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New analytical models to predict the mechanical performance of steel fiber-reinforced alkali-activated concrete

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Abstract

The use of alkali-activated concrete (AAC) as an alternative construction material to Portland cement-based concrete (PCC) has been widely encouraged by its enhanced mechanical and durability performance and environmental benefits. However, AAC exhibits low flexural and tensile strength, limiting its application in areas where high post-cracking flexural and tensile load-bearing capacity are needed. Steel fibers can be added to improve the composite ductility and toughness. Steel fiber-reinforced alkali-activated concrete (SFRAAC) is a new emerging technology with research studies evaluating the effect of fiber addition on its mechanical properties still in the early stages. To promote the application of SFRAAC, analytical models predicting their mechanical performance are needed. This study evaluates the applicability to SFRAAC of previously published analytical models developed for steel fiber-reinforced cement-based concrete (SFRPCC). Experimental data available in the literature have been collected to create an extensive database to validate and then calibrate these currently available correlations between mechanical properties for SFRAAC. The prediction models considered in this study correlate the mechanical performance of SFRAAC, that is, compressive strength, modulus of elasticity, splitting tensile strength, flexural and residual flexural strength, to the compressive strength of the reference concrete without fibers, the fiber volume fraction and the fiber reinforcing index. Thus, by knowing the performance of the AAC matrix and the fiber properties and dosage, it is possible to predict the overall mechanical behavior of the steel fiber-reinforced composite.

KEYWORDS

analytical models, fiber-reinforced alkali-activated concrete, mechanical properties, steel fibers

1 | INTRODUCTION

Steel fiber-reinforced concrete (SFRPCC) based on Portland cement has been widely used in the last decades to enhance the crack resistance of structural members and hence their durability and service life. The crack-bridging ability of the fibers improves the concrete ductility and post-cracking load-bearing capacity under tensile, shear and torsion loading.[1,2] Design-oriented strength prediction models played a fundamental role in promoting the use of SFRPCC as a structural material in engineering practice. Being able to derive the mechanical behavior of SFRPCC, that is, compressive and tensile behavior, solely by knowing the compressive strength of the reference concrete matrix and the fiber type and dosage facilitates the formulation of concrete mix design designed to meet the performance requirements of the end application.

Although several empirical models have been proposed for SFRPCC,[1–6] their applicability is limited to the type of concrete and steel fibers used. Furthermore, only the experimental data generated in each study are used to derive strength prediction models, making them unsuitable for different types of concrete or fiber. Wang et al.[2] reviewed several empirical models to derive the main mechanical properties of SFRPCC, that is, compressive strength, splitting tensile and flexural strengths and modulus of elasticity. They observed that the compressive strength of the reference concrete and the fiber volume fraction and reinforcing index, that is, the product of the fiber volume fraction and its aspect ratio (length/diameter), are the main factors affecting the mechanical performance of SFRPCC. However, the majority of the existing models are calibrated on a limited amount of experimental data and have limited accuracy when applied to different types of steel fibers or concrete. Furthermore, several currently available empirical models correlate the mechanical performance of SFRPCC with its compressive strength, but models able to predict the compressive strength of SFRPCC from the compressive strength of the reference concrete are limited. Guler et al.[1] evaluated the applicability of several models available in the literature to predict the compressive, splitting and flexural strength of SFRPCC to their own experimental data, highlighting the necessity of new empirical models. The empirical strength prediction models proposed by Guler et al.[1] correlate the cube compressive strength, the splitting tensile strength and the flexural strength of SFRPCC solely to the cube compressive strength of the reference concrete without steel fibers, the fiber volume fraction, and reinforcing index. Only using the compressive strength of the plain concrete and the type and dosage of the steel fibers used, it is possible to derive the mechanical performance of the composite.

Among the currently available empirical models to predict the mechanical performance of SFRPCC, the linear correlations proposed by Guler et al.[1] are concise and require only three input parameters: the compressive strength of the reference concrete without fibers, the fiber

TABLE 1 Existing models for the prediction of the mechanical properties of SFRPCC.

Mechanical properties	Empirical model	Ref.
Compressive strength	$f'_{cuf} = 0.92f'_{cu} - 1.44v_f + 14.6RI_v$	1
Modulus of elasticity	$E_{cyf} = 4.58(f\prime_{cu})^{0.5} + 0.42f'_{cu}RI_v + 0.39RI_v$	3
Splitting tensile strength	$f'_{sptf} = 0.12f'_{cu} - 0.71v_f + 6.47RI_v$	1
Flexural strength	$f'_{lf} = 0.24f'_{cu} + 1.12v_f + 7.10RI_v$	1

Note: f'_{cuf} and f'_{cu} are the cube compressive strength of SFRPCC and PCC, respectively, f'_{spf} and f'_{lf} are the splitting tensile and flexural of SFRPCC, respectively, E_{cyf} is the modulus of elasticity of SFRPCC, v_f is the fiber volume fraction, RI_v is the fiber reinforcing index, that is, $(d_f/l_f)v_f$, with d_f and l_f being the fiber diameter and length, respectively, and f'_{cyf} the cylinder compressive strength of SFRPCC.

TABLE 2 Conversion factors accounting for the sample geometry used in the creation of the dataset used in this study.

Mechanical property	Sample geometry (experimental value)	Sample geometry (predicted value)	Equations	Ref
Compressive strength	Cylinder 100 mm × 200 mm	Cylinder 150 mm × 300 mm	$f'_{cyf(150)} = 0.94f'_{cyf(100)}$	42
	Cube 150 × 150 × 150 mm^3		$f'_{cyf(150)} = 0.90f'_{cuf(150)}$	42
	Cube 100 × 100 × 100 mm^3		$f'_{cyf(150)} = 0.81f'_{cuf(100)}$	42
Modulus of elasticity	Cylinder 100 mm × 200 mm	Cylinder 150 mm × 300 mm	$E_{cyf(150)} = E_{cyf(100)}$, $E_{cyf(150)} < 25$ GPa $E_{cyf(150)} = 0.90E_{cyf(100)} + 1.90$, $E_{cyf(150)} \geq 25$ GPa	43
Splitting tensile strength	Cylinder 100 mm × 200 mm	Cylinder 150 mm × 300 mm	$f'_{sptf(150)} = 0.89f'_{sptf(100)}$	42

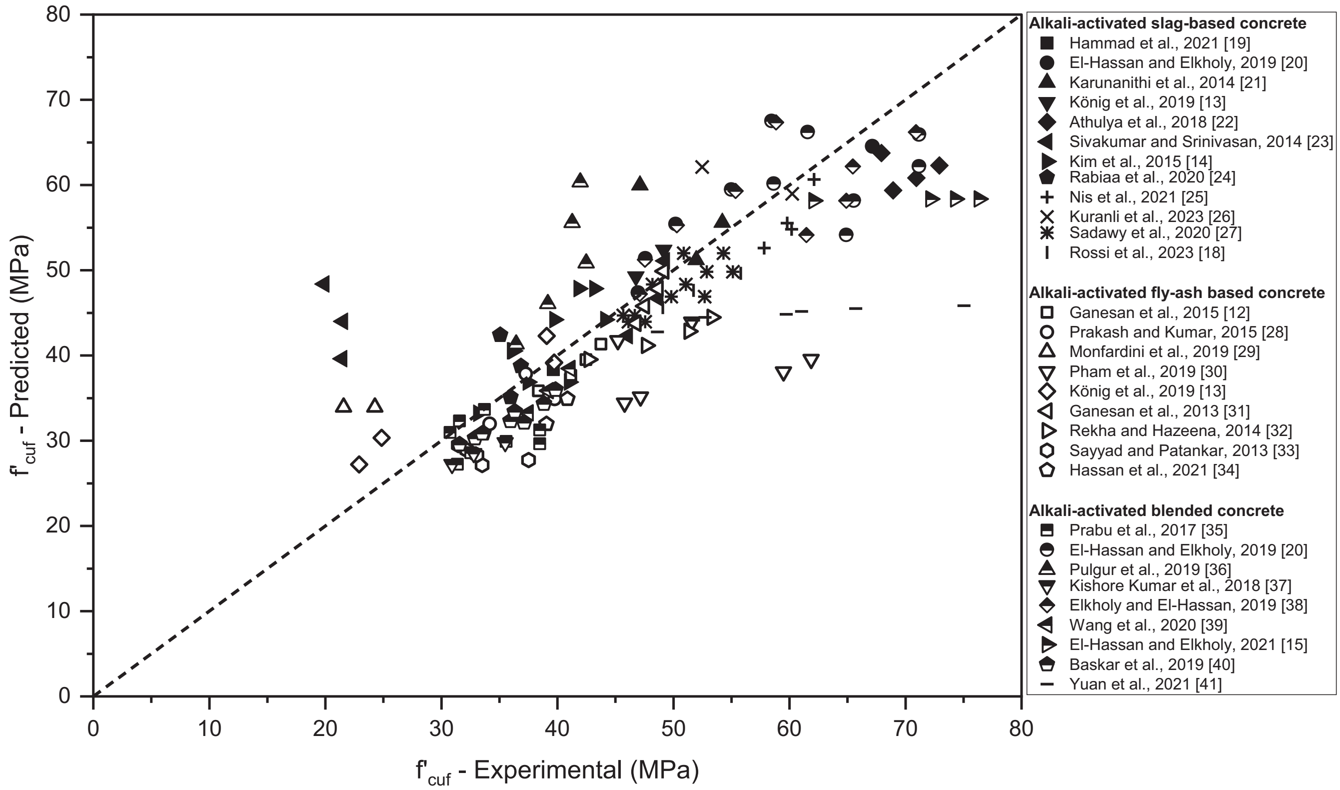

FIGURE 1 Correlation between the experimental and predicted values of the compressive strength of different alkali-activated concretes incorporating different steel fibers at different volume fractions according to the equation proposed by Guler et al.[1]

TABLE 3 IAE values of the correlation used to determine the compressive strength of SFRAAC according to Ref.[1]

	Slag-based AAC	Fly ash-based AAC	Blended AAC
IAE [%]	10.16	16.27	14.71

volume fraction, and the fiber reinforcing index. Thus, the performance of SFRPCC can be quickly predicted by performing a limited number of experiments on the reference concrete without steel fibers. However, Guler et al.[1] provided no correlation to derive the modulus of elasticity of SFRPCC from the compressive strength of the reference concrete. Thomas and Ramaswamy[3] have proposed an empirical equation correlating the modulus of elasticity of SFRPCC to the compressive strength of the reference plain concrete and the fiber reinforcing index. Thus, the correlations proposed by Guler et al.[1] and Thomas and Ramaswamy[3] have been chosen in this study as they allow predicting the performance of SFRPCC directly from the performance of the plain concrete only by knowing the characteristics of the concrete matrix and the steel fibers. Table 1 summarizes the analytical correlations between the mechanical properties of SFRPCC proposed by Guler et al.[1] and Thomas and Ramaswamy.[3]

Deriving empirical strength prediction models plays a vital role in encouraging the use of newly developed construction materials, such as alkali-activated concrete (AAC), for structural applications. AAC has been demonstrated to be a valid environmentally friendly alternative to traditional Portland cement-based concrete (PCC) as a construction material.[7,8] Nevertheless, due to intrinsic internal micro-cracks in its matrix,[9] it also exhibits brittle behavior,[9,10] resulting in poor resistance to crack propagation and low tensile strength.[9,10] As for traditional PCC, the incorporation of steel fibers in AAC enhances its tensile strength, toughness, post-cracking load-bearing capacity, and ductility.[7,10,11] However, steel fiber-reinforced alkali-activated concrete (SFRAAC) is a new emerging material and research studies addressing its mechanical performance and evaluating possible correlations between them are still scarce.[12–18] Furthermore, the intrinsic variability of the AAC matrix, caused by the variety of possible binders and alkaline activators, represents a hindrance to its classification and the characterization of its mechanical behavior. This limits the possibility of deriving a single empirical correlation

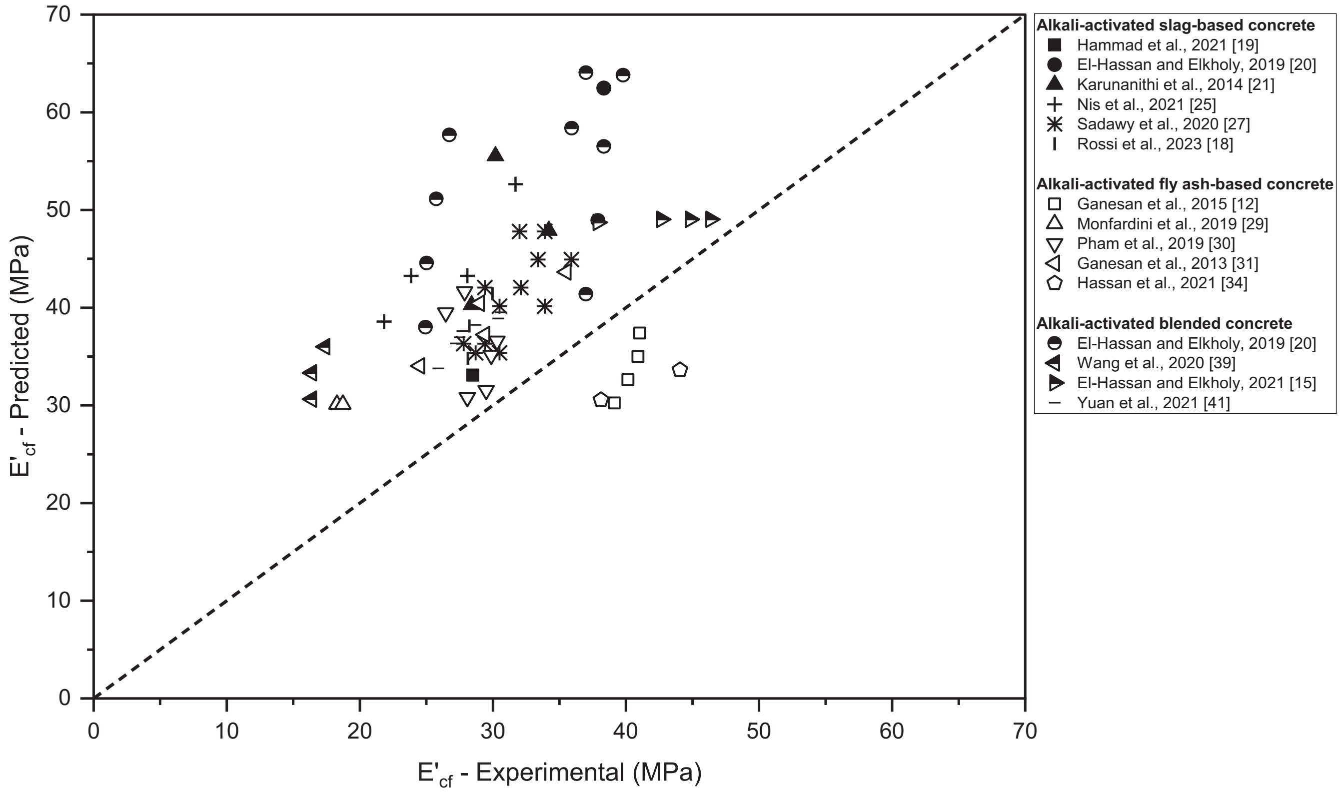

FIGURE 2 Experimental and predicted values of the modulus of elasticity of SFRAAC according to the equation proposed by Thomas and Ramaswamy.[3]

TABLE 4 IAE values of the correlation used to determine the modulus of elasticity of SFRAAC according to Ref.[6]

	Slag-based AAC	Fly ash-based AAC	Blended AAC
IAE [%]	28.86	23.37	32.66

describing the performance of the entire class of AACs. Thus, different alkali-activated systems, that is, high-calcium systems, low-calcium systems, and blended systems, are analyzed separately in this study to better understand the effect of steel fibers on different AAC matrices and to derive accurate analytical equations predicting their mechanical properties.

This study evaluates existing empirical models developed to predict the compressive strength, modulus of elasticity and splitting, and flexural tensile strength of SFRPCC for SFRAAC and recalibrates them for SFRAAC. First, a dataset is created by collecting experimental data available in the literature for different SFRAACs and data from the experimental investigations conducted by the authors in previous studies. Then, the applicability of the existing analytical correlations proposed by Guler et al.[1] and Thomas and Ramaswamy[3] for SFRPCC to SFRAAC is evaluated. Thereafter, these correlations are recalibrated to SFRAAC to improve the reliability of the proposed models.

2 | DATABASE OF MECHANICAL PROPERTIES OF SFRAAC

To evaluate the correlation between the mechanical performances of SFRAAC according to the equations summarized in Table 1, experimental data available in the literature have been collected.[12–15,18–41] Different concrete matrices and steel fiber geometries and dosages have been considered to cover most of the potential mix design formulations for SFRAAC. Data available in the literature on steel fiber-reinforced ground granulated blast furnace slag (high-calcium systems), Class-F fly ash (low-calcium systems), and blended systems (a combination of both) activated by sodium hydroxide, sodium silicate or both have been collected. Only publications reporting the 28-day mean compressive strength in addition to the modulus of elasticity and splitting tensile strength, or at least one of the latter, were considered.

The analytical models proposed by Guler et al.[1] correlate the compressive strength, the splitting tensile

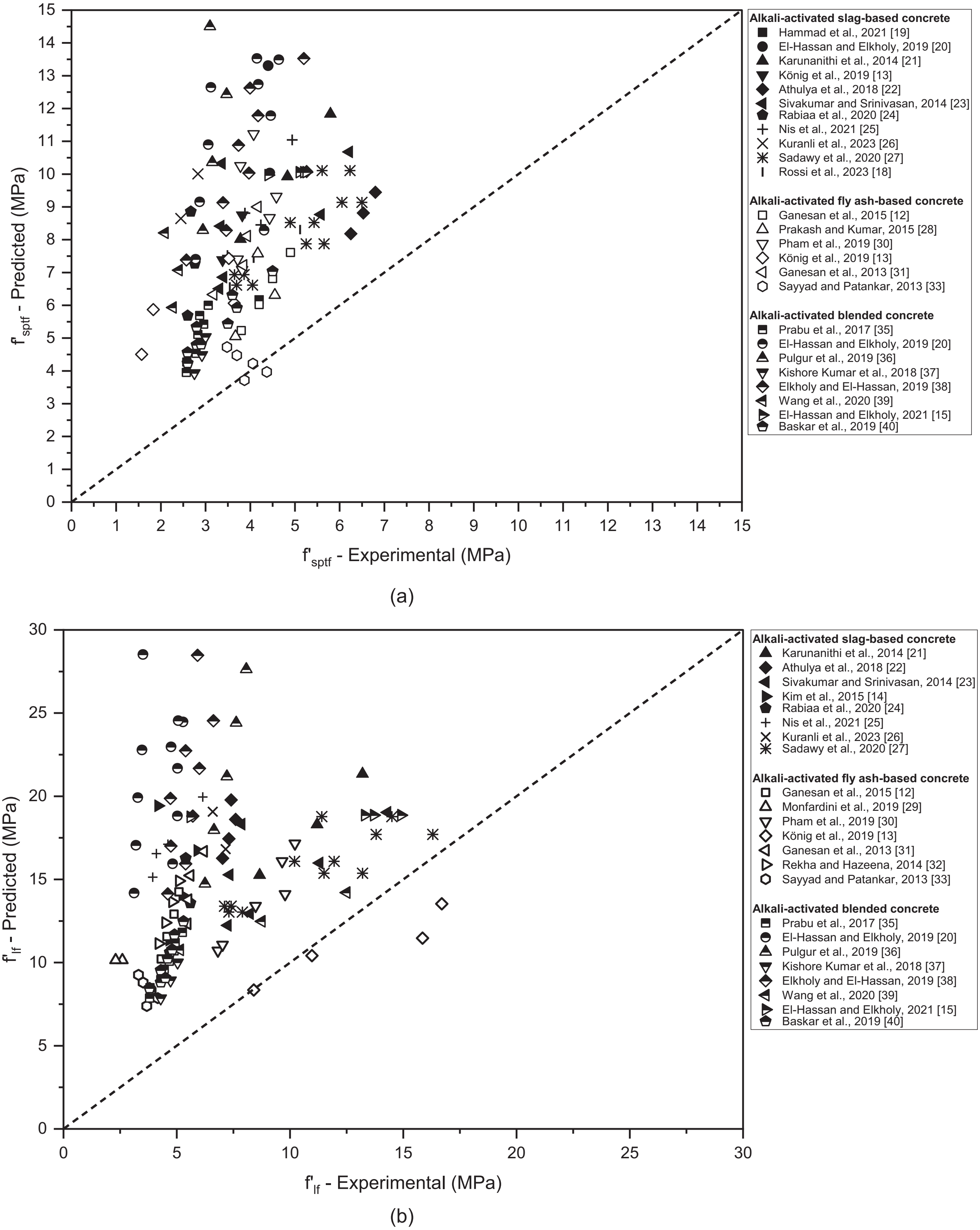

FIGURE 3 Experimental and predicted values of (a) the splitting tensile strength and (b) the flexural strength of SFRAAC according to the equations proposed by Guler et al.[1]

TABLE 5 IAE values of the correlation used to determine the splitting tensile strength and flexural strength of SFRAAC according to Guler et al.[1]

	Slag-based AAC	Fly ash-based AAC	Blended AAC
IAE [%], splitting tensile strength	45.91	43.59	60.34
IAE [%], flexural strength	47.12	50.69	65.08

	New correlations		
Coefficients IAE [%]	Slag-based AAC	Fly ash-based AAC	Blended AAC
A	1.04	0.95	1.20
B	0.00	0.00	0.00
C	2.12	18.78	0.80
IAE	8.68	11.78	8.60

TABLE 6 Proposed values of the coefficients *A*, *B*, and *C* and the corresponding IAE values for each type of alkali-activated concrete.

strength and the flexural tensile strength of SFRPCC to the cube compressive strength of the reference concrete. When in the literature these properties were evaluated on different sample geometries, the conversion factors summarized in Table 2 were applied.

3 | APPLICABILITY OF THE EXISTING ANALYTICAL MODELS TO SFRAAC

3.1 | Compressive strength

Figure 1 shows the correlation between the experimental and the predicted values of the compressive strength of SFRAAC using the equation proposed by Guler et al.[1] and summarized in Table 1. As shown in Figure 1, the correlation proposed by Guler et al.[1] can predict quite accurately the compressive strength of SFRAAC from the compressive strength of the reference matrix without steel fibers. Thus, the effect of the incorporation of steel fibers in AAC matrices is comparable to the one observed in cement-based concretes. Steel fibers up to a volume fraction of 1% have a limited effect on the compressive strength of the composite.[44] To evaluate the accuracy of this correlation, the integral absolute error (IAE) is used, which is defined as:

$$\mathrm{IAE} = \frac{\sum |Q_i - P_i|}{\sum Q_i} \cdot 100 \qquad (1)$$

where Q_i is the experimental data and P_i is the predicted value. Table 3 summarizes the values of IAE for each type of SFRAAC.

3.2 | Modulus of elasticity

Figure 2 shows the experimental and predicted values of the modulus of elasticity of different types of AAC incorporating steel fibers in different volume fractions obtained according to the equation proposed by Thomas and Ramaswamy.[3] AAC exhibits generally lower modulus of elasticity than cement-based concrete[45–49] and the addition of steel fibers has generally a limited effect on the modulus of elasticity.[18] The overestimation of the modulus of elasticity shown in Figure 2 reflects the lower modulus of elasticity of SFRAAC.

Table 4 shows the values of IAE for each type of AAC. Although the correlation can predict quite accurately the values of the modulus of elasticity for blended alkali-activated concrete, the accuracy of this analytical model decreases for slag-based and fly ash-based concretes.

3.3 | Splitting tensile strength and flexural strength

Figure 3 shows the correlation between the experimental and predicted values of the splitting tensile strength and the flexural strength for different SFRAACs as proposed by Guler et al.[1] The equations proposed by Guler et al.[1] highly overestimate the splitting tensile strength and the flexural strength of SFRAAC. AAC exhibits generally more brittle tensile behavior than cement-based concrete of similar strength grade.[49] Although the incorporation of steel fibers enhances the splitting and flexural tensile strengths of AAC, it is directly correlated to the tensile behavior of the reference plain concrete. Thus, SFRAAC shows lower splitting and flexural tensile

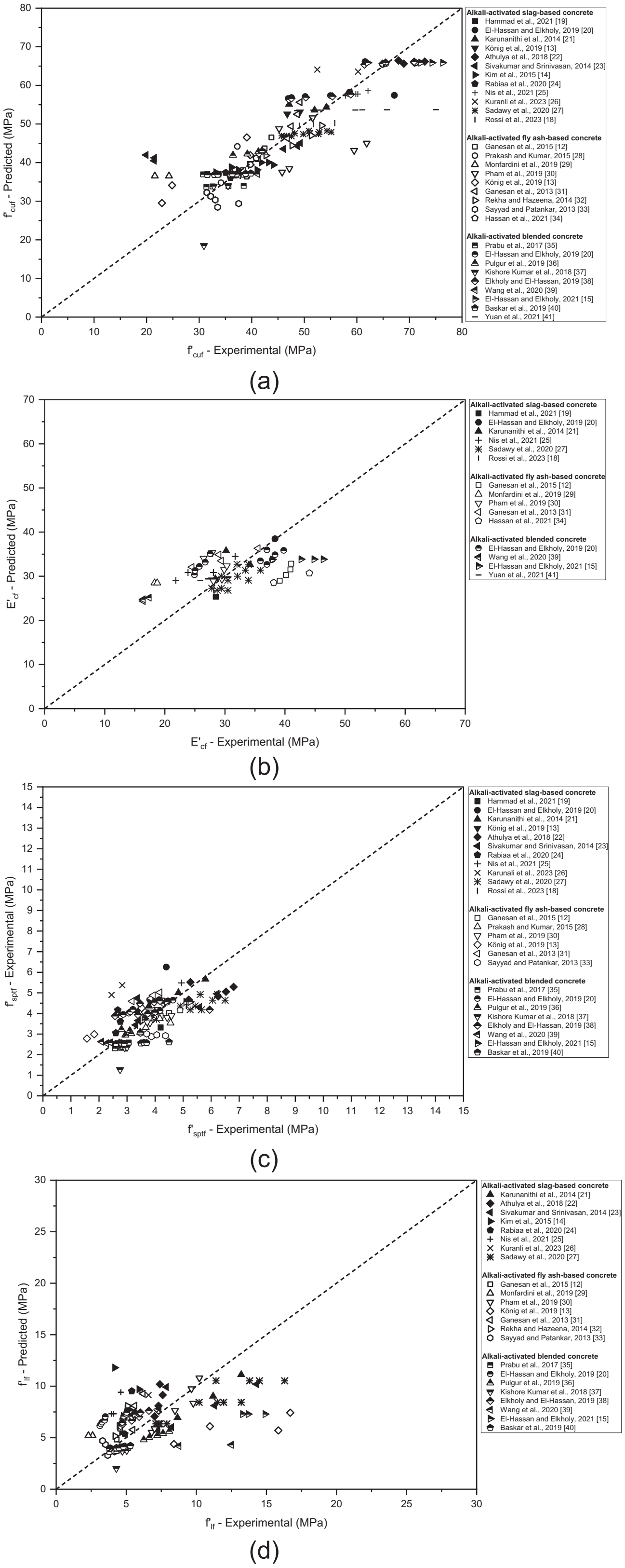

FIGURE 4 Correlation between the experimental and predicted values of (a) compressive strength, (b) modulus of elasticity, (c) splitting tensile strength, and (d) flexural strength of different alkali-activated concretes according to the new proposed equations.

strengths than SFRPCC. Table 5 shows the IAE values for each type of AAC, which confirms the inaccuracy of this correlation for these alternative types of concrete.

4 | NEW PROPOSED CORRELATIONS

The general form of the empirical equations proposed by Guler et al.[1] and Thomas and Ramaswamy[3] has been preserved and their coefficients have been recalibrated. The recalibration has been done by minimizing the objective function, which for this study is the mean of the sum of squares of the difference between the experimental data and the predicted values. The minimization is carried out using the Generalized Reduced Gradient (GRG) nonlinear optimization algorithm available in the Microsoft Excel® Solver add-in. These correlations are derived separately for slag-based, fly ash-based, and blended AAC to account for the effect of the binder type.

4.1 | Compressive strength

The correlation proposed by Guler et al.[1] to predict the compressive strength of steel-fiber reinforced concrete from the compressive strength of the reference concrete without steel fibers can be written in its general form as follows:

$$f'_{\mathrm{cuf}} = Af'_{\mathrm{cu}} - Bv_{\mathrm{f}} + C\mathrm{RI}_{\mathrm{v}} \quad (2)$$

where A, B, and C are the calibrated coefficients. The new values of these coefficients have been summarized in Table 6 along with the corresponding values of IAE for each type of SFRAAC.

As shown in Table 6, for AAC, regardless of the binder type, the fiber volume fraction does not affect the compressive strength of the composite. As most of the data points used to calibrate this correlation refer to AAC incorporating different types of steel fibers in a volume fraction $v_f < 0.50\%$, the effect of v_f on the compressive strength of the composite is minimal. Thus, the value of the coefficient B is equal to 0. The new proposed coefficients give lower IAE values compared to the original model (Figure 4a), corresponding to a decrease of 14.6%, 27.6%, and 41.5% for slag-based, fly ash-based, and blended AAC, respectively.

4.2 | Modulus of elasticity

The equation proposed by Thomas and Ramaswamy[3] correlates the modulus of elasticity of SFRPCC to the compressive strength of the reference concrete and

TABLE 7 Proposed values of the coefficients D, E, and F and the corresponding IAE values for each type of alkali-activated concrete.

	New correlations		
Coefficients IAE [%]	Slag-based AAC	Fly ash-based AAC	Blended AAC
D	3.68	4.55	4.28
E	0.00	0.00	0.06
F	9.07	8.57	0.00
IAE	8.04	20.87	15.74

TABLE 8 Proposed values of the coefficients G–L and the corresponding IAE values for each type of alkali-activated concrete.

	New correlations		
Coefficients IAE [%]	Slag-based AAC	Fly ash-based AAC	Blended AAC
Splitting tensile strength			
G	0.07	0.10	0.08
H	0.00	0.00	0.00
I	1.85	0.87	0.19
IAE	19.85	18.23	16.10
Flexural strength			
J	0.10	0.10	0.13
K	4.17	0.00	0.00
L	0.00	7.05	0.55
IAE	25.31	34.98	36.27

TABLE 9 Proposed strength prediction models to derive the mechanical properties of slag-based, fly ash-based, and blended alkali-activated concrete incorporating steel fibers.

Mechanical properties	Proposed equations
Compressive strength	$f'_{cuf} = \begin{cases} 1.04f'_{cu} + 2.12RI_v \\ 0.95f'_{cu} + 18.78RI_v \\ 1.20f'_{cu} + 0.80RI_v \end{cases}$
Modulus of elasticity	$E'_{cf} = \begin{cases} 3.68(f'_{cu})^{0.5} + 9.07RI_v \\ 4.55(f'_{cu})^{0.5} + 8.57RI_v \\ 4.28(f'_{cu})^{0.5} + 0.06f'_{cu}RI_v \end{cases}$
Splitting tensile strength	$f'_{sptf} = \begin{cases} 0.07f'_{cu} + 1.85RI_v \\ 0.10f'_{cu} + 0.87RI_v \\ 0.08f'_{cu} + 0.19RI_v \end{cases}$
Flexural strength	$f'_{lf} = \begin{cases} 0.10f'_{cu} + 4.17v_f \\ 0.10f'_{cu} + 7.05RI_v \\ 0.13f'_{cu} + 0.55RI_v \end{cases}$

the fiber reinforcing index and can be written in its general form as follows:

$$E_{cyf} = D(f'_{cu})^{0.5} + Ef'_{cu}RI_v + FRI_v \tag{3}$$

Table 7 summarizes the new values of the coefficients D, E, and F and the corresponding IAE.

As shown in Table 7, for alkali-activated slag-based and fly ash-based concrete the coefficient E is equal to 0, that is, the modulus of elasticity of SFRAAC is directly correlated to the square root of the compressive strength of the reference concrete and the fiber reinforcing index. For blended AAC, the coefficient F is equal to 0, showing a limited influence of the fiber reinforcing index on the modulus of elasticity of SFRAAC. The different effects of the coefficients on the prediction of the modulus of elasticity according to the binder type can be related to the limited amount of data available in the literature for the recalibration of the empirical correlation and to their limited variety of fiber volume fractions investigated, as observed for the compressive strength. However, the proposed recalibration provides lower IAE values in comparison to the one observed for the original model, which decreases by 72.1%, 10.7%, and 51.8% for slag-based, fly ash-based, and blended AAC, respectively (Figure 4b).

4.3 | Splitting tensile strength and flexural strength

The equations for the prediction of the splitting tensile and flexural strength according to Guler et al.[1] can be written in their general form as follows:

$$f'_{\mathrm{sptf}} = Gf'_{\mathrm{cu}} - Hv_{\mathrm{f}} + I\mathrm{RI_v} \tag{4}$$

$$f'_{\mathrm{lf}} = Jf'_{\mathrm{cu}} + Kv_{\mathrm{f}} + L\mathrm{RI_v} \tag{5}$$

Table 8 summarizes the values of the coefficients of Equations (4) and (5) and the IAE values of each analytical correlation.

As shown in Table 8, the splitting tensile strength of AAC, regardless of the type of matrix, is not directly correlated to the fiber volume fraction but is mainly affected by the compressive strength of the matrix and the fiber reinforcing index. However, the fiber volume fraction indirectly affects the splitting tensile strength, as the fiber reinforcing index is defined as the product between the fiber aspect ratio (length/diameter) and the fiber volume fraction. As observed for the compressive strength and the modulus of elasticity, values of the coefficients corresponding to v_{f} equal to 0 can be due to the limited variety of the fiber volume fraction for the data points considered. Additional data related to higher fiber volume fractions would be necessary to improve the proposed correlation concerning v_{f}. However, the newly calibrated correlations can predict the splitting tensile strength more accurately in comparison to the original model, as shown by the values of IAE, which decrease by 56.8%, 58.02%, and 73.3% for slag-based, fly ash-based, and blended AAC, respectively (Figure 4c). Lower values of the IAE correspond to a more accurate prediction of the experimental data.

Similar behavior can be observed for the prediction of the flexural strength of AAC. For fly ash-based and blended concrete, the fiber volume fraction has a negligible effect on the flexural strength of the composite, while for slag-based AAC, the fiber volume fraction has a higher effect than the fiber reinforcing index. However, such observation can be due to the limited amount of data points collected and their narrow variability rather than to differences in the material mechanical behavior. The new proposed correlation can predict the flexural strength of SFRAAC with higher accuracy, as shown by the values of IAE decreasing by 42.3%, 31.0%, and 44.3% for slag-based, fly ash-based, and blended concrete, respectively, in comparison to the values observed for the original model (Figure 4d).

Table 9 summarizes the strength prediction equations derived in this study for slag-based, fly ash-based, and blended SFRAAC.

5 | CONCLUSIONS

This paper evaluates the applicability of the currently available analytical equations developed for steel fiber-reinforced cement-based concrete to different types of steel fiber-reinforced AAC. Available analytical correlations proposed for steel fiber-reinforced PCC have been evaluated in this paper and further calibrated using the experimental data available in the literature for steel fiber-reinforced slag-based, fly ash-based, and blended AACs.

AAC generally shows a lower modulus of elasticity and tensile behavior than cement-based concrete of similar strength grade, thus, the analytical correlations developed for SFRPCC overestimate the mechanical performance of SFRAAC and need to be recalibrated. The newly calibrated equations show higher accuracy in predicting the mechanical performance of SFRAAC, with an average improvement of the IAE of 27.9%, 44.9%, 62.8%, and 39.2% for the compressive strength, modulus of elasticity, splitting and flexural tensile strengths, respectively. The newly recalibrated analytical correlations show a negligible effect of the fiber volume fractions on the predictions of the compressive strength and the splitting tensile strength, for which the coefficients B and H, respectively, are equal to zero. This might be due to the limited range of fiber volume fractions investigated in the literature, that is, $v_{\mathrm{f}} < 0.50\%$. Additional data over a wider range of fiber volume fractions, in particular at $v_{\mathrm{f}} > 1\%$, are needed to validate, and further calibrate, if needed, the coefficients of these prediction models.

Evaluating the correlation between the mechanical performance of different AACs incorporating different types and dosages of steel fiber is fundamental to further understanding the behavior of these new alternative binders, facilitating their structural design and promoting their utilization for design purposes. Being able to derive the mechanical performance of SFRAAC from the performance of the reference plain concrete facilitates the formulation of the concrete mix design and the choice of its main components, that is, binder, activator, and fiber type and dosage, to meet the design requirements of the end applications.

However, this study represents only a first step in deriving analytical equations to predict the mechanical performance of SFRAAC. Additional experimental data are needed to further evaluate the effect of steel fibers on the performance of the composite and derive more accurate analytical correlations for design purposes. In particular, different types of binders, that is, different types of ashes (class-C fly ashes, palm oil fuel ashes, and rice husk ash) or slags (ladle slag, copper slag, and EAF slag), alternative binders, such as calcined clays, activated with different types of activators, and incorporating different types of steel fibers at different volume fractions should be investigated. Furthermore, newly developed steel fibers, such as double (4D) and triple (5D) hooked-end steel fibers or hybrid steel fiber reinforcements should be evaluated, to better understand the effect of the concrete matrix and the fiber geometry and dosage on the performance of SFRAAC. This would allow a more detailed classification of the composite and the formulation of more reliable analytical prediction models for SFRAAC and promote its use in practice.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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