm) | a/d | $\rho_l$ (%) | $\rho_w$ (%) | $f_{yl}$ (MPa) | $f_{yw}$ (MPa) | $f_c$ (MPa) | $V_{R,test}$ (kN) | $M_{R,test}$ (kNm) | $l_{b,prov}$ (mm) | $l_{b,req}$ (mm) | $\beta_{lb}$ (-) | $M_{R,pred}$ (kNm) | $\beta_{fl}$ (-) | $V_{R,c}$ (kN) | $V_{R,s}$ (kN) | $V_{R,pred}$ (kN) | $V_{R,max}$ (kN) | $\beta_{sh}$(-) | $\Delta\beta = \beta_{sh}-\beta_{fl}$ | Database $\Delta_{cr}$=0.35 |
| Ignjatovic et al. (2013) | RAC50-1a | 50 | 31.5 | 200 | 300 | 268 | 4.2 | 0.28 | (Φ8/15) 0.34 | 640 | 555 | 35.36 | 27 | 27.0 | 250 | 43.3 | 0.17 | 25.2 | 1.07 | 27.7 | 109.1 | 136.8 | 486.7 | 0.20 | -0.87 | Flexural |
| Ignjatovic et al. (2013) | RAC50-2a | 50 | 31.5 | 200 | 300 | 263 | 4.2 | 1.46 | (Φ10/7.5) 1.05 | 550 | 555 | 35.36 | 110.55 | 110.6 | 250 | 77.9 | 0.31 | 97.6 | 1.13 | 25.3 | 382.8 | 408.1 | 450.6 | 0.27 | -0.86 | Flexural |
| Ignjatovic et al. (2013) | RAC50-3a | 50 | 31.5 | 200 | 300 | 244 | 4.2 | 2.54 | (Φ10/6) 1.31 | 550 | 555 | 35.36 | 160.35 | 160.4 | 250 | 70.0 | 0.28 | 135.2 | 1.19 | 20.5 | 479.0 | 400.8 | 400.8 | 0.40 | -0.79 | Flexural |
| Ignjatovic et al. (2013) | RAC100-1a | 100 | 31.5 | 200 | 300 | 268 | 4.2 | 0.28 | (Φ8/15) 0.34 | 640 | 555 | 34 | 26.8 | 26.8 | 250 | 44.1 | 0.18 | 25.2 | 1.07 | 27.3 | 109.7 | 137.0 | 473.2 | 0.20 | -0.87 | Flexural |
| Ignjatovic et al. (2013) | RAC100-2a | 100 | 31.5 | 200 | 300 | 263 | 4.2 | 1.46 | (Φ10/7.5) 1.05 | 550 | 555 | 34 | 105.4 | 105.4 | 250 | 76.3 | 0.31 | 97.1 | 1.09 | 25.7 | 393.3 | 419.0 | 432.8 | 0.25 | -0.83 | Flexural |
| Ignjatovic et al. (2013) | RAC100-3a | 100 | 31.5 | 200 | 300 | 244 | 4.2 | 2.54 | (Φ10/6) 1.31 | 550 | 555 | 34 | 142.6 | 142.6 | 250 | 63.9 | 0.26 | 133.7 | 1.07 | 22.5 | 507.5 | 376.4 | 376.4 | 0.38 | -0.69 | Flexural |
| Ignjatovic et al. (2013) | NAC1a | 0 | 31.5 | 200 | 300 | 268 | 4.2 | 0.28 | (Φ8/15) 0.34 | 640 | 555 | 34.96 | 28.35 | 28.4 | 250 | 45.8 | 0.18 | 25.2 | 1.13 | 26.5 | 105.4 | 131.9 | 488.5 | 0.21 | -0.91 | Flexural |
| Ignjatovic et al. (2013) | NAC2a | 0 | 31.5 | 200 | 300 | 263 | 4.2 | 1.46 | (Φ10/7.5) 1.05 | 550 | 555 | 34.96 | 108.55 | 108.6 | 250 | 77.1 | 0.31 | 97.5 | 1.11 | 25.5 | 386.8 | 412.4 | 444.8 | 0.26 | -0.85 | Flexural |
| Ignjatovic et al. (2013) | NAC3a | 0 | 31.5 | 200 | 300 | 244 | 4.2 | 2.54 | (Φ10/6) 1.31 | 550 | 555 | 34.96 | 137.6 | 137.6 | 250 | 60.6 | 0.24 | 134.8 | 1.02 | 24.0 | 516.0 | 379.3 | 379.3 | 0.36 | -0.66 | Flexural |
| Ignjatovic (2013) | RAC50-1b | 50 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | – | 555 | - | 33.44 | 91.8 | 90.6 | 250 | 26.2 | 0.10 | 163.3 | 0.55 | 61.8 | 0.0 | 61.8 | 283.2 | 1.49 | 0.93 | Shear NS |
| Ignjatovic (2013) | RAC50-3b | 50 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | (Φ6/15) 0.19 | 555 | 300 | 33.44 | 156.9 | 154.9 | 250 | 56.1 | 0.22 | 163.3 | 0.95 | 21.8 | 43.4 | 65.2 | 325.5 | 2.41 | 1.46 | Shear S |
| Ignjatovic (2013) | RAC1000-1b | 100 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | – | 555 | - | 34.48 | 104.8 | 103.4 | 250 | 29.4 | 0.12 | 165.9 | 0.62 | 59.1 | 0.0 | 59.1 | 298.1 | 1.77 | 1.15 | Shear NS |
| Ignjatovic (2013) | RAC100-3b | 100 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | (Φ6/15) 0.19 | 555 | 300 | 34.48 | 163.4 | 161.3 | 250 | 57.2 | 0.23 | 165.9 | 0.97 | 21.4 | 42.8 | 64.2 | 336.2 | 2.55 | 1.57 | Shear S |
| Ignjatovic (2013) | NAC1b | 0 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | – | 555 | - | 30.8 | 106.3 | 104.9 | 250 | 32.1 | 0.13 | 155.8 | 0.67 | 55.5 | 0.0 | 55.5 | 277.4 | 1.92 | 1.24 | Shear NS |
| Ignjatovic (2013) | NAC3b | 0 | 31.5 | 200 | 300 | 235 | 4.2 | 4.09 | (Φ6/15) 0.19 | 555 | 300 | 30.8 | 159.9 | 157.8 | 250 | 60.4 | 0.24 | 155.8 | 1.01 | 19.3 | 43.1 | 62.4 | 309.9 | 2.56 | 1.55 | Shear S |
| Kim et al. (2013) | RF-S2 | 100 | 25 | 200 | 350 | 300 | 2.5 | 1.94 | – | 651 | - | 34.9 | 72.9 | 54.7 | 150 | 33.5 | 0.22 | 184.7 | 0.30 | 85.7 | 0.0 | 85.7 | 352.4 | 0.85 | 0.55 | Shear NS |
| Kim et al. (2013) | RF-M2 | 100 | 25 | 200 | 530 | 450 | 2.5 | 1.93 | – | 610 | - | 34.9 | 96.4 | 108.5 | 150 | 29.7 | 0.20 | 393.7 | 0.28 | 123.6 | 0.0 | 123.6 | 517.3 | 0.78 | 0.50 | Shear NS |
| Kim et al. (2013) | RF-L2 | 100 | 25 | 200 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 34.9 | 125.1 | 187.7 | 150 | 28.8 | 0.19 | 738.9 | 0.25 | 154.3 | 0.0 | 154.3 | 686.0 | 0.81 | 0.56 | Shear NS |
| Kim et al. (2013) | RF-M3 | 100 | 25 | 300 | 530 | 450 | 2.5 | 2.00 | – | 600 | - | 34.9 | 159.8 | 179.8 | 150 | 31.7 | 0.21 | 599.2 | 0.30 | 181.2 | 0.0 | 181.2 | 784.8 | 0.88 | 0.58 | Shear NS |
| Kim et al. (2013) | RF-L4 | 100 | 25 | 400 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 34.9 | 256.6 | 384.9 | 150 | 29.5 | 0.20 | 1477.8 | 0.26 | 305.9 | 0.0 | 305.9 | 1377.9 | 0.84 | 0.58 | Shear NS |
| Kim et al. (2013) | RH-S2 | 50 | 25 | 200 | 350 | 300 | 2.5 | 1.94 | – | 651 | - | 32.6 | 60.6 | 45.5 | 150 | 29.2 | 0.19 | 181.8 | 0.25 | 88.5 | 0.0 | 88.5 | 326.1 | 0.69 | 0.43 | Shear NS |
| Kim et al. (2013) | RH-M2 | 50 | 25 | 200 | 530 | 450 | 2.5 | 1.93 | – | 610 | - | 32.6 | 108.9 | 122.5 | 150 | 35.1 | 0.23 | 387.9 | 0.32 | 114.3 | 0.0 | 114.3 | 505.2 | 0.95 | 0.64 | Shear NS |
| Kim et al. (2013) | RH-L2 | 50 | 25 | 200 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 32.6 | 126.1 | 189.2 | 150 | 30.3 | 0.20 | 727.0 | 0.26 | 148.7 | 0.0 | 148.7 | 656.4 | 0.85 | 0.59 | Shear NS |
| Kim et al. (2013) | RH-M3 | 50 | 25 | 300 | 530 | 450 | 2.5 | 2.00 | – | 600 | - | 32.6 | 154.2 | 173.5 | 150 | 32.0 | 0.21 | 590.2 | 0.29 | 177.4 | 0.0 | 177.4 | 745.2 | 0.87 | 0.58 | Shear NS |
| Kim et al. (2013) | RH-L4 | 50 | 25 | 400 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 32.6 | 261.5 | 392.3 | 150 | 31.5 | 0.21 | 1454.0 | 0.27 | 293.7 | 0.0 | 293.7 | 1321.0 | 0.89 | 0.62 | Shear NS |
| Kim et al. (2013) | NA-S2 | 0 | 25 | 200 | 350 | 300 | 2.5 | 1.94 | – | 651 | - | 31.8 | 75.5 | 56.6 | 150 | 36.9 | 0.25 | 180.6 | 0.31 | 80.8 | 0.0 | 80.8 | 333.5 | 0.93 | 0.62 | Shear NS |
| Kim et al. (2013) | NA-M2 | 0 | 25 | 200 | 530 | 450 | 2.5 | 1.93 | – | 610 | - | 31.8 | 106.9 | 120.3 | 150 | 35.0 | 0.23 | 385.6 | 0.31 | 113.7 | 0.0 | 113.7 | 495.2 | 0.94 | 0.63 | Shear NS |
| Kim et al. (2013) | NA-L2 | 0 | 25 | 200 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 31.8 | 125.9 | 188.9 | 150 | 30.8 | 0.21 | 722.5 | 0.26 | 146.9 | 0.0 | 146.9 | 645.5 | 0.86 | 0.60 | Shear NS |
| Kim et al. (2013) | NA-M3 | 0 | 25 | 300 | 530 | 450 | 2.5 | 2.00 | – | 600 | - | 31.8 | 156.7 | 176.3 | 150 | 33.0 | 0.22 | 586.7 | 0.30 | 174.2 | 0.0 | 174.2 | 735.0 | 0.90 | 0.60 | Shear NS |
| Kim et al. (2013) | NA-L4 | 0 | 25 | 400 | 680 | 600 | 2.5 | 1.94 | – | 651 | - | 31.8 | 256.4 | 384.6 | 150 | 31.4 | 0.21 | 1445.0 | 0.27 | 292.1 | 0.0 | 292.1 | 1294.9 | 0.88 | 0.61 | Shear NS |
| Knaack and Kurama (2014) | S50-1a | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 43.6 | 44 | 33.4 | 200 | 37.8 | 0.19 | 40.6 | 0.82 | 30.0 | 0.0 | 30.0 | 265.1 | 1.47 | 0.64 | Shear NS |
| Knaack and Kurama (2014) | S50-1b | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 43.6 | 39.1 | 29.7 | 200 | 33.6 | 0.17 | 40.6 | 0.73 | 32.2 | 0.0 | 32.2 | 255.7 | 1.21 | 0.48 | Shear NS |
| Knaack and Kurama (2014) | S50-2a | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 40.2 | 43.7 | 33.2 | 200 | 39.6 | 0.20 | 40.2 | 0.83 | 28.9 | 0.0 | 28.9 | 250.6 | 1.51 | 0.69 | Shear NS |
| Knaack and Kurama (2014) | S50-2b | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 40.2 | 41.2 | 31.3 | 200 | 37.3 | 0.19 | 40.2 | 0.78 | 30.0 | 0.0 | 30.0 | 246.1 | 1.38 | 0.60 | Shear NS |
| Knaack and Kurama (2014) | S100-1a | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 41.4 | 36.4 | 27.7 | 200 | 32.4 | 0.16 | 40.4 | 0.69 | 32.7 | 0.0 | 32.7 | 241.8 | 1.11 | 0.43 | Shear NS |
| Knaack and Kurama (2014) | S100-1b | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 41.4 | 38 | 28.9 | 200 | 33.8 | 0.17 | 40.4 | 0.72 | 31.9 | 0.0 | 31.9 | 244.9 | 1.19 | 0.48 | Shear NS |
| Knaack and Kurama (2014) | S100-2a | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 35.7 | 39.9 | 30.3 | 200 | 39.1 | 0.20 | 39.7 | 0.76 | 28.8 | 0.0 | 28.8 | 225.2 | 1.39 | 0.62 | Shear NS |
| Knaack and Kurama (2014) | S100-2b | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 35.7 | 36.1 | 27.4 | 200 | 35.4 | 0.18 | 39.7 | 0.69 | 30.5 | 0.0 | 30.5 | 218.5 | 1.18 | 0.49 | Shear NS |
| Knaack and Kurama (2014) | S0-1a | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 32.6 | 31.1 | 23.6 | 200 | 32.4 | 0.16 | 39.3 | 0.60 | 31.7 | 0.0 | 31.7 | 197.0 | 0.98 | 0.38 | Shear NS |
| Knaack and Kurama (2014) | S0-1b | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 32.6 | 36.9 | 28.0 | 200 | 38.5 | 0.19 | 39.3 | 0.71 | 28.8 | 0.0 | 28.8 | 207.0 | 1.28 | 0.57 | Shear NS |
| Knaack and Kurama (2014) | S0-2a | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 50.3 | 40.4 | 30.7 | 200 | 31.5 | 0.16 | 41.1 | 0.75 | 33.9 | 0.0 | 33.9 | 284.1 | 1.19 | 0.44 | Shear NS |
| Knaack and Kurama (2014) | S0-2b | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | – | 570 | - | 50.3 | 42.3 | 32.1 | 200 | 33.0 | 0.17 | 41.1 | 0.78 | 33.0 | 0.0 | 33.0 | 288.1 | 1.28 | 0.50 | Shear NS |
| Knaack and Kurama (2014) | F50-1a | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 40 | 55.0 | 41.8 | 200 | 62.5 | 0.31 | 41.5 | 1.01 | 18.0 | 189.7 | 207.7 | 265.8 | 0.26 | -0.74 | Flexural |
| Knaack and Kurama (2014) | F50-1b | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 40 | 56.7 | 43.1 | 200 | 64.5 | 0.32 | 41.5 | 1.04 | 17.5 | 186.7 | 204.2 | 268.3 | 0.28 | -0.76 | Flexural |
| Knaack and Kurama (2014) | F50-2a | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 39.3 | 54.3 | 41.3 | 200 | 62.5 | 0.31 | 41.4 | 1.00 | 18.0 | 190.8 | 208.8 | 261.7 | 0.26 | -0.74 | Flexural |
| Knaack and Kurama (2014) | F50-2b | 50 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 39.3 | 54.3 | 41.3 | 200 | 62.5 | 0.31 | 41.4 | 1.00 | 18.0 | 190.8 | 208.8 | 261.7 | 0.26 | -0.74 | Flexural |
| Knaack and Kurama (2014) | F100-1a | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 43.8 | 54.9 | 41.7 | 200 | 58.7 | 0.29 | 41.9 | 1.00 | 19.2 | 189.9 | 209.1 | 282.1 | 0.26 | -0.73 | Flexural |
| Knaack and Kurama (2014) | F100-1b | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 43.8 | 54.9 | 41.7 | 200 | 58.7 | 0.29 | 41.9 | 1.00 | 19.2 | 189.9 | 209.1 | 282.1 | 0.26 | -0.73 | Flexural |
| Knaack and Kurama (2014) | F100-2a | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 38.5 | 58.0 | 44.1 | 200 | 67.7 | 0.34 | 41.3 | 1.07 | 16.8 | 184.5 | 201.2 | 263.4 | 0.29 | -0.78 | Flexural |
| Knaack and Kurama (2014) | F100-2b | 100 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 38.5 | 55.9 | 42.5 | 200 | 65.2 | 0.33 | 41.3 | 1.03 | 17.3 | 188.1 | 205.4 | 260.4 | 0.27 | -0.76 | Flexural |
| Knaack and Kurama (2014) | F0-1a | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 38.6 | 56.1 | 42.6 | 200 | 65.2 | 0.33 | 41.3 | 1.03 | 17.3 | 187.8 | 205.1 | 261.1 | 0.27 | -0.76 | Flexural |
| Knaack and Kurama (2014) | F0-1b | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 38.6 | 56.7 | 43.1 | 200 | 66.0 | 0.33 | 41.3 | 1.04 | 17.1 | 186.7 | 203.8 | 262.0 | 0.28 | -0.77 | Flexural |
| Knaack and Kurama (2014) | F0-2a | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 46.5 | 57.6 | 43.8 | 200 | 59.3 | 0.30 | 42.1 | 1.04 | 19.1 | 185.1 | 204.3 | 298.1 | 0.28 | -0.76 | Flexural |
| Knaack and Kurama (2014) | F0-2b | 0 | 19 | 150 | 230 | 200 | 3.8 | 1.3 | (Φ10/9.5) 1.10 | 572 | 420 | 46.5 | 57.6 | 43.8 | 200 | 59.3 | 0.30 | 42.1 | 1.04 | 19.1 | 185.1 | 204.3 | 298.1 | 0.28 | -0.76 | Flexural |
| Kang et al. (2014) | N50-0.5 | 50 | 25 | 135 | 270 | 230 | 3.9 | 0.5 | (Φ10/10) 1.6 | 377 | 400 | 29 | 15.15 | 13.6 | 165 | 33.5 | 0.20 | 13.2 | 1.03 | 22.7 | 228.1 | 198.7 | 198.7 | 0.08 | -0.96 | Flexural |
| Kang et al. (2014) | N50-1.0 | 50 | 25 | 135 | 270 | 230 | 3.9 | 1 | (Φ10/10) 1.6 | 408 | 400 | 29 | 27.1 | 24.4 | 165 | 39.0 | 0.24 | 23.4 | 1.04 | 20.5 | 222.9 | 202.1 | 202.1 | 0.13 | -0.91 | Flexural |
| Kang et al. (2014) | N50-1.5 | 50 | 25 | 135 | 270 | 230 | 3.9 | 1.5 | (Φ10/10) 1.6 | 389 | 400 | 29 | 36.45 | 32.8 | 165 | 43.0 | 0.26 | 32.8 | 1.00 | 20.7 | 233.6 | 195.0 | 195.0 | 0.19 | -0.81 | Flexural |
| Kang et al. (2014) | N50-1.8 | 50 | 25 | 135 | 270 | 230 | 3.9 | 1.8 | (Φ10/10) 1.6 | 410 | 400 | 29 | 56.1 | 50.5 | 165 | 65.5 | 0.40 | 46.4 | 1.09 | 17.4 | 225.8 | 200.2 | 200.2 | 0.28 | -0.81 | Flexural |
| Kang et al. (2014) | N0-0.5 | 0 | 25 | 135 | 270 | 230 | 3.9 | 0.5 | (Φ10/10) 1.6 | 377 | 400 | 38.6 | 17.65 | 15.9 | 165 | 32.3 | 0.20 | 13.3 | 1.20 | 24.0 | 213.9 | 237.9 | 254.8 | 0.07 | -1.12 | Flexural |
| Kang et al. (2014) | N0-1.0 | 0 | 25 | 135 | 270 | 230 | 3.9 | 1 | (Φ10/10) 1.6 | 408 | 400 | 38.6 | 31.35 | 28.2 | 165 | 37.2 | 0.23 | 23.8 | 1.19 | 21.9 | 209.2 | 231.1 | 258.7 | 0.14 | -1.05 | Flexural |
| Kang et al. (2014) | N0-1.5 | 0 | 25 | 135 | 270 | 230 | 3.9 | 1.5 | (Φ10/10) 1.6 | 389 | 400 | 38.6 | 40.95 | 36.9 | 165 | 39.9 | 0.24 | 33.6 | 1.10 | 22.9 | 223.1 | 246.0 | 247.2 | 0.17 | -0.93 | Flexural |
| Kang et al. (2014) | N0-1.8 | 0 | 25 | 135 | 270 | 230 | 3.9 | 1.8 | (Φ10/10) 1.6 | 410 | 400 | 38.6 | 58.7 | 52.8 | 165 | 56.6 | 0.34 | 48.1 | 1.10 | 20.7 | 221.6 | 242.3 | 248.4 | 0.24 | -0.85 | Flexural |
| Arezoumandi et al. (2015) | RAC100 NS-4 1 | 100 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 30 | 114.8 | 137.8 | 250 | 44.5 | 0.18 | 247.5 | 0.56 | 128.6 | 0.0 | 128.6 | 689.7 | 0.89 | 0.34 | None |
| Arezoumandi et al. (2015) | RAC100 NS-6 1 | 100 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 30 | 143.2 | 171.8 | 250 | 37.0 | 0.15 | 325.1 | 0.53 | 128.9 | 0.0 | 128.9 | 629.4 | 1.11 | 0.58 | Shear NS |
| Arezoumandi et al. (2015) | RAC100 NS-8 1 | 100 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 30 | 131.4 | 157.7 | 250 | 25.5 | 0.10 | 407.0 | 0.39 | 149.2 | 0.0 | 149.2 | 584.7 | 0.88 | 0.49 | Shear NS |
| Arezoumandi et al. (2015) | RAC100 NS-4 2 | 100 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 34.1 | 113 | 135.6 | 250 | 40.2 | 0.16 | 250.7 | 0.54 | 138.1 | 0.0 | 138.1 | 748.4 | 0.82 | 0.28 | None |
| Arezoumandi et al. (2015) | RAC100 NS-6 2 | 100 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 34.1 | 124.1 | 148.9 | 250 | 29.5 | 0.12 | 332.3 | 0.45 | 145.9 | 0.0 | 145.9 | 665.0 | 0.85 | 0.40 | Shear NS |
| Arezoumandi et al. (2015) | RAC100 NS-8 2 | 100 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 34.1 | 140.3 | 168.4 | 250 | 25.0 | 0.10 | 419.9 | 0.40 | 155.4 | 0.0 | 155.4 | 644.2 | 0.90 | 0.50 | Shear NS |
| Arezoumandi et al. (2015) | RAC50 NS-4 1 | 50 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 32.1 | 117.5 | 141.0 | 250 | 43.5 | 0.17 | 249.2 | 0.57 | 131.6 | 0.0 | 131.6 | 725.6 | 0.89 | 0.33 | None |
| Arezoumandi et al. (2015) | RAC50 NS-6 1 | 50 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 32.1 | 151.3 | 181.6 | 250 | 37.4 | 0.15 | 329.0 | 0.55 | 130.1 | 0.0 | 130.1 | 666.7 | 1.16 | 0.61 | Shear NS |
| Arezoumandi et al. (2015) | RAC50 NS-8 1 | 50 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 32.1 | 171.8 | 206.2 | 250 | 31.8 | 0.13 | 414.0 | 0.50 | 139.4 | 0.0 | 139.4 | 643.5 | 1.23 | 0.73 | Shear NS |
| Arezoumandi et al. (2015) | RAC50 NS-4 2 | 50 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 35.5 | 111.7 | 134.0 | 250 | 38.7 | 0.15 | 251.6 | 0.53 | 141.7 | 0.0 | 141.7 | 766.7 | 0.79 | 0.26 | None |
| Arezoumandi et al. (2015) | RAC50 NS-6 2 | 50 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 35.5 | 148.6 | 178.3 | 250 | 34.4 | 0.14 | 334.4 | 0.53 | 137.9 | 0.0 | 137.9 | 710.1 | 1.08 | 0.54 | Shear NS |

| Study information | | Aggregate information | | Section properties | | | Loading and reinforcement | | | Material properties | | | Test results | | Anchorage check | | | Bending check | | Shear check | | | | | Database selection | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| Author | Specimen | coarse RCA (%) | $d_{max}$ (mm) | b (mm) | h (mm) | d (mm) | a/d | $\rho_l$ (%) | $\rho_w$ (%) | $f_{yl}$ (MPa) | $f_{yw}$ (MPa) | $f_c$ (MPa) | $V_{R,test}$ (kN) | $M_{R,test}$ (kNm) | $l_{b,prov}$ (mm) | $l_{b,req}$ (mm) | $\beta_{lb}$ (-) | $M_{R,pred}$ (kNm) | $\beta_{fl}$ (-) | $V_{R,c}$ (kN) | $V_{R,s}$ (kN) | $V_{R,pred}$ (kN) | $V_{R,max}$ (kN) | $\beta_{sh}$(-) | $\Delta\beta = \beta_{sh}$-$\beta_{fl}$ | Database $\Delta_{cr}$=0.35 |
| Arezoumandi et al. (2015) | RAC50 NS-8 2 | 50 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 35.5 | 168.7 | 202.4 | 250 | 29.2 | 0.12 | 423.7 | 0.48 | 147.7 | 0.0 | 147.7 | 685.6 | 1.14 | 0.66 | Shear NS |
| Arezoumandi et al. (2015) | NAC NS-4 1 | 0 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 37.3 | 121.2 | 145.4 | 250 | 40.6 | 0.16 | 252.7 | 0.58 | 139.8 | 0.0 | 139.8 | 808.1 | 0.87 | 0.29 | None |
| Arezoumandi et al. (2015) | NAC NS-6 1 | 0 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 37.3 | 143.2 | 171.8 | 250 | 32.0 | 0.13 | 336.9 | 0.51 | 143.7 | 0.0 | 143.7 | 727.8 | 1.00 | 0.49 | Shear NS |
| Arezoumandi et al. (2015) | NAC NS-8 1 | 0 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 37.3 | 173.5 | 208.2 | 250 | 29.1 | 0.12 | 428.0 | 0.49 | 149.7 | 0.0 | 149.7 | 712.7 | 1.16 | 0.67 | Shear NS |
| Arezoumandi et al. (2015) | NAC NS-4 2 | 0 | 25 | 300 | 460 | 400 | 3.0 | 1.27 | – | 450 | - | 34.2 | 129.9 | 155.9 | 250 | 46.1 | 0.18 | 250.8 | 0.62 | 129.4 | 0.0 | 129.4 | 776.1 | 1.00 | 0.38 | Shear NS |
| Arezoumandi et al. (2015) | NAC NS-6 2 | 0 | 25 | 300 | 460 | 375 | 3.2 | 2.03 | – | 450 | - | 34.2 | 167 | 200.4 | 250 | 39.6 | 0.16 | 332.5 | 0.60 | 128.3 | 0.0 | 128.3 | 712.0 | 1.30 | 0.70 | Shear NS |
| Arezoumandi et al. (2015) | NAC NS-8 2 | 0 | 25 | 300 | 460 | 375 | 3.2 | 2.71 | – | 450 | - | 34.2 | 170.8 | 205.0 | 250 | 30.3 | 0.12 | 420.2 | 0.49 | 144.3 | 0.0 | 144.3 | 670.5 | 1.18 | 0.70 | Shear NS |

**Annotations:**

**$d_{max}$ -** maximum aggregate size
**b -** cross-section width
**h -** cross-section height
**d -** effective cross-section height
**a/d -** shear span-to-height ratio
**$\rho_l$ -** longitudinal reinforcement ratio
**$\rho_w$ -** transverse reinforcement ratio
**$f_{yl}$ -** longitudinal reinforcement yield stress
**$f_{yw}$ -** transverse reinforcement yield stress
**$f_c$ -** concrete compressive strength
**$V_{R,test}$ -** measured shear strength

**$M_{R,test}$ -** measured flexural strength
**$l_{b,prov}$ -** provided anchorage length
**$l_{b,req}$ -** required anchorage length
**$\beta_{lb}$ -** provided-to-required anchorage length ratio
**$M_{R,pred}$ -** predicted flexural strength
**$\beta_{fl}$ -** measured-to-predicted flexural strength ratio
**$V_{R,c}$ -** predicted shear strength attributed to concrete
**$V_{R,s}$ -** predicted shear strength attributed to transverese reinforcement
**$V_{R,pred}$ -** predicted shear strength
**$V_{R,max}$ -** limit for predicted shear strength
**$\beta_{sh}$ -** measured-to-predicted shear strength ratio