Mechanical properties of multiple-recycled coarse aggregate concrete under combined compression and shear loading

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Abstract: The mechanical properties and strength failure criteria of natural coarse aggregate and multiple recycled coarse aggregate concrete under the combined compression and shear loading states are investigated in this study. The failure pattern, peak shear strength, and peak shear displacement are compared in terms of the number of regeneration cycles and normal compressive stress ratios. The results reveal that both the peak shear strength and peak shear displacement of concrete increase with the enlarged normal stress ratio. The shear failure pattern with higher severity corresponds to more spalling powder and debris deposited on the shear fracture surface. When the times of coarse aggregate regeneration increase, the peak shear strength decreases, and the descending trend becomes more evident with the increased vertical compressive stress ratio, whereas the peak shear displacement significantly fluctuates, regardless of the regeneration time and the normal compressive stress ratios. With normal compressive stress, the contact friction strength becomes the dominated component of peak shear strength consisting of cohesive strength, contact friction strength, and shear dilation strength. Based on the different stress expressions, three compression-shear failure criterion models considering the times of coarse aggregate regeneration under planar stress state were established for concrete. Despite the strong correlation with the correlation factors ($R^2$) larger than 0.96 for all the models, the failure criterion model based on stress invariance and failure criterion model based on octahedral stresses in the quadratic parabolic functional forms provides the highest predictive accuracy. The related outcomes are expected to fill the gap of the related research on recycled aggregate concrete.

Keywords: Multiple recycled concrete; Regeneration cycle; Compression-shear combined stress;
1. Introduction

The rapid development of the infrastructure construction industry has been acknowledged worldwide as a major contributor to global energy and natural resources consumption [1]. More seriously, the construction and demolition (C&D) of buildings result in a huge amount of waste, which poses a heavy burden to solid waste management, environmental protection and sustainable development [2]. According to the China Environmental Protection Union, the amount of C&D waste, which contributed over 40% of total municipal solid wastes, reached 2.6 billion tons in 2020, while only 5% of the waste was recycled [3, 4]. The prime concerns of C&D waste promote the recycling of C&D waste into construction materials becoming a hot and urgent research topic cooperated by industry, academics, and government.

Reuse of aggregates from waste concrete which makes up the largest proportion of C&D waste to substitute virgin aggregates for the fabrication of recycled aggregate concrete (RAC) is one of the most effective strategies to reduce the construction waste and preserve the natural aggregate resource, consequently contributing towards improving circular economy and sustainability of construction sectors [5]. Although the properties of RA have been extensively studied over two decades, the proper application of RAC as structural components is yet at the budding stage [6-8]. On the one hand, the recycled aggregates (RA) in the manufacturing process are subjected to extrusion, impact, grinding and other external mechanical forces, which initiate microcracks and defects inside the RA and increase their porosity [9]. On the other hand, there are inherent defects and additional interfacial transition zones (ITZs) caused by the old paste or mortar adhered on RA that possesses high water absorption and results in ineffectual bonding between RA and cement matrix, subsequently
The suitable utilization of recycled coarse aggregate concrete in structural components necessitates comprehensive investigations on the mechanical properties of recycled coarse aggregate concrete under various loading states. Researchers and practitioners have conducted numerous research work on the mechanical properties of RAC such as compressive, flexural, shear and splitting tensile strength [14-21]. Rahal and Hassan [22] studied the compressive strength, shear strength and shear failure pattern of RAC and natural aggregate concrete (NAC); they concluded that RAC had the inferior compressive and shear strength. In addition, they established a relationship between tensile cracking strength and shear strength RAC based on linear elastic finite element analysis. Wang et al. [23] prepared RAC with RA and grade F fly ash, and then compared the RAC with the NAC produced with identical mixture proportion. The results illustrated the compressive strength, flexural strength and direct shear strength of RAC were degraded to approximately 85% of those of NAC. Recently, an experiment was performed to study the influence of fine recycled aggregate (FRA) on the compressive and splitting tensile properties of RAC with various replacement ratios of coarse recycled aggregate (CRA); the results revealed that the impact of FRA on the compressive and splitting tensile strength is independent of the CRA dosage [24]. Nevertheless, the current research on the mechanical properties of recycled RAC as structural concrete is still rare, especially for the behaviors of RAC under the complicated or coupled loading states.

In real scenarios, the structural concrete served in infrastructures is frequently in a combined stress state of compressive and shear stress, rather than a single uniaxial compression (tension) state and a pure shear state. For instance, the shear area of columns or prestressed concrete beams, and the core area of beam-column joints of frame structures are in a state of combined compressive-shear stress.
Previous investigations on the concrete under combined actions of compression and shear mainly focus on the conventional concrete, and very limited studies emphasize on the RAC with a single regeneration cycle. Sun et al. [25] investigated the effects of freeze-thaw cycles and normal compressive stress on the peak strain, peak shear strength, cohesion, and friction coefficient of concrete. It is shown that with the increase of freeze-thaw cycles, the shear strength of concrete gradually decreased while the peak shear deformation linearly increased; based on the compression-shear failure criterion model in the form of quadratic parabolic function in octahedral stress space, a compression-shear failure criterion for concrete considering the number of freeze-thaw cycles under plane stress state was proposed. Deng et al. [26] investigated the failure mechanism of two categories of recycled concrete by in terms of the parameters of the replacement ratio of recycled coarse aggregate and normal compressive stress ratio. It was indicated that for RAC with the same grade, the shear strength increased parabolically and linearly, with the increment of the normal compressive stress ratio and the replacement rate of recycled coarse aggregate, respectively [26]. It was also proposed that the shear strength of recycled concrete was mainly comprised of cohesive strength, total occlusal strength, and interfacial friction strength, where the interfacial friction strength dominated and is accounted for approximately 25 to 70% of the shear strength. Liu et al [27] comprehensively assessed the peak shear strength and shear strength components, shear failure modes, deformation characteristics and shear stress-displacement curves of coral concrete under compression-shear composite stress state by the triaxial tests. It is found in the presence of vertical compressive strength, the contact friction became major components of the peak shear strength, among the cohesive strength, contact friction strength and shear dilation strength. Xie et al. [28] explored the mechanical properties of superabsorbent polymer (SAP) internally cured concrete (SAPC). It was illustrated that the shear strength and the
residual strength of SAPC increased with the increase of normal pressure, whereas the shear strength and friction coefficient of SAPC decreased with the increase of SAP content. Additionally, a SAPC failure criterion based on octahedral stress was proposed. According to Wang et al. [29], the failure mode of RAC under combined compressive-shear stress is mainly affected by normal pressure, although the reinforcement ratio showed the little impact. It is also found that both the shear strength and toughness significantly enhanced with the increased normal pressure, and a shear stress-strain model for RAC under the composite compressive-shear stress was proposed, which showed good agreement with experimental results.

Although some achievements have been made on the mechanical properties of RAC with single regeneration, the relevant research on the multi-recycled coarse aggregate concrete with superior sustainability is rarely reported. It is not yet reached an agreement on how sequential cycles of regeneration will vary the properties of the resulting aggregates. Some studies have investigated the mechanical properties of multi-recycled coarse aggregate concrete under single stress conditions. Most studies agreed that the compressive strength of RAC increased regeneration cycles of coarse aggregate due to the deteriorated physio-chemical properties of multiple recycled aggregates [30, 31]. For example, both the water absorptivity and Los Angles wear of RA increased with the number of regeneration cycles while the density decreased [32]. Similarly, Thomas et al. [33] adopted computerized X-ray micro-tomography to diagnose the different phases of RA, it was found that the volume fraction of adhered old mortar reached 80% of the aggregates. However, Huda et al. [34] reported that although the compressive strength of fully recycled coarse aggregate concrete degraded with the increased regeneration cycles of coarse aggregate, the splitting tensile test exhibited an initial ascending trend. To the best of our knowledge, this is the first work aiming to compressively study the
mechanical properties of multiple recycled coarse aggregate concrete under composite compressive-shear stress. Particularly, this study investigated the mechanical properties and strength failure criteria of multiple recycled coarse aggregate concrete affected by two main factors: normal compressive stress ratio and number of coarse aggregate regeneration cycles, attempting to provide the essential data and theoretical reference for multiple recycled coarse aggregate concrete under complex stress conditions. The related outcomes should facilitate the suitable application of multiple-recycled coarse aggregate concrete in engineering structures.

2. Experimental program

2.1 Raw materials and mix design

In this test, natural coarse aggregate (NA) with a particle size of 5-20mm is selected to prepare natural coarse aggregate concrete (NAC). NA is crushed to extract the 1st generation recycled coarse aggregate (RA1I), then RA1 is utilized to prepare the 1st generation recycled coarse aggregate concrete (RACI). The 2nd generation recycled coarse aggregate concrete (RACII) and the 3rd generation recycled coarse aggregate concrete (RACIII) are manufactured in an identical way by crushing the recycled aggregates from previous regeneration cycle. It shall be noted that RA in each regeneration cycle is fully acquired from RA in the previous cycle. The morphology of four types of RA in different regeneration cycles is depicted in Fig. 1. The quality of four types of RA is assessed in terms of crushing index, apparent density and water absorption in accordance with the requirements of GB/T25177-2012 (Table 1) [35]. The crushing index is an indicator for the crushing resistance of RA, and is determined based on the following formula in accordance with GB/T 14685-2011 [36]:

\[ Q = \frac{G_1 - G_2}{G_1} \times 100 \]  

where \( Q \) crushing index; \( G_1 \) mass of specimen; \( G_2 \) Mass of specimen retaining on sieve after crush
The standard sand with the fineness of 2.8 in accordance with GB/T 14684-2011 [37] is served as fine aggregate. P.O. 42.5 Portland cement (Hailuo Co., Ltd, China) in accordance with GB/T 175-2007 [38] is used for mix design. Table 2 lists the main physical and mechanical properties of cement. Table 3 lists the chemical composition of cement. The naphthalene-based water reducing agent is used to achieve the proper workability of the mixture. To avoid the interruptions from inconsistent effective water to cement ratio, the recycled coarse aggregates were pre-soaked in water for 24 hours and subsequently dried in air to reach a saturated surface dry condition prior to the mixing process [39].

The mix proportion of RAC with different regeneration cycles is shown in Table 4, in accordance with JGJ 55-2000 (Specification for mix proportion design of ordinary concrete). The water to cement (w/c) ratio is fixed at 0.37 for all groups.

2.2 Specimen and testing method

Normal compressive stress ratio and number of regeneration cycles are designed as main parameters to study the mechanical properties of RCA under composite compressive-shear stress. Five normal compressive stress levels ($k = \sigma / f_c = 0, 0.2, 0.4, 0.6, 0.8$, where $f_c$ is the uniaxial compressive strength) were conducted on four kinds of RAC with the different number of regenerations cycles of coarse aggregates (NAC, RACI, RACII and RACIII). Uniaxial compression test was primarily carried out to acquire the uniaxial compressive strength of RAC to determine the magnitude of the compressive stress corresponding to the designed normal compressive strength ratio. A total of sixty 100 mm × 100 mm × 100 mm cubic specimens were prepared for the uniaxial compression test and compression-shear combination test. Each test for an individual group contains three replicates. The mixing process is described as follows. Firstly, the weighted sand and coarse aggregate were added into a concrete test.
mixer and mixed for about 3 minutes. Then the cement powder is poured into the mixer, and the mixing continues additional 3 minutes. Finally, pre-mixed water reducing agent/ water solution was dumped into the dry mixture, and the mixing sustained a further 3-5 minutes. After 48 hours of sealed curing, specimens were demolded and cured in saturated calcium hydroxide solution for additional 26 days before testing.

The microcomputer-controlled electro-hydraulic servo rock straight shear instrument (YZW-600Y) was used for the uniaxial compression test and the combined compression-shear test, as shown in Fig. 2. The equipment can apply vertically, and transverse loads up to 600kN and 500kN, respectively. The vertical and transverse strokes of the working range are 100mm. The working range of the shear loading rate is 0.1-30kN/s. Load indication accuracy and displacement measurement accuracy are both ±0.5%. Before the compression-shear test, an initial 5kN vertical force is applied to enable the specimen to be tightly fitted with the shear box. The formal loading regime includes several steps. Firstly, the force-controlled mode was adopted with a loading rate of 5kN/s to the specified loading magnitude required for the different normal compressive stress levels ($\sigma/f_c$), then the transverse load was applied at displacement-controlled mode and a loading rate of 1mm/min until the specimen was destroyed. The test was stopped when a complete descending section was shown in shear load-displacement curve.

The uniaxial compression test prior to the compression-shear test was carried out with the same machine with a vertical compressive force-controlled mode and a loading rate of 5.0kN/s until the specimens were destroyed.
3. Results and discussions

3.1 Strength, deformation, and failure mode

3.1.1 Uniaxial compression test

The results of uniaxial compressive strength of concrete with different number of coarse aggregate regeneration cycles are shown in Fig. 3(a). As the number of RAC regeneration cycles increased, the concrete uniaxial compressive strength gradually decreased. Among them, reference concrete (NAC) exhibits the highest uniaxial compressive strength, reaching 50.3 MPa. The result is consistent with previous studies [11, 32, 34, 40, 41]. With the increased number of coarse aggregate regeneration cycles, the crushing index and water absorption rate of recycled coarse aggregate (RCA) significantly increase, while the apparent density slightly decreases in Table 1. The degraded quality of RCA and the ineffective bonding between RCA and matrices with additional ITZs due to the increased amount of adhered old mortar result in the gradually decreased compressive strength of RAC with increased regeneration cycles. The comparable results with other studies for multiple RAC with 100% RCA are shown in Fig. 3(b). It is depicted that the overall descending trend of compressive strength with the increased regeneration cycles is much more moderate. In this study, the reducing rate of the compressive strength for RAC until 2 regeneration cycles is comparable to the study by Abreu et al. [32], while the counterpart is after 2 regeneration cycles is comparable to the study by [41]. Different from the most studies that showed an asymptotic descending trend with a more significant reduction after the third regeneration cycle [11, 33, 34, 41, 42], a more linearly descending tendency of compressive strength is shown in this study, indicating that the compressive strength is still well retained after the third regeneration cycle. The much more moderate reduction of the compressive strength is probably due to less induced porosity and adhered old mortar during the regeneration
process in this study, which is further substantiated by the slightly reduced apparent density of RCA with increased regeneration cycles. The failure patterns of NAC and multiple RAC with the different number of regeneration cycles are shown in Fig. 4. It is seen that the failure patterns for both NAC and multiple RAC are in the form of two tips of the inverted pyramids connected in the middle. The NAC is rarely fractured, and the destroyed surface of NAC is uneven due to the protrusion of NCA. With the increased number of regeneration cycles, a more severe fracture can be captured while the fracture surfaces are more planar.

3.1.2 Combined compression-shear test

The failure patterns under composite compressive-shear stress for NAC and multiple RAC with different number of regeneration cycles and with the different levels of normal compressive stress ($\sigma/f_c$) are shown in Fig. 5. It is found that a typical shear failure pattern is shown for both NAC and different RAC under the pure shear loading state ($\sigma/f_c = 0$) with horizontal cracks manifested [29]. However, it seems that the amount of spalled or exfoliated fines left on the shear fault surface increases with increased regeneration cycles, proving the weak cohesion or ineffective bonding between the coarse aggregates and cement matrix, which confirms the increased amount of adhered old mortar on RCA with increased regeneration cycles. With the increase of compressive stress, both the numbers and angles of the diagonal cracks increase. The spalling or exfoliation of fines and limps becomes more serious, and more obvious friction trails appear on the failure surface. The severity of shear destruction increases with the increase of the normal compressive stress ratio $k$. When $k<0.6$, the main body of concrete remains after the destruction, while when $k\geq0.6$, the residual number of concrete decreases, and the breaking surface is also smoothed by the increased friction and produces large amounts of debris and powder. Interestingly, when the normal compressive stress ratio $k$ is kept
constant and the number of coarse aggregate regeneration $N$ increases, the shear failure also has the phenomenon of intensification, with a slight increase in fine chips and powder on the failure surface and a certain reduction of the residual amount of the main body of concrete after the destruction.

The peak shear strength ($\tau_p$) and the corresponding peak shear displacement ($s_p$) of the concrete under the combined compression-shear stress are shown in Figs. 6 and 7. From Fig. 6(a), the peak shear strength gradually increases with the increase in the vertical compressive stress ratio for the same type of concrete. This is because the contact friction strength $\tau_f$ dominates the peak shear strength $\tau_p$ of concrete when the specimen is suffered vertical compressive stress. According to the formula $\tau_f = u\sigma$ (where $u$ coefficient of friction; $\sigma$ normal stress), contact friction strength increases with the increase of the applied normal stress; accordingly, the peak shear strength increases with the vertical compressive strength ratio. In addition, the peak shear displacement $s_p$ also increases with the increase of vertical compressive stress ratio $k$ as shown in Fig. 6(b). Since the high vertical stress results in the increase of the contact friction strength among the shear fault surface, the required peak shear displacement for the complete shear failure substantially increases. As shown in Fig. 7(a), for the pure shear state, there is no significant fluctuation in the peak shear strength among different types of concrete, which is partially explained by the well retained performance of the recycled coarse aggregates discussed in previous sections [43]. Furthermore, the pure shear strength for all groups is relatively low with the brittle and quick failure, which cannot fully reflect the effect of the number of coarse aggregate regeneration cycles on the pure shear strength of RAC. Under the composite compressive-shear stress state, the peak shear strength of concrete decreases as the increased regeneration cycles of RCA, which should be interpreted by two main reasons. On the one hand, as the number of coarse aggregate regeneration increases, the uniaxial compressive strength of RAC
decreases. Consequently, when the vertical compressive stress ratio is constant, the vertical pressure exerted on RAC with the increased regeneration cycles is smaller. On the other hand, the increased number of coarse aggregate regeneration cycles will increase the severity of the shear failure of RAC, thus reducing the contact friction coefficient of the shear plane. As shown in Fig. 7(b), the peak shear displacement of RAC is insignificantly changed with the increased regeneration cycles at a fixed compressive stress ratio, although there is an overall tendency to decrease. Therefore, it shall be concluded that the number of RCA regeneration cycles significantly reduces the peak shear strength of concrete, while the effect on the peak shear displacement of concrete is not significant.

To further analyze the reasons for the increase of peak shear strength and peak shear displacement of concrete with the increase of vertical compressive stress ratio $k$, it is necessary to investigate the increments of the peak shear strength and the peak shear displacement, which are shown in Figs. 8 and 9, respectively. As shown in Fig. 8, the increment of peak shear strength for all groups tends to decrease asymptotically as the compressive stress ratio ($k$) increases, with a more significant increment when $k \leq 0.4$ and a relatively small increment for $k = 0.6$ and $k = 0.8$. The possible reason can be explained by the failure patterns in Fig. 5. In the failure process of NAC and multiple RAC, when the compressive stress ratio increases, the severity of shear failure increases and the concrete specimen continues to shrink, resulting in the shrink of the effective friction area of the shear plane. In addition, the concrete shear failure surface produces many debris and powder, which aggravates the relative sliding of the shear surface, resulting in a reduction in the contact friction strength. When $k \leq 0.4$, since the severity of shear failure is limited and the contact friction coefficient is not significantly reduced, therefore peak shear increment is relatively large. The contact friction coefficient decreased with increased severity of shear failure, resulting in a significant reduction of peak shear strength.
increment when \( k > 0.4 \). As depicted in Fig. 9, peak shear displacement has the similar trend to peak shear strength with the increased compressive stress ratio \( k \). Since the compressive stress ratio \( k \) reduces the contact friction coefficient of the shear plane, which results in a decrease in peak shear strength, therefore the shear displacement required for complete shear destruction of concrete is reduced.

### 3.2 Components assemblage of shear bearing capacity

Waseem et al. [44] proposed that the shear strength of concrete consists of three components: cohesive strength, aggregate interlocking strength, and contact friction strength. Based on the fact that the asperities on the shear plane may mutually rotate or elevate as the shear displacement increases and leads to shear dilation [45, 46], Liu et al. [27] further proposed that the aggregate interlocking strength is included in the shear strength provided by shear dilation, thus the shear strength of concrete (\( \tau_p \)) contains consists of cohesive strength (\( \tau_c \)), contact friction strength (\( \tau_f \)) and shear dilation strength (\( \tau_d \)) with showed in following equation.

\[
\tau_p = \tau_c + \tau_f + \tau_d
\]

where \( \tau_p \) peak shear strength (MPa); \( \tau_c \) cohesion strength; \( \tau_f \) is contact friction strength; \( \tau_d \) shear dilation strength.

There two assumptions are made for the simplified analysis in this study. Firstly, if the shear load-displacement curve has a smooth and gradual declining section, contact friction strength is fully contributed by the residual shear strength, which is determined by an average value of the gentle section of the curve with the end point where the descending of shear strength not exceed the 1% of peak shear strength within the range of 1 mm shear displacement [47]. If the shear load-displacement curve exhibits a brittle failure pattern, the contact friction strength should be determined by the
inflection point which implies the contact friction strength on the shear failure surface is fully overcome. Secondly, the effect of vertical compressive stress is ignored, which means that the cohesion strength is constant with the variation of the vertical compressive stress ratio [27].

Accordingly, based on the above assumptions, the cohesion strength for both NAC and RAC with the different number of regeneration cycles are acquired by the pure shear strength state (normal compressive stress ratio \( k = 0 \)), while the contact friction strength is attained from the shear load-displacement curve. The shear dilation strength is obtained by subtracting the sum of cohesion strength and contact friction strength from the peak shear strength. The components assemblage of shear strength components NAC and RAC with the different number of regeneration cycles are shown in Fig.10. It is shown that the cohesive strength for all groups decreases as the normal compressive stress ratio increases. Since the cohesive strength is mainly associated with the chemical bonding of the mortar, which is fixed for a specific type of concrete, the percentage of cohesive strength contributing to the peak shear strength continuously decreases when peak shear stress increases with the increased normal compressive strength ratio. The percentage of the contact friction strength for all groups increases significantly with the increase of normal compressive stress ratio and accounts for more than half of the peak shear strength, which shows a good agreement with the statement that the contact friction strength dominates peak shear strength once the vertical compressive stress is applied. The percentage composition of shear dilation strength is not significantly varied; one possible reason is that the shear dilation strength is acquired by indirect methods, which cannot fully characterize the shear dilation strength in real scenarios.

The variation of different components of shear strength with respect to the number of regeneration cycles is presented in Fig.11. It is noted that there is no significant difference in the cohesive strength
for both NAC and RAC with the different number of regeneration cycles in Fig. 11(a), indicating that the number of RCA regeneration cycles has a minimal effect on the cohesive strength. In addition, there is an irregular trend for the variation of shear dilation strength with the increased regeneration cycles, and most of the magnitudes of the cohesive strength are in the range of 2 to 6 MPa in Fig. 11(c). Moreover, Although the shear dilation strength of concrete is obtained by indirect methods and is not very accurate, it can be roughly concluded that the shear dilation strength of concrete is not sensitive to the number of coarse aggregate regeneration within three times. As shown in Fig. 11(b), the contact friction strength for all groups increases with the increase of the normal compressive stress ratio. Although the increase of normal pressure will intensify the destruction of concrete shear surface and make the contact friction coefficient of shear surface decrease, the contact friction strength of shear surface increases due to the significant increase of normal compressive stress. In addition, despite an initial increase in contact friction strength for RACI at the $\sigma/f_c$ of 0.4, 0.6 and 0.8, the contact friction strength depicts a descending trend in general with the increased regeneration cycles.

To comprehensively study the mechanism behind the variation of contact friction strength with increased generation cycles for different types of concrete. Two parameters, normal stress ($\sigma$) and contact friction coefficient ($u$), which jointly contribute to the contact friction strength, are investigated in terms of the normal compressive strength ratio ($\sigma/f_c$) and the number of RCA regeneration cycles (N). As shown in Fig. 12(a), it is seen that with the increase of normal compressive strength ratio, the friction coefficient of the shear plane for all four types of concrete gradually decreases, indicating that the increase of normal pressure decreases the friction coefficient of the shear plane of concrete. However, it is shown that the friction coefficient at $\sigma/f_c$ of 0.2 is the largest among the different normal compressive strength ratios, which is approximately 0.2 larger than the friction coefficient with
the other three ratios. Moreover, the friction coefficient at $\sigma/f_c$ of 0.2 presents a monotonically descending trend with the increased regeneration cycles, while the friction coefficient under the other three ratios initially increases after the first regeneration and then decreases monotonically in Fig. 12(b). The possible explanation is that when the normal compressive stress ratio increases, larger friction is required for the shear plane to resist, thus the spalled debris and powder are easy to cause the shear plane to slide and subsequently reduce the contact friction coefficient. The improvement in the friction coefficient after the first regeneration for $\sigma/f_c$ of 0.4, 0.6 and 0.8 can be ascribed to the increased amount of adhered old mortar on the coarse aggregate after first regeneration, resulting in the increased friction coefficient due to the enlarged roughness [48]. However, with the further increased number of regeneration cycles, the severity of the concrete damage intensifies, thus the increased spalled or exfoliated fines and debris between the shear plane promote the tendency of concrete contact surfaces to mutually slide, which leads to a continuous decrease in the friction coefficient of the shear plane. When the normal compressive stress ratio $\sigma/f_c < 0.6$, the shear failure of the four types of concrete is moderate, the difference in the effective contact area of the shear surface and the difference in the corresponding normal pressure are relatively small, hence the contact friction strength of the four types of concrete is mainly determined by the friction coefficient, therefore. When the normal compressive stress ratio $\sigma/f_c$ reaches 0.8, the severity of the shear failure is intense and accordingly the effective contact area slightly increased and should be partially responsible for the variation of contact friction strength. Nevertheless, the friction coefficient is still the dominated factor, consequently, both NAC and RAC with the different number of regeneration cycles depict a descending trend with the increased normal compressive stress ratio.
3.3 Strength failure criterion

When concrete is subjected to the combined compression-shear stress state in Fig. 13 (a), the plane stress can be transformed to the principal stress state of the tensile-compression composite stress state (Fig. 13 (b) and (c)). The tensile principal stress should mainly be responsible for the specimen failure [29]. The principal stresses are:

\[
\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\tau^2 + \left(\frac{\sigma_x - \sigma_y}{2}\right)^2} = \frac{\sigma_x}{2} + \sqrt{\tau^2 + \left(\frac{\sigma_x}{2}\right)^2}
\]

(3)

\[
\sigma_3 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\tau^2 + \left(\frac{\sigma_x - \sigma_y}{2}\right)^2} = \frac{\sigma_x}{2} - \sqrt{\tau^2 + \left(\frac{\sigma_x}{2}\right)^2}
\]

(4)

\[
\sigma_2 = 0
\]

(5)

where \(\sigma_x\) and \(\sigma_y\) plane normal stresses; \(\tau\) plane shear stress; \(\sigma_1\) principle tensile stress; \(\sigma_3\) principle compressive stress; \(\sigma_2\) principal stress along Z-axis (\(\sigma_2 = 0\) for the plane stress state).

With the increase of compressive strength, the angle \(\alpha\) between the direction of action of the principal compressive stress and the specimen decreases while the angle between the direction of action of the principal tensile stress and the specimen increases, and the value of the principal tensile stress increases. When the specimen is destroyed by compressive-shear combined load, the greater the vertical compressive stress, the greater the angle between the direction of action of the principal tensile stress and the specimen. In addition, the angle of oblique cracks is affected by the direction of action of the principal tensile stress also shows an increasing trend.

3.3.1 Strength failure criteria based on \(\xi - r\)

The principal stress state of the unitary body can be determined by a stress vector OP \((\sigma_1, \sigma_2, \sigma_3)\) in the principal stress space-rectangular coordinate system, which is decomposed into NP in the isotropic \(\pi_0\) plane past the origin of coordinates and ON in the direction normal to the \(\pi_0\) plane [49] in Fig. 14. The hydrostatic stress \((\xi)\) and deviatoric stress \((r)\) are:
\[ \xi = \frac{1}{\sqrt[3]{3}} (\sigma_1 + \sigma_2 + \sigma_3) \]  

(6)

\[ r = \frac{1}{\sqrt[3]{3}} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \]  

(7)

Then adopting hydrostatic stress (\(\xi\)) and deviatoric stress (\(r\)) as variables to establish the failure criterion under the combined compression-shear stress:

\[ A\xi - r = B \]  

(8)

The composite compressive-shear failure criteria for NAC and RAC with different regeneration cycles (RACI, RACII and RACIII) based on \(\xi - r\) is attained by conducting linear regression analysis on the experimental results based on Eq. (8):

\[ 2.9618\xi - r = -18.2093 \quad (N = 0; \quad R^2 = 0.9652) \]  

(9)

\[ 2.9102\xi - r = -17.4593 \quad (N = 1; \quad R^2 = 0.9668) \]  

(10)

\[ 2.8481\xi - r = -17.1219 \quad (N = 2; \quad R^2 = 0.9697) \]  

(11)

\[ 2.8765\xi - r = -16.2517 \quad (N = 3; \quad R^2 = 0.9755) \]  

(12)

Based on the hypothesis that there is a linear correlation between fitting coefficients \((A; B)\) and number of RCA regeneration cycles \((N)\) (i.e.,\(A = a_1 + a_2N\); \(B = b_1 + b_2N\)). The correlations between fitting parameters \((A; B)\) and the number of RCA regeneration cycles \((N)\) are acquired from linear regression analysis on experimental results:

\[ A = 2.9469 - 0.0318N \]  

(13)

\[ B = -18.1921 + 0.6210N \]  

(14)

As a result, the modified failure criterion for NAC and RAC with different regeneration cycles (RACI, RACII and RACIII) based on \(\xi - r\) and considering the number of RCA regeneration cycles \((N)\) is:

\[ (2.9464 - 0.0318)\xi - r = 0.621N - 18.1921 \]  

(15)
Fig. 15 presents the predicted fitting curves of modified failure criteria and the experimental results. It is seen that all correlation factors ($R^2$) of the fitting curves are above 0.96, which indicate the strong correlation between the predicted fitting curves and the test data.

3.3.2 Strength failure criteria based on stress invariance

The first principal stress invariant ($I_1$) reflects the volume deformation part of the plastic deformation of the structure, and the second deviation stress invariance ($J_2$) reflects the distortion part of the plastic deformation of the structure. The strength failure model based on $I_1$ and $J_2$ can effectively describe the effect of hydrostatic stress on the behaviour of the material and reflect its dilatation characteristics [50, 51]. $I_1$ and $J_2$ are calculated by Eqs. (16) and (17), respectively:

\[
I_1 = \sigma_1 + \sigma_2 + \sigma_3
\]

\[
J_2 = \frac{1}{6} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]
\]

The strength failure criteria based on $I_1 - J_2$ is established as shown in Eq. (18) below:

\[
AI_1 - J_2 = B
\]

Similarly, the composite compressive-shear failure criteria for NAC and RAC with different regeneration cycles (RACI, RACII and RACIII) based on $I_1 - J_2$ is attained by conducting linear regression analysis on the experimental results based on Eq. (18):

\[
36.6013I_1 - J_2 = 13.3360 \ (N = 0; R^2 = 0.9961)
\]

\[
34.2827I_1 - J_2 = 11.4700 \ (N = 1; R^2 = 0.9961)
\]

\[
32.6470I_1 - J_2 = 13.1040 \ (N = 2; R^2 = 0.9952)
\]

\[
31.8309I_1 - J_2 = 16.3320 \ (N = 3; R^2 = 0.9936)
\]

The correlations between fitting parameters ($A$; $B$) and the number of RCA regeneration cycles ($N$) are acquired from linear regression analysis on experimental results:
\[ A = 36.2325 - 1.5947N \]  \hspace{1cm} (23)

\[ B = 11.9688 + 1.0618N \]  \hspace{1cm} (24)

Analogously, the modified failure criterion for NAC and RAC with different regeneration cycles (RACI, RACII and RACIII) based on \( I_1 - J_2 \) and considering the number of RCA regeneration cycles \( N \) is:

\[ (36.2325 - 1.5947N)I_1 - J_2 = 1.0618N + 11.9688 \]  \hspace{1cm} (25)

Fig. 16 presents the predicted fitting curves of modified failure criteria and the experimental results. It is seen that all correlation factors \( (R^2) \) of the fitting curves are above 0.99, which indicates the strong correlation between the predicted fitting curves and the test data.

### 3.3.3 Strength failure criteria based on octahedral stresses

The strength failure criterion for concrete based on octahedral stresses is the most popular multi-parameters strength criterion proposed and modified by Bresler [52], Guo and Wang [53], and Willamand Warnke [54], which is expressed as a linear function and a quadratic parabolic function in terms of octahedral normal stress \( (\sigma_{oct}) \) and octahedral shear stress \( (\tau_{oct}) \), as shown in Eqs. (26) and (27), respectively:

\[ \frac{\tau_{oct}}{f_{oct}} = A + B \frac{\sigma_{oct}}{f_{oct}} \]  \hspace{1cm} (26)

\[ \frac{\tau_{oct}}{f_{oct}} = A + B \frac{\sigma_{oct}}{f_{oct}} + C \left( \frac{\sigma_{oct}}{f_{oct}} \right)^2 \]  \hspace{1cm} (27)

The octahedral normal stress \( (\sigma_{oct}) \) and octahedral shear stress \( (\tau_{oct}) \) are calculated as:

\[ \sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \]  \hspace{1cm} (26)

\[ \tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \]  \hspace{1cm} (27)

The composite compressive-shear failure criteria for NAC and RAC with different regeneration cycles (RACI, RACII and RACIII) based on octahedral stresses \( \sigma_{oct} - \tau_{oct} \) is attained by conducting
linear regression and nonlinear regression analyses on the experimental results based on Eq. (26) and Eq. (27), respectively:

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1284 + 1.9932 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} (N = 0; R^2 = 0.9715)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1282 + 1.9619 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} (N = 1; R^2 = 0.9729)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1277 + 1.9240 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} (N = 2; R^2 = 0.9777)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1274 + 1.9403 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} (N = 3; R^2 = 0.9801)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0912 + 3.1002 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 4.1527 \left(\frac{\sigma_{\text{oct}}}{f_{\text{oct}}}\right)^2 (N = 0; R^2 = 0.9978)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0924 + 3.0356 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 4.0259 \left(\frac{\sigma_{\text{oct}}}{f_{\text{oct}}}\right)^2 (N = 1; R^2 = 0.9984)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0957 + 2.8866 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 3.6109 \left(\frac{\sigma_{\text{oct}}}{f_{\text{oct}}}\right)^2 (N = 2; R^2 = 0.9991)
\]

\[
\frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0971 + 2.8503 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 3.4122 \left(\frac{\sigma_{\text{oct}}}{f_{\text{oct}}}\right)^2 (N = 3; R^2 = 0.9990)
\]

The correlations between fitting parameters \((A; B)\) and number of RCA regeneration cycles \((N)\) for the linear function form of the octahedral failure criterion are acquired from linear regression analysis on experimental results:

\[
A = 0.1284 - 0.0003N
\]

\[
B = 1.9843 - 0.0197N
\]

The correlations between fitting parameters \((A; B; C)\) and number of RCA regeneration cycles \((N)\) for the quadratic parabolic function form of the octahedral failure criterion are acquired from linear regression analysis on experimental results:

\[
A = 0.0912 + 0.0020N
\]

\[
B = 3.1030 - 0.0899N
\]

\[
C = -4.1959 + 0.2637N
\]

Analogously, the modified failure criterion for NAC and RAC with different regeneration cycles...
(RACI, RACII, and RACIII) based on octahedral stresses $\sigma_{oct} - \tau_{oct}$ and considering the number of RCA regeneration cycles ($N$) for the linear function and the quadratic parabolic function, respectively, are:

\[
\frac{\tau_{oct}}{f_{oct}} = (0.1284 - 0.0003N) + (1.9843 - 0.0197N)\frac{\sigma_{oct}}{f_{oct}} \quad (41)
\]

\[
\frac{\tau_{oct}}{f_{oct}} = (0.0912 + 0.0020N) + (3.1030 - 0.0899N)\frac{\sigma_{oct}}{f_{oct}} + (-4.1959 + 0.2637N)(\frac{\sigma_{oct}}{f_{oct}})^2 \quad (42)
\]

Fig.17 presents the predicted fitting curves of modified failure criteria and the experimental results. It is seen that all correlation factors ($R^2$) of the fitting curves are above 0.99, which indicates the strong correlation between the predicted fitting curves and the test data.

The fitting coefficients of three modified failure criteria for multiple recycled coarse aggregate concrete under the plane stress state of the compressive-shear composite stress based on different stress expressions and considering the number of the coarse aggregate regeneration cycles are summarized in Table 5. It is seen that all three modified failure criteria have the correlation factors ($R^2$) larger than 0.96, thus can be sufficiently used to properly describe the strength failure criterion of the multiple-recycles coarse aggregate concrete with up to three recycled cycles. Among the different modified failure criteria, the modified failure criteria based on stress invariance and the modified failure criteria based on octahedral stresses in the quadratic parabolic functional form present the highest predictive accuracy, with the correlation factors ($R^2$) larger than 0.99.

4. Conclusions

This study comprehensively investigated the mechanical properties of multiple recycled coarse aggregate concrete under the combined compressive and shear stresses, in terms of the failure pattern, peak shear displacement, and peak shear strength. Based on the experimental results, the shear strength components and their compositions of the peak shear strength were analyzed. In addition, the effects
of the normal compressive stress ratio and the number of coarse aggregate regeneration cycles on the
above properties were also investigated. Finally, the compression-shear strength failure model of
multiple regenerated coarse aggregate concrete was established based on different stress expressions.
In summary, the following conclusions can be drawn as below:

(1) Among the four types of concrete, natural coarse aggregate concrete has the highest uniaxial
compressive strength, and the uniaxial compressive strength of concrete decreases as the increase
of the number of coarse aggregate regeneration. However, the mechanical strength reduction is not
significant, and the difference in uniaxial compressive strength between natural coarse aggregate
concrete and the 3rd generation recycled coarse aggregate concrete after three regeneration cycles
are only 5 MPa. As the number of coarse aggregate regeneration cycles increases, more crushed
mortar is evidently left on the shear failure surface, and there is more evident for both coarse
aggregate and cement mortar underwent failure simultaneously in the shear plane.

(2) Both the normal compressive stress ratio and the number of coarse aggregate regeneration cycles
have the certain effect on the failure patterns of multiple RAC under the combined action of
compressive and shear stresses, with the former having a more significant effect. With the increased
normal compressive stress ratio, both the peak shear strength of concrete increases and the severity
increases. Traces of coarse aggregate and cement mortar subjected to friction and tiny concrete
fragments on the shear breaking surface also increase. However, the increase in the number of
coarse aggregate regeneration decreases the peak shear strength.

(3) The peak shear strength and the peak shear displacement of the multiple RAC increase with the
increased normal compressive stress ratio and slightly decrease with the increased number of
course aggregate regeneration cycles. The increments of both the peak shear strength and the peak
shear displacement decrease as the number of coarse aggregate regeneration increases. The increase of normal compressive stress ratio significantly improves the shear strength of concrete under the combined compressive and shear stresses and improves the plastic properties of concrete. Nevertheless, the increased number of coarse aggregate regeneration cycles reduces the shear strength of concrete under the combined compressive and shear stresses and aggravate the brittle failure of concrete.

(4) The components of shear strength of concrete include cohesive strength, shear dilation strength and contact friction strength. With the increased normal compressive stress ratio, the proportion of cohesive strength decreases, the proportion of shear dilation strength fluctuates around 20%, and the proportion of contact friction strength significantly increases. In the presence of vertical compression, the proportion of contact friction strength is more than half, which is the main factor affecting the peak shear strength of multiple RAC. In addition, with the increased number of coarse aggregate regeneration cycles, the cohesive strength is not significantly varied. There is an irregular trend for the variation of shear dilation strength, with most of the magnitudes of the cohesive strength are in the range of 2 to 6 MPa.

(5) Based on the different stress expressions, three modified strength failure criteria models considering the number of coarse aggregate regeneration cycles are proposed for predicting the shear strength of multiple regenerated coarse aggregate concrete under the combined compressive-shear stresses. Despite the strong correlation with the correlation factors ($R^2$) for larger than 0.96 for all the models, the modified failure criteria based on stress invariance and the modified failure criteria based on octahedral stresses in the quadratic parabolic functional form present the highest predictive accuracy, with the correlation factors ($R^2$) larger than 0.99.
Acknowledgments

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References


[34] S.B. Huda, M.S. Alam, Mechanical behavior of three generations of 100% repeated recycled coarse aggregate concrete, Construction and building materials 65 (2014) 574-582.


[51] D.C. Drucker, W. Prager, Soil mechanics and plastic analysis or limit design, Quarterly of applied mathematics 10(2) (1952) 157-165.


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<th>Mixes</th>
<th>Crush indicator (%)</th>
<th>Apparent density (kg/m³)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>11.63</td>
<td>2828</td>
<td>1.1</td>
</tr>
<tr>
<td>RA1</td>
<td>14.79</td>
<td>2746</td>
<td>5.74</td>
</tr>
<tr>
<td>RA2</td>
<td>16.1</td>
<td>2728</td>
<td>8.43</td>
</tr>
<tr>
<td>RA3</td>
<td>18.07</td>
<td>2710</td>
<td>9.7</td>
</tr>
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</table>
Table 2 Main physical and mechanical properties of cement

<table>
<thead>
<tr>
<th>Consistency (%)</th>
<th>Specific surface (m²/kg)</th>
<th>Compressive strength (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Setting time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3-day 28-day</td>
<td>3-day 28-day</td>
<td>Initial Final</td>
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<tr>
<td>0.3</td>
<td>359</td>
<td>28.6</td>
<td>57.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Percentage</td>
<td>SiO$_2$</td>
<td>Al$_2$O$_3$</td>
<td>CaO</td>
<td>MgO</td>
</tr>
<tr>
<td>------------</td>
<td>--------</td>
<td>-------------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>%</td>
<td>20.52</td>
<td>7.63</td>
<td>60.14</td>
<td>2.59</td>
</tr>
</tbody>
</table>
Table 4 Mix proportion of concrete

<table>
<thead>
<tr>
<th>Mixes</th>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Aggregate (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Water reducer (kg/m³)</th>
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</thead>
<tbody>
<tr>
<td>NAC</td>
<td>195</td>
<td>527</td>
<td>630</td>
<td>1074</td>
<td>2.635</td>
</tr>
<tr>
<td>RACI</td>
<td>195</td>
<td>527</td>
<td>619</td>
<td>1054</td>
<td>2.635</td>
</tr>
<tr>
<td>RACII</td>
<td>195</td>
<td>527</td>
<td>617</td>
<td>1050</td>
<td>2.635</td>
</tr>
<tr>
<td>RACIII</td>
<td>195</td>
<td>527</td>
<td>614</td>
<td>1046</td>
<td>2.635</td>
</tr>
</tbody>
</table>
Table 5 Modified failure criteria based on stress expressions

Modified failure criteria based on $\xi - r$

<table>
<thead>
<tr>
<th>Series</th>
<th>Fitting equation</th>
<th>$N$</th>
<th>Coefficients</th>
<th>Predicted curves</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A$  $B$  $C$</td>
<td>$A\xi - r = B$</td>
<td></td>
</tr>
<tr>
<td>NAC</td>
<td>$A\xi - r = B$</td>
<td>0</td>
<td>2.9469</td>
<td>$2.9469\xi - r = -18.192$</td>
<td>0.9652</td>
</tr>
<tr>
<td>RACI</td>
<td>$A\xi - r = B$</td>
<td>1</td>
<td>2.9150</td>
<td>$2.9150\xi - r = -17.5711$</td>
<td>0.9668</td>
</tr>
<tr>
<td>RACII</td>
<td>$A\xi - r = B$</td>
<td>2</td>
<td>2.8832</td>
<td>$2.8832\xi - r = -16.9500$</td>
<td>0.9721</td>
</tr>
<tr>
<td>RACIII</td>
<td>$A\xi - r = B$</td>
<td>3</td>
<td>2.8514</td>
<td>$2.8514\xi - r = -16.3290$</td>
<td>0.9755</td>
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Modified failure criteria based on $l_1 - f_2$

<table>
<thead>
<tr>
<th>Series</th>
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<th>$N$</th>
<th>Coefficients</th>
<th>Predicted curves</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A$  $B$  $C$</td>
<td>$A l_1 - f_2 = B$</td>
<td></td>
</tr>
<tr>
<td>NAC</td>
<td>$A l_1 - f_2 = B$</td>
<td>0</td>
<td>36.2325</td>
<td>$36.2325 l_1 - f_2 = 11.9688$</td>
<td>0.9961</td>
</tr>
<tr>
<td>RACI</td>
<td>$A l_1 - f_2 = B$</td>
<td>1</td>
<td>34.6378</td>
<td>$34.6378 l_1 - f_2 = 13.0300$</td>
<td>0.9961</td>
</tr>
<tr>
<td>RACII</td>
<td>$A l_1 - f_2 = B$</td>
<td>2</td>
<td>33.0410</td>
<td>$33.0410 l_1 - f_2 = 14.0924$</td>
<td>0.9952</td>
</tr>
<tr>
<td>RACIII</td>
<td>$A l_1 - f_2 = B$</td>
<td>3</td>
<td>31.4484</td>
<td>$31.4484 l_1 - f_2 = 15.1542$</td>
<td>0.9936</td>
</tr>
</tbody>
</table>

Modified failure criteria based on $\sigma_{oct} - \tau_{oct}$(Linear function form)

<table>
<thead>
<tr>
<th>Series</th>
<th>Fitting equation</th>
<th>$N$</th>
<th>Coefficients</th>
<th>Predicted curves</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A$  $B$  $C$</td>
<td>$A \sigma_{oct} - \tau_{oct} = B$</td>
<td></td>
</tr>
</tbody>
</table>
\[
\begin{align*}
\text{NAC} & & \frac{\tau_{\text{oct}}}{f_{\text{oct}}} & = 0.1284 & 1.9843 & \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = A + B \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \\
& & & 0.1284 + 1.9843 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} & 0.9715 \\
& & \Rightarrow & = A + B \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \\
\text{RACI} & & 1 & 0.1281 & 1.9647 & \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1281 + 1.9647 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \\
& & & 0.1281 + 1.9647 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} & 0.9729 \\
\text{RACII} & & 2 & 0.1278 & 1.9450 & \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1278 + 1.9450 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \\
& & & 0.1278 + 1.9450 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} & 0.9777 \\
\text{RACIIII} & & 3 & 0.1275 & 1.9253 & \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.1275 + 1.9253 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \\
& & & 0.1275 + 1.9253 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} & 0.9801
\end{align*}
\]

**Modified failure criteria based on** \( \sigma_{\text{oct}} - \tau_{\text{oct}} \) *(Quadratic parabolic function form)*

<table>
<thead>
<tr>
<th>Series</th>
<th>Fitting equation</th>
<th>( N )</th>
<th>Coefficients</th>
<th>Predicted curves</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAC</td>
<td>( \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = A + B \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} + C \left( \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \right)^2 )</td>
<td>0</td>
<td>0.0912, 3.1030, -4.1955</td>
<td>( \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0912 + 3.1030 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 4.1955 \left( \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \right)^2 )</td>
<td>0.9977</td>
</tr>
<tr>
<td>RACI</td>
<td>1</td>
<td>0</td>
<td>0.0932, 3.0131, -3.9323</td>
<td>( \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0932 + 3.0131 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 3.9323 \left( \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \right)^2 )</td>
<td>0.9984</td>
</tr>
<tr>
<td>RACII</td>
<td>2</td>
<td>0</td>
<td>0.0952, 2.9232, -3.6686</td>
<td>( \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0952 + 2.9232 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 3.6686 \left( \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \right)^2 )</td>
<td>0.9991</td>
</tr>
<tr>
<td>RACIIII</td>
<td>3</td>
<td>0</td>
<td>0.0972, 2.8334, -3.4050</td>
<td>( \frac{\tau_{\text{oct}}}{f_{\text{oct}}} = 0.0972 + 2.8334 \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} - 3.4050 \left( \frac{\sigma_{\text{oct}}}{f_{\text{oct}}} \right)^2 )</td>
<td>0.9990</td>
</tr>
</tbody>
</table>
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[32, 34, 40, 41]

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(b) RACI (N=1)  

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(d) RACIII (N=3)
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