Application of Predictive Models for Evaluating the Compressive, Tensile and Flexural Strength Relationships of Botchem Concrete made with Kgale Aggregates

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Abstract— The work presented herein attempts to ascertain the accuracy or otherwise of some current prediction models for the tensile-compressive strength and the flexural-compressive strength relationships of concrete made with BOTCHEM cement and Kgale aggregates in Botswana. Towards this end, concrete of four different characteristic strengths ranging from 20 MPa to 50 MPa was manufactured and the compressive, split tensile and flexural tensile strengths were determined experimentally. Some current prediction models including those of ACI 318-99, Arioglu et al. (2006), Oluokun (1991), CEB-FIP Model Code (1990), ACI 318-2005 and CEN (2002) amongst others , were used to evaluate the split tensile and/or flexural tensile strengths. It was found that with respect to the split tensile strength, the predictions were unsafe in almost all cases for concrete in the range 35 MPa to 50 MPa. Concerning the flexural tensile strength, the predictions were unsafe in the whole range 20 MPa to 50 MPa. It was concluded that these empirical relationships for the split tensile/compressive strength and for the flexural tensile/compressive strength suggested in the literature have low validity range of characteristic compressive strengths. It is necessary to seek for alternative expressions to predict more accurately the nature of these relationships in relation to concretes made form local cements and aggregates. For a more complete solution, it is also logical to extend the investigations to cover the range of characteristic compressive strengths encountered in engineering practice.

Index Terms— Compressive, split tensile, flexural tensile, strength, relationship.

1 INTRODUCTION

A knowledge of the tensile strength of concrete is useful in assessing the performance of structures. For example the value of the tensile strength is of interest in evaluating the shear resistance of reinforced and prestressed concrete beams. Also with reference to the punching shear phenomenon in reinforced and prestressed flat slabs, Franklin [1] has stated that the tensile strength of concrete affects the cracking load levels and crack patterns, the effective stiffness of the structure and the degree of non-linearity in response to load, the strength in diagonal tension as well as the resistance to shear. It is also a very important parameter in the design of liquid retaining structures. However due to the fact that uniaxial tensile tests on concrete present some considerable difficulty, splitting tensile tests are generally carried out on cylindrical specimens. The splitting tensile strength f_t is determined on the basis of the theory of elasticity by the formula $f_t = 2P_u/(\pi DL)$, where f_t is the splitting tensile strength in MPa, P_u is the measured peak load in Newtons, D is the diameter of the cylindrical specimen in millimetres and L is the length of the specimen in millimetres. On account of the differences between the assumed boundary conditions and the exact test set-up, the correctness of the split tensile test for determining the uniaxial tensile strength has been questioned in the literature; it is suggested by Hannant et al. [2] and the CEB-FIP Model Code [3] that a factor of $\lambda = 0.9$ be applied to the split tensile strength in order to estimate the direct tensile strength.

The flexural tensile strength of concrete or modulus of rupture f_r on the other hand, is an important parameter in the evaluation of the deflection and cracking behaviour of concrete structures, as well as ascertaining the minimum flexural reinforcement. In fact, the accurate assessment of flexural strength is fundamental because it provides a means of judging the quality of concrete being used, and a basis to predict the resistance and durability of the material. It aids in the design of structural elements like beams and cantilevers and provides a useful tool for the development of stronger and higher performance concretes. The flexural tensile strength is generally determined by the utilization of a three-point flexural test technique on a specimen of rectangular cross-section. The application of simple beam theory to the results will yield the modulus of rupture.

In spite of all the foregoing however, the compressive strength of concrete is largely regarded as the preeminent mechanical property or characteristic of the material. In addition the compressive strength is relatively easy to conduct, whether on concrete cubes or cylinders. The concrete cube strength is often converted to a cylinder equivalent strength by the multiplication of a factor in the range 0.8 to 0.85. More particularly, in view of the near universality of the compressive strength test coupled with its ease of assessment relative to the split tensile and flexural tensile strength tests, there has been considerable interests over the past few decades in ascertaining the relationship that exist between these three parameters, – namely the split tensile/compressive strength relation, and the flexural tensile/compressive strength ratio. The relationship between the split tensile and compressive strength is commonly accepted to be of the form $f_t = k_1 (f_c)^{n_1}$, where k_1 and n_1 are coefficients to be determined empirically. Similarly, the flexural tensile/compressive strength relationship is generally taken as $f_r = k_2(f_c)^{n_2}$, where again, k_2 and n_2 are empirical coefficients.

The various predictive equations to express the above relationships are well documented in the literature, and no attempt is made in the present study to exhaustively explain them. It is sufficient to state here that most of them are of the power series form with the coefficients n_1 and n_2 being either 0.5 or 2/3. Notwithstanding, Ahmed et al. [4] have argued that in respect of the flexural tensile strength the coefficients k_2 and n_2 depend on the aggregate properties and mineralogy, the composition of the concrete, and the curing and testing conditions. They also concluded that the empirical relationships between the flexural tensile and compressive strength proposed in the literature and major standards have low validity range of compressive strengths.

With reference to the relationship between the tensile and compressive strengths of concrete, Freyne et al. [5] in their study on high performance concretes stated that the cement type influences the tensile strength characteristics to a greater degree than the compressive strength, and therefore the applicability or relevance of the existing empirical relationships should be confirmed for differing cement types. Earlier, Gardener [6] had proposed relationships specifically for Types I and III cements and fly ash concrete.

From what has been said thus far, it is apparent that the aggregate type as well as cement type may be factors whose significance might not have been sufficiently appreciated in the development of empirical relationships between the various mechanical characteristics of concrete. In the Republic of Botswana, the popular BOTCHEM cement and also Kgale quarry aggregates have found widespread application in the building and civil engineering construction industry. Ngwenya and Franklin [7] citing the Pretoria Portland Cement Company or PPC stated that BOTCHEM cement is a Type II containing fly ash in the range 21%–35% and a slower rate of hydration than average. Kgale aggregates on the other hand are found in the greater Gaborone area and are granitic in nature, according to an investigation on mineral aggregate production in Botswana conducted by Tshwenyego and Poulin [8].

As a consequence of the above therefore, the work reported herein is concerned primarily with the tensile/compressive and the flexural tensile/compressive strength relationships for concrete made with BOTCHEM cement and Kgale quarry aggregates. More specifically, the applicability and accuracy of some current and well known predictive models have been tested against experimental results obtained from concretes manufactured using these local materials. Towards this goal, four different concrete mixes having 28-day compressive strengths ranging from 20 MPa up to 50 MPa have been utilized. The prediction models employed in this study include those of Oluokun [9], ACI 318-99 [10], CEB-FIP Model Code [3], European Committee for Standardization, CEN [11], ACI 318-2005 [12] and Arioglu et al. [13], amongst others.

2 Experimental Procedure

2.1 Materials, Mix Design, Casting and Test Methods

For the current study, BOTCHEM Portland cement CEM II/B-W 32.5R containing a controlled amount of fly ash and having a 28-day compressive strength of 32.5 MPa was employed in conjunction with crushed coarse and fine aggregates sourced from Kgale quarries. The coarse aggregate proportions were practically exclusively between the 13.2 mm and 6.7 mm sieve sizes, while the fine aggregate constituents were very largely between 4.75 mm and 0.15 mm sieve sizes. Not unexpectedly, the fine aggregates were found to be well graded with a fineness modulus of 3.12; in contrast, the coarse aggregates were poorly graded.

Four different mix designs for characteristic compressive cube strengths of 20 MPa, 30 MPa, 40 MPa and 50 MPa respectively were carried out using the Portland Cement Institute (PCI) mix design method based on ACI 211.1 – 81 as described by Addis and Goodman [14]. All concreting and testing work was carried out in the Structures Laboratory of the Civil Engineering Department at the University of Botswana, Gaborone. Details of the mix design proportions for the different designated strengths are given by Franklin and Kangootui [15] and will not be presented here. However it can be noted in passing that water-cement ratios of 0.63, 0.50, 0.41, and 0.37 in that order were utilized. In total, thirty-six 100 mm cubes, twenty-four 150 mm x 300 mm cylinders, and twenty-four 100 mm x 100 mm x 400 mm beams were manufactured for the determination of the compressive, split tensile and flexural tensile strengths respectively.

The testing of the hardened concrete specimens for the designated strength classes was carried out at 7, 14 and 28 days after casting. With reference to the compressive strength tests, an Amsler test machine with loading applied at a constant rate until specimen failure was employed to crush three 100 mm cubes on any given day using the stipulated South African standard SANS 5863: 2006 [16]. Concerning the split tensile tests, the same Amsler test machine was used; however two 150 mm x 300 mm cylinders were tested at any given time under a constant loading rate until splitting failure. In this case, plywood packing strips were incorporated and testing was done in accordance with SANS 6253: 2006 [17]. In respect of the flexural tensile strength tests, a Dennison testing machine which applied a three-point loading at constant rate until specimen failure was adopted for testing two 100 mm x 100 mm x 400 mm concrete beams on any given day. In this instance, all testing complied with the SANS 5864: 2006 [18] standard. For all the concrete specimens highlighted, the average value of the loads recorded was taken as the failure load. The experimental set-ups for the compressive, split tensile and flexural tensile tests are shown in Figs. 1, 2 and 3, in that order.

Fig. 1. Compressive strength test set-up

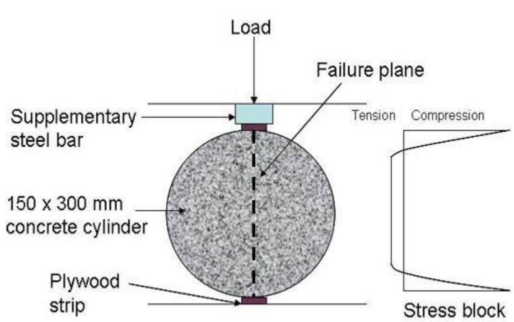

Fig. 2. Split cylinder strength test set-up

Fig. 3. Flexural strength test set-up

3 Results and Discussion

3.1 Predicted Values of the Split Tensile Strength

The results of the compression tests on 100 mm cubes were converted to their equivalent cylinder values by multiplying the cube strength by 0.83 as recommended by Mindess et al. [19]. The cylinder compressive strengths determined at 28 days for the four designated strength classes as designed, are shown in Table 1. Also indicated are the corresponding split tensile strength results conducted using 150 mm x 300 mm cylinders. In line with the stated objectives of the present study, the predicted split tensile strengths based on the recommendations of a number of researchers and standards reported in the literature are also shown. The ratios of the split tensile test results to the predicted values f_{test}/f_{pred} have not been tabulated.

The predicted models used here in the order presented are $f_t = 0.59(f_c')^{0.5}$ for ACI 363R-1992 [20]; $f_t = 0.321(f_c')^{0.661}$ for Arioglu et al. [13]; $f_t = 0.56(f_c')^{0.5}$ for ACI 318-99 [10]; $f_t = 0.294(f_c')^{0.69}$ for Oluokun [9]; $f_t = 0.313(f_c')^{2/3}$ for Raphael [21]; $f_t = 0.3016(f_c')^{2/3}$ for the CEB-FIP Model Code [3] and $f_t = 0.22(f_c')^{2/3}$ for Chen and Su [22]. It is obvious that in almost all cases for concrete in the range 35 MPa – 50 MPa cylinder compressive strengths, the predictions are unsafe. The only exception in this regard is for the predictions of Chen and Su [22] which nonetheless are consistently very conservative.

TABLE 1
PREDICTED VALUES OF THE SPLIT TENSILE STRENGTH VIA THE COMPRESSIVE STRENGTH

	Strengths in MPa for specified classes							
	Class 20		Class 30		Class 40		Class 50	
	f_c'	f_t	f_c'	f_t	f_c'	f_t	f_c'	f_t
Test	27.3	2.87	34.1	3.33	42.8	3.28	51.7	3.53
1*		3.08		3.45		3.86		4.24
2*		2.86		3.31		3.84		4.36
3*		2.93		3.27		3.66		4.03
4*		2.88		3.36		3.93		4.47
5*		2.84		3.29		3.83		4.34
6*		2.73		3.17		3.69		4.19
7*		1.99		2.31		2.69		3.05

1* – ACI 363R-1992 [20], 2* - Arioglu et al. [13], 3* - ACI 318-99 [10], 4* - Oluokun [9], 5* - Raphael [21], 6* - CEB-FIP Model Code [3], 7* - Chen and Su [22]

The above results are made more explicit in Figs. 4 to 10 which show the test results and the predictions of the split tensile strength by the different authorities based on the same order as laid down in Table 1. With respect to the three major codes, the ratio of test to predicted tensile strength varies from 0.833 to 0.965 for ACI 363R-1992 [20], from 0.876 to 1.018 for ACI 318-99 [10] and from 0.842 to 1.051 for the CEB-FIP Model Code 1990 [3]. It is apparent that the majority of the predictions are on the unsafe side, the discrepancy being more prominent in the 30 MPa to 40 MPa compressive strength range. It is clearly seen that only the values of Chen and Su [22] are on the safe side, albeit very conservative.

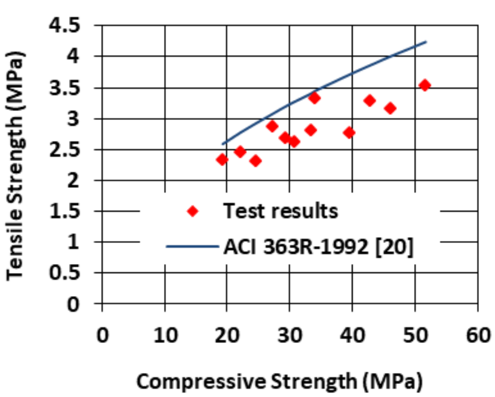

Fig. 4. Prediction of tensile strengths based on provisions of ACI 363 R-1992 [20]

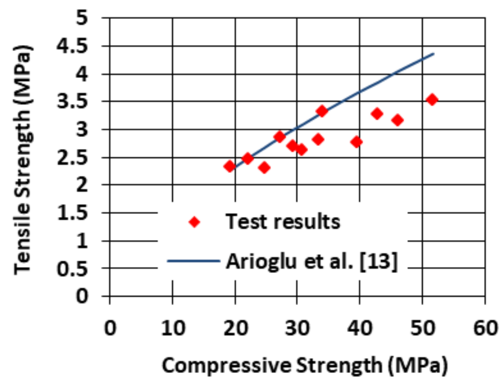

Fig. 5. Prediction of tensile strengths based on recommendations of Arioglu et al. [13]

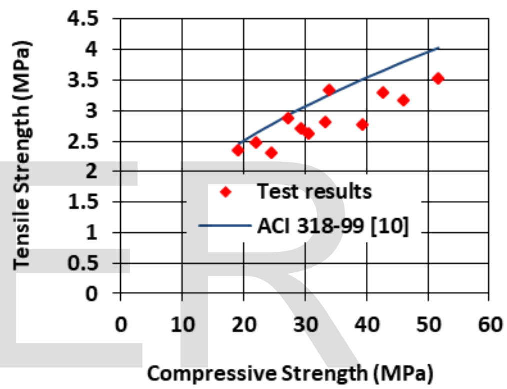

Fig. 6. Prediction of tensile strengths based on provisions of ACI 318-99 [10]

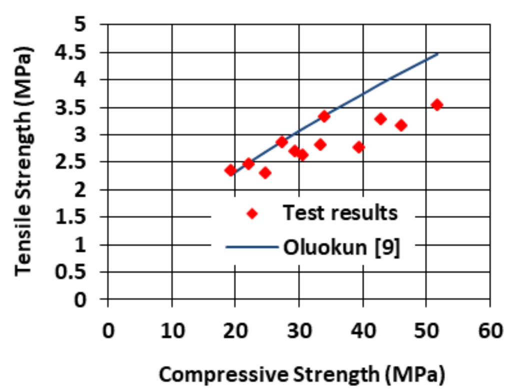

Fig. 7. Prediction of tensile strengths based on recommendations of Oluokun [9]

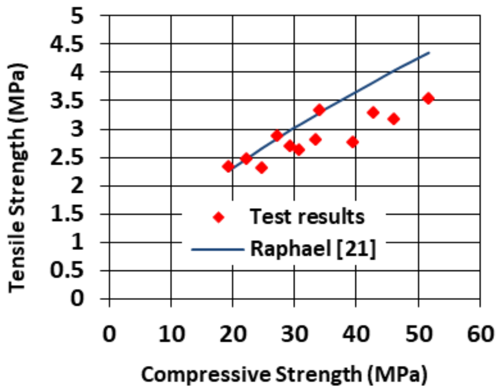

Fig. 8. Prediction of tensile strengths based on recommendations of Raphael [21]

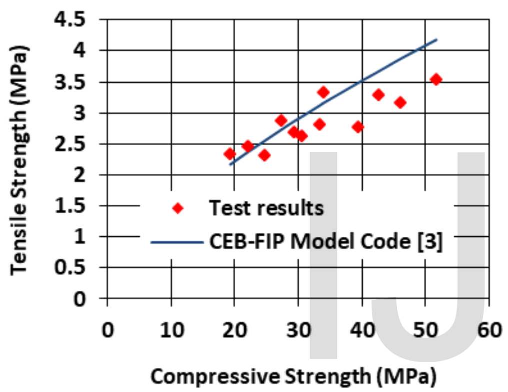

Fig. 9. Prediction of tensile strengths based on provisions of CEB-FIP Model Code 1990 [3]

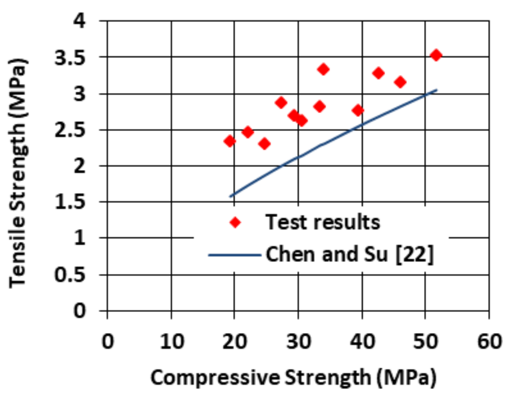

Fig. 10. Predictions of tensile strengths based on recommendations of Chen and Su [22]

3.2 Predicted Values of the Flexural Tensile Strength

The results of the cylinder compressive strength at 7, 14 and 28 days for the four designated strength classews as designed together with the corresponding flexural tensile strength test results conducted using 100 mm x 100 mm x 400 mm concrete beams are shown in Table 2. Also indicated are the predictions of the modulus of rupture based on a number of well known standards/codes. The ratios of the flexural tensile test results to the predicted values f_{test}/f_{pred} have not been tabulated.

TABLE 2
PREDICTED VALUES OF THE FLEXURAL TENSILE STRENGTH VIA THE COMPRESSIVE STRENGTH

	Strengths in MPa for specified classes							
	Class 20		Class 30		Class 40		Class 50	
	f_c'	f_r	f_c'	f_r	f_c'	f_r	f_c'	f_r
Test	27.3	2.30	34.1	2.84	42.8	2.68	51.7	3.24
1*		2.70		3.02		3.38		3.72
2*		4.23		4.73		5.30		5.82
3*		3.10		3.60		4.18		4.75
4*		3.27		3.66		4.10		4.50

1* – ACI 318-2005 [12], 2* - CEB-FIP Model Code [3], 3* - CEN-2002 [11], 4* - IS 456-2000 [23]

The predicted models used in Table 2 in the order tabulated are $f_r = 0.517(f_c')^{0.5}$ for ACI 318-2005 [12]; $f_r = 0.81(f_c')^{0.5}$ for the CEB-FIP Model Code [3]; $f_r = 0.342(f_c')^{2/3}$ for the European Committee for Standardization, CEN-2002 [11] and in addition $f_r = 0.626(f_c')^{0.5}$ for the Indian Standard IS 456-2000 [23].It is apparent that in all cases for the complete range of 20 MPa to 50 MPa compressive strengths, the predictions are consistently unsafe. There are no exceptions in this respect.

The above observations are made even clearer in Figs. 11 to 14 which show the experimental values and the predictions of the flexural tensile strengths by the different standards and codes following the same order highlighted in Table 2. It is quite obvious from the results presented that the modulus of rupture of concrete made from the granitic Kgale crushed aggregates and BOTCHEM cement is markedly different and consistently lower than the predictions of several well known standards and codes, whose values have been derived empirically based on tests carried out in all probability on concretes utilizing different types of cements and aggregates from those employed in the present study.

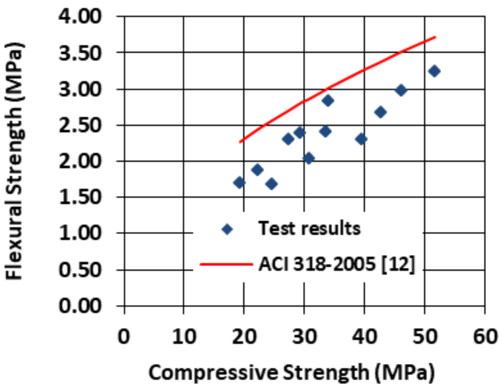

Fig. 11. Prediction of flexural strength based on provisions of ACI 318-2005 [12]

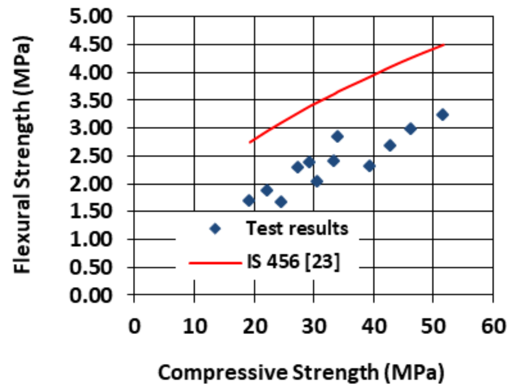

Fig. 14. Prediction of flexural strength based on the provisions of IS 456-2000 [23]

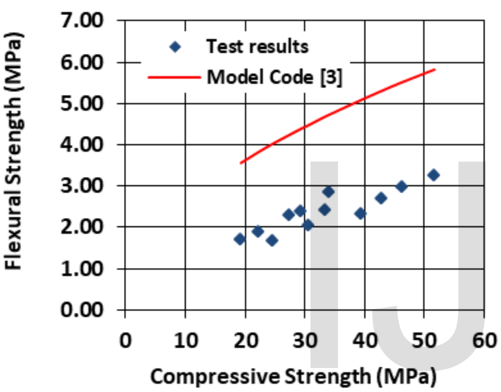

Fig. 12. Prediction of flexural strength based on provisions of the CEB-FIP Model Code [3]

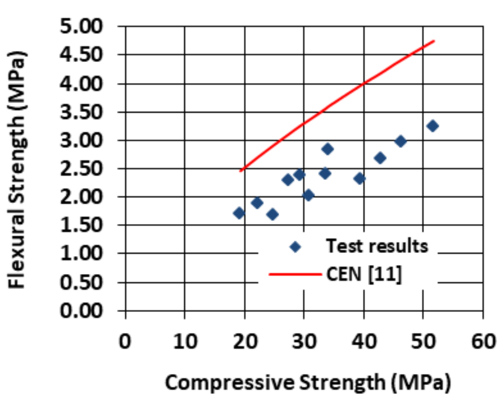

Fig. 13. Prediction of flexural strength based on provisions of the CEN-2002 [11]

4 Conclusions and Recommendations

The work presented here details the results of the investigation regarding the compressive, split-tensile and flexural tensile strengths carried out on concrete made using local materials in Botswana, namely Kgale crushed aggregates and BOTCHEM cement. In this study, an attempt has been made to ascertain the accuracy or otherwise of the split-tensile strength/compressive strength relationships, and the flexural tensile strength/compressive strength formulas proposed by several investigators and standards presented in the literature. Based on the present investigation, the following conclusions can be drawn.

Firstly, several of the popular prediction models used in estimating the split-tensile strength yield inaccurate results. More specifically, the predictions are generally unsafe for cylinder compressive strengths in the range 35 MPa to 50 MPa. The only relatively consistent model is that of Chen and Su [22] which yields conservative results for all levels of cylinder compressive strength namely 20 MPa to 50 MPa, considered in the present study.

In respect of the flexural tensile strength, all the predictive models recommended by rather well known standards and codes are consistently unsafe over the complete range of cylinder compressive strengths explored. There is strong evidence to suggest that the flexural tensile strengths of concretes are dependent to some extent on the type of cement as well as the aggregates used in their manufacture.

In view of the disparities noted in respect of practically all of the prediction models, it may be more prudent to explore alternative expressions or models to cater for concretes made from local materials like BOTCHEM cement and Kgale aggregates. For more fruitful and generalized results, such exercise should cover if possible, the complete range of compressive strengths of concrete that would be expected to be encountered in civil engineering design and construction practice.

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