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A physically-based and code-aligned design method for longitudinal shear of RACCS

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Abstract

Concrete remains a cornerstone of structural engineering, but its production and lifecycle generate significant environmental pressures, primarily due to the extraction of natural aggregates, intensive energy use, and the increasing generation of demolition waste, underscoring the need for circular and sustainable alternatives. Recycled Aggregate Concrete (RCA) from Construction and Demolition Waste (CDW) constitutes a key strategy toward resource efficiency and waste minimization. Nonetheless, its integration into structural members remains challenging due to RCA's inherent heterogeneity, higher porosity, and the consequent alteration of the bond behavior at the steel–concrete interface. This study investigates the longitudinal shear behaviour of Recycled Aggregate Concrete Composite Slabs (RACCS) with the aim of extending the applicability of the Eurocode 4 m - k design method to system incorporating recycled aggregates and providing an experimentally supported interpretation of the semi-empirical parameters m and k governing the steel-concrete interface. A dataset of 48 full-scale four-point bending tests covering six RCA replacement ratios (0–100%) and three span lengths was analyzed using linear least-squares regression, to derive the m and k parameters representing mechanical interlock and frictional resistance. Results indicate a non-linear response, with optimal interlock around 30% RCA and degradation beyond this threshold due to ITZ weakening, while frictional effects intensify at higher replacement ratios. A new set of experimentally calibrated correction factors $\alpha(\text{rRCA})$ and $\beta(\text{rRCA})$ was introduced, recalibrating the m - k formulation as a function of the RCA replacement ratio. The proposed formulation is able to reproduce the experimental trend of longitudinal shear resistance across the investigated RCA range, with deviations generally within $\pm 10\%$ compared to the experimental results.

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1. Introduction

The construction industry is one of the largest consumers of natural resources and a major contributor to environmental impacts worldwide. It is responsible for approximately 50% of global raw material extraction, around 40% of total energy consumption, and 30–50% of solid waste generation (Munir et al., 2024; Zia and Holly, 2025). A large share of these impacts is associated with the production of concrete, which requires extensive quantities of natural aggregates and energy-intensive manufacturing processes. To mitigate these environmental pressures, the reuse of CDW as Recycled Concrete Aggregate (RCA) has emerged as a promising strategy aligned with circular economy principles. RCA can partially or fully replace natural aggregates in concrete mixtures, reducing landfill disposal and preserving non-renewable resources (Hurtado-Alonso et al., 2025). However, recycled aggregates are typically more porous and heterogeneous than natural aggregates and often contain adhered residual mortar, which alters the properties of the interfacial transition zone (ITZ), the thin region around aggregate particles where the bond between cement paste and aggregate develops (Li et al., 2021; Xiong et al., 2021; Ying et al., 2025a). In Recycled Aggregate Concrete (RAC), this region becomes more complex and generally weaker due to the coexistence of old adhered mortar, the original ITZ from the parent concrete, and the new ITZ formed with the fresh cement paste, ultimately affecting the mechanical performance of the resulting concrete. This aspect becomes particularly relevant in steel–concrete composite slabs, where the structural performance depends on the effectiveness of longitudinal shear transfer at the interface between the profiled steel sheeting and the concrete layer (Bi et al., 2025). Steel–concrete composite slabs are widely adopted in modern steel buildings due to their structural efficiency and reduced self-weight, as the profiled steel sheeting acts both as permanent formwork during construction and as tensile reinforcement in the composite element. Among the possible failure modes, longitudinal shear failure is the most frequently observed and is typically characterized by significant end slip between the concrete slab and the profiled steel sheeting before the ultimate bending capacity is reached (Saccone et al., 2025a). This mechanism is influenced by several factors, including the geometry of the profiled steel sheeting, the characteristics of the embossments, the mechanical properties of the concrete, and the overall slab configuration (Ni et al., 2025; Qi et al., 2024). In this context, rib shear connectors formed by embossments in the profiled steel sheeting contribute to the mobilization of longitudinal shear resistance through mechanical interlock, while friction along the steel–concrete interface provides an additional mechanism for shear transfer (Burnet and Oehlers, 2001), see Fig.1. Experimental investigations have shown that the use of RCA can significantly affect the bond behaviour at the steel–concrete interface, although the mechanisms governing this interaction remain only partially understood (Stochino et al., 2024).

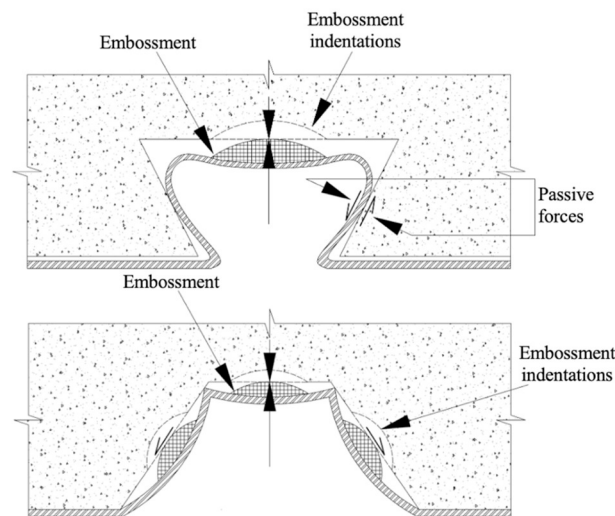


Fig. 1. Rib shear connectors formed by indentations or embossments in the profiled steel sheeting (Saccone et al., 2025b).

In design practice, the longitudinal shear resistance of composite slabs is commonly evaluated using the m – k method specified in Eurocode 4 (EN 1994-1-1). This semi-empirical approach derives the interface parameters from full-scale bending tests, although the parameters m and k are often treated as regression coefficients without a clear physical interpretation. The lack of a physically consistent interpretation becomes even more critical when recycled aggregates are used, since the altered microstructure of Recycled Aggregate Concrete (RAC) can modify both mechanical interlock and frictional behaviour at the interface. Despite the growing interest in sustainable construction materials, only a limited number of studies have investigated the application of the m – k method to composite slabs incorporating recycled aggregates (Chen et al., 2023; Lu et al., 2023). Moreover, experimental investigations typically consider only extreme replacement ratios, while the progressive influence of intermediate RCA contents remains insufficiently explored.

The present study examines the longitudinal shear behaviour of steel–concrete composite slabs made with RAC, with the aim of extending the applicability of the Eurocode 4 m – k design method to composite slabs incorporating RCA. The analysis relies on an experimental dataset obtained from 48 full-scale four-point bending tests covering six RCA replacement ratios (from 0 to 100%) and three span lengths, allowing the progressive influence of RCA content on longitudinal shear resistance to be evaluated. Particular attention is given to the interpretation of the empirical parameters m and k , which represent the two main shear transfer mechanisms at the steel–concrete interface: mechanical interlock provided by the embossments of the profiled steel sheeting and friction along the interface. To account for the influence of RCA content on the interface behaviour, the conventional semi-empirical m – k formulation is adapted by introducing correction functions dependent on the RCA replacement ratio. These functions modify the reference parameters m_0 and k_0 obtained for natural aggregate concrete, allowing the formulation to incorporate the progressive effect of recycled aggregates. In this way, the structure of the Eurocode-based method is preserved while extending its applicability to Recycled Aggregate Concrete Composite Slabs (RACCS) and providing a experimentally supported interpretation of the evolution of the interface parameters.

2. The m – k method for longitudinal shear design

The longitudinal shear resistance of steel–concrete composite slabs is commonly evaluated using the m – k methods and the Partial Shear Connection Method (PSC) specified in Eurocode 4 (EN 1994-1-1:2004). Both approaches rely on experimental results obtained from full-scale bending tests, although they differ in their theoretical background. The PSC method is derived from composite beam theory assuming partial interaction, whereas the m – k method follows a semi-empirical regression-based formulation calibrated from experimental data. The m – k method originated from a research program conducted by the American Iron and Steel Institute (AISI) at Iowa State University in the late 1960s, aimed at developing unified design criteria for composite floor systems. Early experimental investigations conducted by (Ong and Mansurt, 1986; Porter and Ekberg, 1976) identified longitudinal shear failure at the steel–concrete interface as the governing failure mode, leading to the development of regression equations relating the longitudinal shear strength to two empirical coefficients, m and k (Porter and Ekberg, 1976; Schuster, 1972). In the current Eurocode 4 formulation, the design longitudinal shear resistance is expressed as

$$\frac{V_{l,Rd}}{b d_p} = m \frac{A_p}{b L_s} + k \quad (1)$$

where $V_{l,Rd}$ is the design shear resistance, A_p is the cross-sectional area of the profiled steel sheeting, L_s is the shear span, b is the slab width, and d_p is the distance between the centroid of the steel sheet and the compressed surface of the slab.

Although originally introduced as empirical regression parameters, subsequent experimental studies have shown that the coefficients m and k can be associated with the main mechanisms governing shear transfer at the steel–concrete interface. From a mechanical standpoint, these parameters reflect distinct contributions to the interface behaviour. The parameter m is primarily associated with the mechanical interlock generated by the embossments of the profiled steel sheeting (Hedao et al., 2012; Mohammed, 2010). As slip develops, the surrounding concrete bears against these indentations, mobilizing passive resistance that increases with the effectiveness of the embossment geometry and the mechanical engagement between the steel profile and the concrete matrix. Conversely, the

parameter k represents the distributed frictional resistance acting along the steel–concrete contact surface after the initial chemical adhesion between the two materials has been lost during the early stages of loading (Ahmed et al., 2019; Salonikios et al., 2012). These mechanisms can be significantly influenced by the properties of RAC, particularly through modifications of the interfacial transition zone (ITZ). In conventional concrete, the ITZ between natural aggregates and cement paste is already characterized by higher porosity and lower mechanical strength compared to the bulk matrix. In RAC, this condition becomes more complex due to the presence of adhered residual mortar on recycled aggregates, which leads to the formation of multiple transition zones: the original ITZ surrounding the natural aggregate in the parent concrete and a new ITZ formed between the recycled aggregate and the fresh cement paste (Wang et al., 2021; Ying et al., 2025b). Consequently, the overall volume of porous interfacial regions in RAC is generally higher than in natural aggregate concrete, resulting in reduced tensile strength and increased deformability of the matrix. These microstructural characteristics directly affect the interaction between the concrete and the profiled steel sheeting (Liu et al., 2019; Lyu and Han, 2019). In particular, the weaker ITZ may reduce the effectiveness of mechanical interlock at the embossments, as the concrete tends to crack or shear locally at the contact points. Conversely, the rougher surface texture associated with recycled aggregates and residual mortar can enhance frictional resistance along the steel–concrete interface. As a result, the relative contribution of the two mechanisms represented by the parameters m and k may change with increasing recycled aggregate content.

3. Full-scale experimental dataset for RACCS

The experimental dataset used in this study derives from two full-scale testing campaigns carried out in 2023 and 2024 by (Alibeigibeni et al., 2025; Stochino et al., 2024) aimed at investigating the flexural response and longitudinal shear behaviour of RACCS. A total of 48 composite slab specimens were tested under standardized four-point bending conditions. Open-trapezoidal profiled steel sheeting with embossed ribs was adopted for all specimens.

Table 1. EDA-derived representative longitudinal shear force value selected from the 48 full-scale tests and used for the m - k regression analysis

$f(\%RCA)$	L_s (mm)	b (mm)	d_p (mm)	A_p (mm ²)	V_u (kN)
0	550	660	125	885.3	23
0	650	660	125	885.3	21
0	750	660	125	885.3	19
20	550	660	125	885.3	25
20	650	660	125	885.3	21
20	750	660	125	885.3	20
30	650	660	125	885.3	19
30	750	660	125	885.3	16
50	550	660	125	885.3	24
50	750	660	125	885.3	21
70	550	660	125	885.3	21
70	650	660	125	885.3	20
70	750	660	125	885.3	19
100	550	660	125	885.3	22
100	650	660	125	885.3	22
100	750	660	125	885.3	21

Six concrete mixtures were considered, labelled as M0, M20, M30, M50, M70 and M100, where the numerical index denotes the percentage replacement of natural aggregates (both fine and coarse fractions) with recycled concrete aggregates. To ensure comparability between mixtures and isolate the influence of recycled aggregate content on structural performance, all mixes were produced with the same cement content (366 kg/m³) and water–cement ratio

(0.51). The experimental campaigns were structured differently: in the 2023 program only one specimen for M0, M30, M50, and M100 was tested for each span length, whereas the 2024 campaign included three specimens per span for M0, M20, M70, and M100 mixture. Therefore, the 48 individual test results were not directly used in the regression analysis. Due to this heterogeneous distribution of specimens, the experimental results were processed using an Exploratory Data Analysis (EDA) procedure considering central tendency, dispersion and mechanically inconsistent outliers, to derive representative values of longitudinal shear resistance. Specifically, after stratifying the data by $r(\%RCA)$ and L_s , the representative values were selected by considering the mean value for intermediate spans and adjusted mean values, $\mu - \sigma$ and $\mu + \sigma$, respectively, for short and long spans, to account for data dispersion and avoid biased regression inputs. The resulting reduced dataset, reported in Table 1, was used for the m – k regression analysis. Since M30 and M50 were represented by only two span-dependent values after this selection, the corresponding regression parameters should be regarded as trend-defining indicators and should be interpreted with caution.

4. Regression analysis for the identifications of m – k parameters

The m – k coefficients for RACCS were determined through a linear least-squares regression performed separately for each recycled aggregate replacement ratio. According to the provisions of Eurocode 4 (EN 1994-1-1), the longitudinal shear resistance of composite slabs can be expressed through the empirical m – k formulation reported in Eq. (1). The regression coefficients obtained for each RAC mixture are summarized in Table 2. Due to the limited number of representative values available for some mixtures, the coefficient of determination R^2 is reported only as a descriptive indicator of the linear least-squares regression of experimental data points and should not be interpreted as a standalone measure of model reliability.

Table 2. Regression-derived interface parameters m (slope) and k (intercept) for the different RAC mix configuration

$r(\%RCA)$	m (kN/mm ²)	k (kN/mm ²)	R^2
0	74.5882	0.0990	0.9976
20	87.0775	0.0831	0.9375
30	104.8139	0.0141	1.000
50	47.6940	0.1717	1.000
70	16.4571	0.2100	0.9880
100	7.0036	0.2550	0.4047

For M30 and M50, the regression yielded $R^2=1$; however, this result is a consequence of the limited number of available data points after the exclusion of outliers through the EDA procedure, since the regression was performed using only two observations. Therefore, these values should not be interpreted as evidence of a particularly strong correlation, but rather as a consequence of the reduced dataset, which is also below the minimum number of specimens recommended by Eurocode 4 for the determination of the m – k parameters. Consequently, the regression results for these mixtures should be interpreted with caution and regarded mainly as indicative of the overall trend of the longitudinal shear resistance. For the M100 mixture, the low R^2 value reflects the higher dispersion of the experimental results rather than a limitation of the regression procedure itself. This suggests that, at full RCA replacement, the steel–concrete interface response becomes more variable and more sensitive to local heterogeneities, leading to a less predictable longitudinal shear behaviour.

4.1 Discussion of the m – k regression results

The regression results reported in Table 2 illustrate the evolution of the m – k parameters with increasing RCA replacement ratio and the associated changes in the interface shear transfer mechanisms.

The m parameter exhibits a non-monotonic evolution with increasing RCA content. From M0 to M30, m increases, suggesting that moderate levels of recycled aggregates may improve the engagement between concrete and the

embossments of the steel deck, possibly due to the rougher surface texture associated with residual mortar. For higher replacement ratios, however, m decreases progressively. This reduction is attributed to the deterioration of the concrete matrix, including increased porosity, lower cohesion, and weakening of the interfacial transition zone (ITZ), which limit the ability of the concrete to effectively mobilize the embossments and promote microcracking in the highly stressed regions around the deck ribs. In contrast to the behaviour of the m parameter, the evolution of k follows a different trend. After a slight reduction between M0 and M30, the intercept increases from M50 onwards, indicating a progressively greater contribution of friction at the steel–concrete interface. This behaviour is consistent with the higher macro-scale roughness introduced by recycled aggregates with adhered mortar, which increases the effective contact area and enhances frictional resistance after slip initiation.

These opposite trends highlight that m and k represent two distinct mechanisms governing longitudinal shear transfer. As the RCA content increases, the interface behaviour gradually shifts from an interlock-dominated response toward a friction-dominated mechanism.

5. Preliminary design adaptation of the Eurocode m - k formulation for RACCS

The experimental evidence discussed in the previous sections indicates that increasing recycled aggregate content progressively modifies the balance between mechanical interlock and friction at the steel–concrete interface. To address this aspect, a preliminary design-oriented adaptation of the m - k method is proposed in which the influence of the recycled aggregate replacement ratio is incorporated through correction coefficients applied to the reference parameters of natural aggregate concrete (M0).

The parameter α_{RCA} describes the variation of the mechanical interlock contribution and is defined as the ratio between the m value of a given RAC mix and the corresponding parameter of the reference configuration M0. Similarly, the coefficient β_{RCA} quantifies the change in frictional resistance and is defined as the ratio between the k parameter of the RAC mixture and that of M0. A hybrid parabolic–exponential expression was therefore adopted as an empirical fitting function to represent both correction factors. The resulting analytical expressions are reported in Eqs. (2) and (3), while the corresponding fitting curves are illustrated in Fig.2.

$$\alpha_{\text{RCA}}(x) = (-10.0097x^2 + 9.4706x + 0.9833)\exp^{-3.0703x} \quad (2)$$

$$\beta_{\text{RCA}}(x) = (26.7378x^2 - 7.1443x + 1.0403)\exp^{-2.0702x} \quad (3)$$

Based on these correction functions, the Eurocode 4 design formulation can be rewritten without altering its conceptual framework. The reference parameters m_0 and k_0 , obtained for the natural aggregate concrete configuration M0, are scaled through the correction functions α_{RCA} and β_{RCA} leading to the modified formulation reported in Eq. (4), where V_{mod} represent the predicted modified longitudinal shear strength.

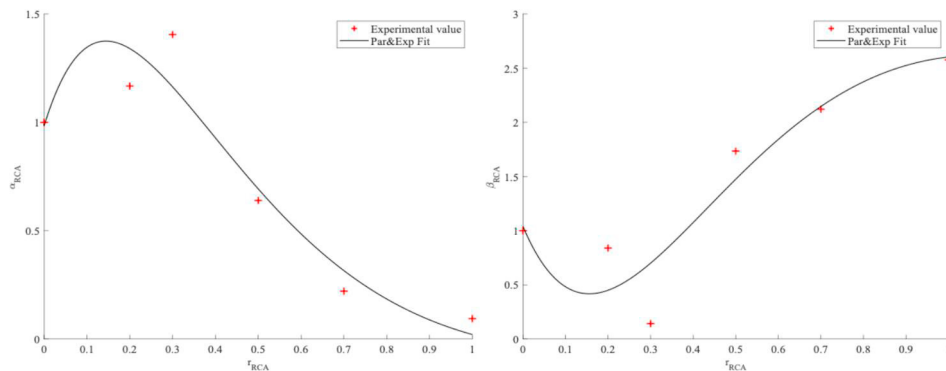


Fig. 2 Combined parabolic and exponential fitting functions of the correction coefficients α_{RCA} and β_{RCA} .

$$\frac{V_{\text{mod}}}{b d_p} = \alpha_{\text{RCA}} m_0 \frac{A_p}{b L_s} + \beta_{\text{RCA}} k_0 \quad (4)$$

The proposed formulation was validated by comparing the predicted longitudinal shear resistance with the experimental results obtained from the reference test campaigns. Table 3 reports the experimental values (V_{exp}) and the predictions provided by the proposed extension formulation (V_{mod}). The comparison between V_{mod} and the experimental results is therefore intended to verify whether the proposed formulation is able to reproduce the experimental evolution of longitudinal shear resistance as the RCA replacement ratio varies. The results show that the proposed model successfully captures the experimental trend across the investigated RCA range, with deviations generally within $\pm 10\%$.

Table 3. Comparison between experimental longitudinal shear resistance and modified formulation predictions.

$r(\%RCA)$	L_s (mm)	V_{exp} (kN)	V_{mod} (kN)	$r(\%RCA)$	L_s (mm)	V_{exp} (kN)	V_{mod} (kN)
0	550	23	23.2	50	550	24	22.4
0	650	21	20.9	50	750	21	19.7
0	750	19	19.2	70	550	21	22.3
20	550	25	23.8	70	650	20	21.5
20	650	21	20.7	70	750	19	21.0
20	750	20	18.4	100	550	22	21.6
30	650	19	20.5	100	650	22	21.5
30	750	16	18.5	100	750	21	21.4

6. Conclusion

This study investigated the longitudinal shear behaviour of RACCS, with the aim of extending the applicability of the Eurocode 4 m–k design method to systems incorporating recycled aggregates. The analysis also provided a mechanically based interpretation of the empirical parameters m and k , relating them to the main shear-transfer mechanisms acting at the steel–concrete interface, namely mechanical interlock and friction. The regression analysis showed that RCA content affects these two contributions in different ways, suggesting a progressive transition in the governing shear-transfer mechanism. Mechanical interlock appears to be more relevant at lower to intermediate replacement levels, while frictional resistance becomes increasingly significant at higher RCA contents. However, the trend observed around 30% r_{RCA} should be considered only indicative, since the corresponding regression was based on only two representative values. To account for the influence of RCA content, a preliminary design-oriented adaptation of the m–k method was proposed through continuous correction coefficients applied to the baseline parameters of the natural aggregate concrete configuration. The formulation reproduced the experimental trend of longitudinal shear resistance with satisfactory accuracy, with predictions generally within $\pm 10\%$ of the test results. Nevertheless, the proposed approach should be regarded as a preliminary calibration, due to the limited and unbalanced experimental dataset, in which some replacement ratios were represented by only a few span-dependent values, which limits the statistical robustness of the regression-derived parameters and of the corresponding correction functions. Further experimental work is therefore required to improve the statistical robustness of the formulation, especially in the transition range between 30% and 40% r_{RCA} , where the current indication of a possible peak in mechanical interlock needs additional validation. Future studies should also assess the applicability of the proposed approach to different deck geometries and embossment configurations, since alternative profiles, such as re-entrant or dovetail decks, may involve different shear-transfer mechanisms. From a design perspective, the proposed method provides a practical and efficient tool for estimating the longitudinal shear capacity of RACCS, facilitating the integration of RAC within existing design frameworks and supporting their adoption in sustainable construction.

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