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PREDICTION OF THE MECHANICAL CHARACTERISTICS OF CEMENT TREATED DEMOLITION WASTE FOR ROAD BASES AND SUBBASES

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Abstract

Because of environmental impacts (dumping of waste and lack of natural resources), recycling and reuse of construction and demolition waste (CDW) as road base materials have become important issues. Mixtures of recycled crushed concrete and crushed masonry can be used very well as unbound base materials but the feasibility of stabilizing CDW with cement needed to be investigated because this could result in a road base material with excellent performance. This paper presents the influence of four material variables (cement content, degree of compaction, the ratio of masonry to concrete by mass and curing time) on the mechanical properties of cement treated mix granulate mixtures made of recycled crushed masonry and crushed concrete aggregates (CTMiGr). The testing program included unconfined compressive strength and indirect tensile strength tests. From the compression tests also the static elastic modulus was obtained. Based on experimental results, a general model to estimate the mechanical properties of CTMiGr$_r$ has been established in relation to the above-mentioned material variables. This equation is very useful for the initial design of CTMiGr mixtures and for pavement design purposes. The research has shown that CTMiGr mixtures can be used very well as base and subbase material.

1. INTRODUCTION

In the Netherlands, a small country of 41000 km^2 and 16 million inhabitants, approximately 15 million tons of CDW is produced per year representing a volume of approximately 22 million m^3. Because of environmental reasons and lack of space it is not considered acceptable anymore to dump the waste. Therefore recycling has become very important and at the moment approximately 90% of all CDW is recycled and re-used in the Netherlands primarily as (sub)base material for roads. It has been shown (van Niekerk, 2002) that excellent performing base courses can be constructed in this way. However, in order to increase the re-usability of crushed concrete – crushed masonry mixtures, research have started into the applicability of cement treated CDW.

The required mechanical parameters for pavement design with a Cement Treated Granular Material (CTGM) layer are the stiffness modulus, the ultimate strength and the strain at ultimate strength. Current practice however is to use the unconfined compressive strength as the most important design parameter. In many cases the stiffness modulus and tensile strength are estimated from the unconfined compressive strength by means of regression equations. Current practice is to compose mixtures of varying composition with various amounts of cement and water in order to decide on the optimum mixture composition. This however is a time consuming procedure and therefore there is a need to predict the mechanical characteristics of such mixtures from composition parameters.

Research on asphalt concrete mixtures (Schönian, 1999) has shown that it is possible to relate fatigue characteristics and mixture stiffness to the characteristics of the bitumen and the volumetric mix composition. Similar relationships have been developed for the compressive strength of cement concrete mixtures (de Larrard, 1999). So in principle it should be possible to derive similar relationships to predict the mechanical characteristics of CTGM mixtures.

This research aims to obtain, through laboratory tests, basic mechanical properties (stiffness and strength) of cement treated mix granulates with recycled crushed masonry and crushed concrete aggregates (CTMiGr). The recycled crushed masonry and concrete aggregates are sourced from demolished buildings and structures in the Netherlands. The influence of the cement content, the degree of compaction, the masonry content and the curing time on the compressive strength, the elastic modulus and the indirect tensile strength have been explored. Furthermore models have been developed that allow the mechanical properties of CTMiGr to be predicted.

2. MATERIALS AND MIXTURE DESIGN

2.1 Materials.

Two different recycled aggregates, collected from two Dutch companies, were used in this study. One is recycled crushed concrete aggregates (RCA) and the other is recycled crushed masonry aggregates (RMA). Both recycled aggregates were divided into six fractions: 31.5-22.4 mm, 22.4-16.0 mm, 16.0-8.0 mm, 8.0-5.6 mm, 5.6-2.0 mm, <2.0 mm. Figure 1 shows aggregate particles of both materials with a size of 31.5 -22.4mm. EN 42.5 Portland cement and tap water were used to prepare the test specimens.

The aggregate gradation for the test mix granulates was designed using Equation 1:

$$P = F + (100 - F)\,(d^{n} - 0.063^{n}) / (D^{n} - 0.063^{n}) \qquad \text{(Eq. 1)}$$

Where:
P = percentage passing sieve size d [mm]
D = maximum particle size (31.5 mm in this study)
F = Filler content (F=2.24, close to the fines content (< 0.063 mm) in crushed concrete aggregates)
n = a parameter describing the shape of the grading curve (n=0.45 in this study)

(a) Crushed masonry (b) Crushed concrete

Figure 1. Crushed Masonry and Concrete Aggregates (Size 31.5 -22.4 mm).

2.2 Mixture Design.

Four material variables were selected to investigate their influence on the compressive strength, the stiffness and the indirect tensile strength of the CTMiGr mixture. They are:

- ratio of amount of masonry to concrete,
- cement content,
- degree of compaction, and
- curing time

Four ratios of masonry to concrete content by mass were chosen to prepare the test mixtures. They are 100%:0%, 65%:35%, 35%:65%, 0%:100%, respectively. Figure 2 shows cross sections of CTMiGr specimens with different masonry contents.

Figure 2. Cross Section of CTMiGr specimens (masonry content decreases from left to right).

The cement content (C) and the degree of compaction (DC) were designed by using the central composite design method in two factors for a given CTMiGr mixture (Robinson, 2000).

The cement content is based on the ratio of cement mass to the total mass of aggregates and varied from 2.5% to 5.5%. The degree of compaction refers to the One Point Proctor density and varied from 97% to 105%. The central point is 4% cement content and 101% degree of compaction. Figure 3 shows the central composite mixture design with those two variables and five levels.

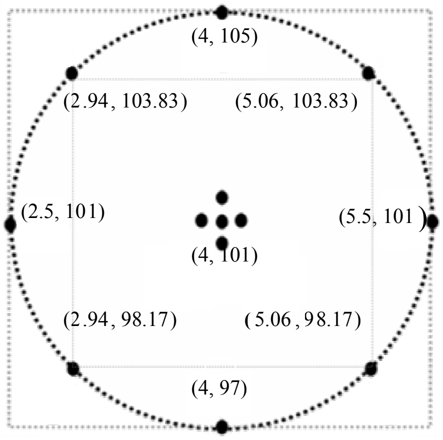

Figure 3. Central Composite Design for Cement Content and Degree of Compaction.

The influence of the curing time was taken into account for the mixtures at the central points. The corresponding mechanical properties of those specimens were tested at 7 days, 28 days and 90 days curing.

2.3 Determination of moisture content.

The water content is determined by the One Point Proctor test, Annex B of EN 13286-2. The degree of compaction for the mixture design is relative to the density obtained from the One Point Proctor test. The reason why the standard Proctor test was not adopted is that due to the porous nature of recycled aggregates, free water in the pore system (internal or in-between particles) can not be easily kept. As a result, the free water will flow away, which results in loss of cement paste in the mixture. The One Point Proctor test is done at a water content that ensures good workability for the CTMiGr mixture.

Table 1 lists the actual moisture content and dry density of CTMiGr after the One-Point-Proctor compaction. The proper water content is proportional to the masonry content, while the dry density decreases with increasing masonry content. Moreover, the moisture content of CTMiGr is over 9% to obtain a good workability. This value is higher than the optimum moisture content that is normally found for cement treated natural aggregates which ranges between 5% and 8% (Sherwood, 1995).

2.4 Mixture preparation

In the laboratory the CTMiGr mixtures were firstly mixed by using a laboratory mixer. The fresh mixture was then compacted in three layers in a mould Φ150×150 mm by using a vibrating hammer. After 24-hours curing at room temperature, all specimens were demolded and subjected to a fog-room curing at 20ºC. After a curing time of 7, 28 or 90 days, the specimens were ready for testing.

Table 1. Actual Moisture Content and Dry Density of CTM_iG_r after One-Point-Proctor Compaction

Ratio of RMA to RCA	Actual water (%)	Dry density (g/cm^3)	Appearance of fresh CTMG
100% : 0%	11.81	1.662	A little shinny; less bleeding
65% : 35%	10.94	1.754	
35% : 65%	10.44	1.834	
0% : 100%	9.54	1.907	

3. TEST METHODS

The unconfined compressive strength (UCS) tests, during which also the elastic modulus was determined, were performed using a 245 kN MTS actuator in the displacement controlled mode. The displacement rate was controlled by three linear variable differential transducers (LVDTs) in the axial direction of the specimen. A friction reduction system was used to minimize the shear stresses that develop between the specimen and the loading platens (Erkens, 2002). A strain rate of 10^{-5}/second was used in the UCS test. The force and the deformation were automatically recorded by a MP3 program. The elastic modulus is determined from the linear part of the stress-strain curve at the beginning of the test. Figure 4 (a) shows the experimental set-up.

The indirect tensile strength (ITS) was determined using a 150 kN MTS actuator in the displacement controlled mode. The set up is shown in Figure 4 (b). The axial displacement rate for the ITS test was 0.2 mm/second and controlled by two LVDTs. The data of force and deformation were automatically recorded by means of a Labview program.

(a) Compression test (b) Indirect tensile test

Figure 4. Compression and Indirect Tension Test Set-ups in the Laboratory.

4. TEST RESULTS AND DISCUSSION

4.1 Influence of cement content and degree of compaction.

Figure 5 shows the UCS, the elastic modulus and the indirect tensile strength of CTMiGr in relation to the cement/water ratio, the dry density and the masonry content. The dry density is related to the degree of compaction according to the mixture design in Table 1. One will observe that the UCS, the elastic modulus and the ITS increase with increasing ratio of cement (C)/water (W) and increase exponentially with increasing dry density or degree of compaction (D). The masonry content (M) influences the slope of the curves.

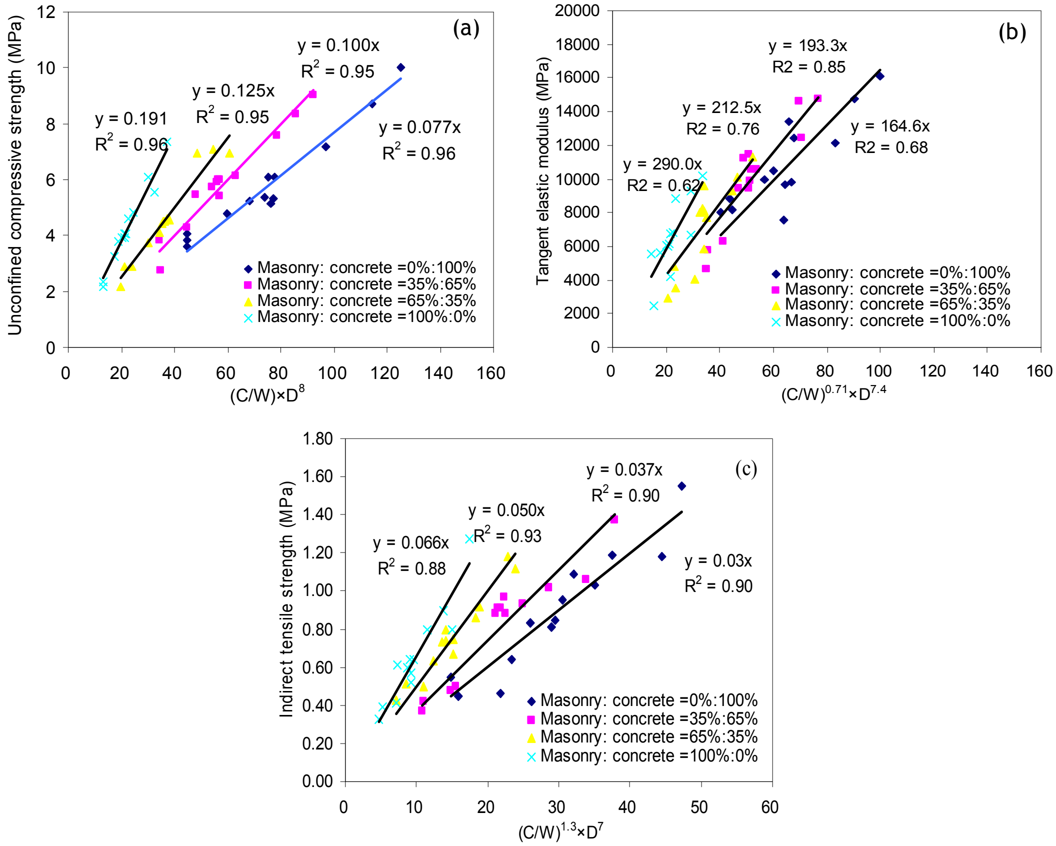

Figure 5. Influence of Cement content and Dry density on the Mechanical Properties of CTMG at 28 Days: (a) UCS; (b) Elastic Modulus; (c) ITS.

Regression equations 2, 3 and 4 represent the influence of the cement/water ratio and the dry density:

$f_c = a\,D^8\,(C/W)$ (Eq. 2)
$E_c = a\,D^{7.4}\,(C/W)^{0.71}$ (Eq. 3)
$f_{it} = a\,D^{7.0}\,(C/W)^{1.3}$ (Eq. 4)

Where: D = dry density [g/cm^3],
C = cement content by the whole mass of aggregates [%],
W = water content by the whole mass of aggregates [%],
a = parameter determined by the masonry content.

It is a well-known fact that the cement content and the degree of compaction of cement treated materials are important parameters to improve the cohesiveness and mechanical properties of cement-stabilized materials (Terrel e.a., 1979; Committee of State Road Authorities, 1986). The relationships obtained in this study indicate that it is more economic and efficient to achieve a high strength by good compaction rather than by trying to increase the cement content. A high density obtained by means of compaction is the best way to ensure long-term durability. This is also recognized by other researches (Sherwood, 1995).

4.2 Influence of masonry content.

Figure 5 shows that the slope of the relationships increases with increasing masonry content. Figure 6 shows the influence of the masonry content on the mechanical properties of CTM_iG_r. The regression models for the UCS, the elastic modulus and the ITS are:

$$f_c = 0.0747\,(C/W)\,D^{8}\,e^{0.0088M} \qquad \text{(Eq. 5)}$$

$$E_c = 161.3\,(C/W)^{0.71}\,D^{7.4}\,e^{0.0053M} \qquad \text{(Eq. 6)}$$

$$f_{it} = 0.0293\,(C/W)^{1.3}\,D^{7}\,e^{0.008M} \qquad \text{(Eq. 7)}$$

In these equations, M is the masonry content by mass of the total aggregates, %.

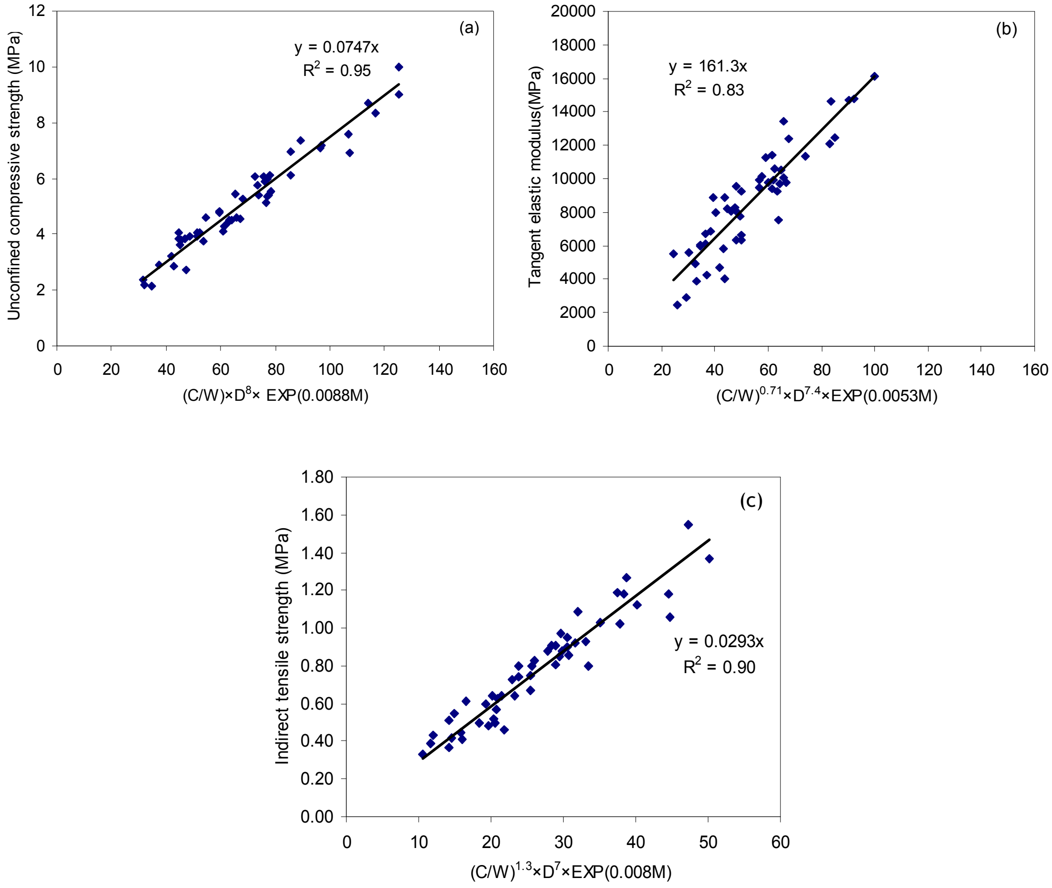

Figure 6. Influence of Masonry Content on (a) UCS; (b) Elastic Modulus; (c) ITS at 28 Days.

This study clearly shows that the masonry content is an important factor that influences the mechanical performance of CTMiGr. In practice, the masonry content in the recycled demolition waste is varying to some extent. The presented equations however allow taking this variation into account.

4.3 Influence of curing time

The curing time is another important factor that influences the development of the mechanical properties of cement treated materials. Several models like the ACI model have been reported by other researchers (Lim e.a., Terrel e.a., 1979; European Standard, 2004) and the curing model for CTMiGr is inspired by these models. Figure 7 shows the influence of the curing time on the mechanical properties of CTM$_i$G$_r$. Equations 8, 9 and 10 show the influence of curing time:

$$f_c = 0.0747 \cdot \frac{C}{W} \cdot D^{8} \cdot e^{0.0088 \cdot M} \cdot e^{(2.31 \cdot [1-(\frac{28}{t})^{0.1}])} \qquad \text{(Eq. 8)}$$

$$E_c = 161.3 \cdot (\frac{C}{W})^{0.71} \cdot D^{7.4} \cdot e^{0.0053 \cdot M} \cdot e^{(2.52 \cdot [1-(\frac{28}{t})^{0.1}])} \qquad \text{(Eq. 9)}$$

$$f_{it} = 0.0293 \cdot (\frac{C}{W})^{1.3} \cdot D^{7} \cdot e^{0.008 \cdot M} \cdot e^{(1.6 \cdot [1-(\frac{28}{t})^{0.2}])} \qquad \text{(Eq. 10)}$$

Where: t = curing time [days].

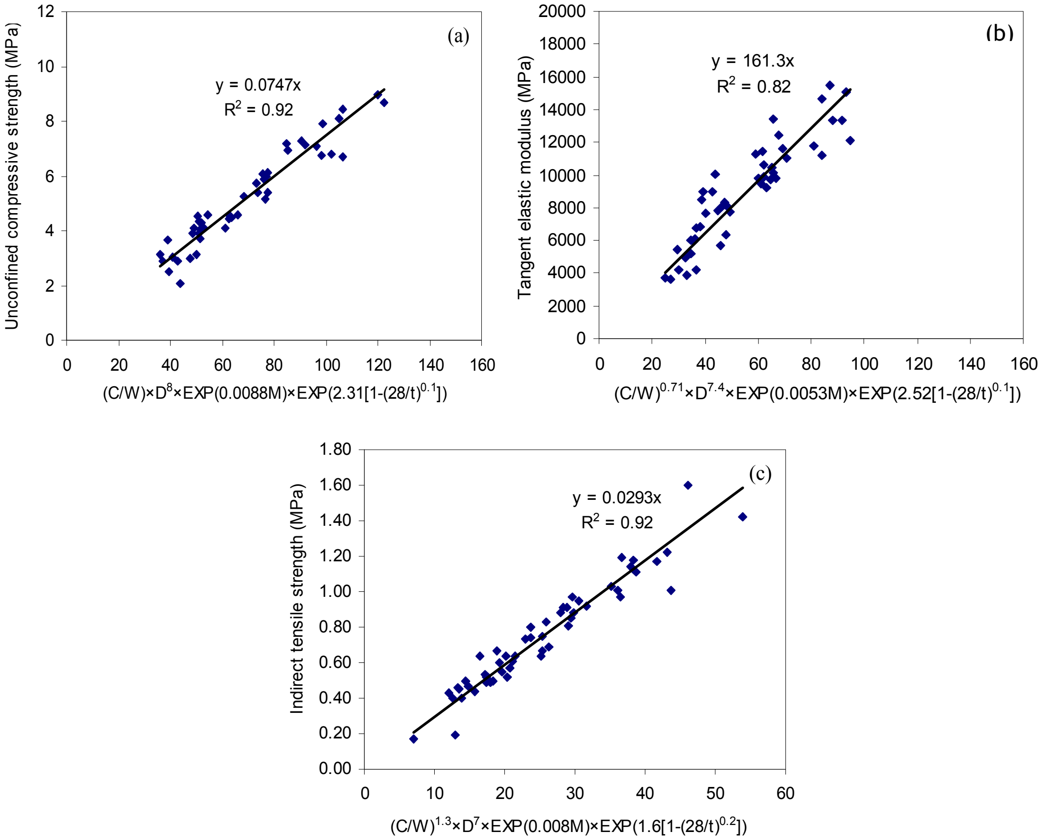

Figure 7. Influence of Curing Time on (a) UCS; (b) Elastic Modulus; (c) ITS.

A general estimation model for the mechanical properties of CTM_iG_r, which is based on the materials parameters, as established in this study can be written as:

$$f\ ,\ \ E\ = A\cdot\left(\frac{C}{W}\right)^{n1}\cdot D^{n2}\cdot e^{K_1\cdot M}\ \cdot e^{\left(S\cdot\left[1-\left(\frac{28}{t}\right)^{K_2}\right]\right)} \qquad \text{(Eq. 11)}$$

5. STRENGTH CRITERIA FOR CEMENT TREATED BASE/SUBBASE LAYERS

Different countries are using different specifications for the UCS of cement treated base and subbase materials. Table 2 lists the UCS requirements in three countries (Committee of State Road Authorities, 1986; Department of Transport, 1991; Technical Specifications China, 2000). The specifications require specimen preparation to be done with either modified proctor compaction or the standard one.

Table 2. Unconfined Compressive Strength Requirements of Cement Treated Granular Materials.

Country	Curing and preparation	UCS (MPa)			
		C1	C2	C3	C4
South Africa	7 days with 100% modified compaction	6-12	3-6	1.5-3	0.75-1.5
	7 days with 97% modified compaction	4-8	2-4	1-2	0.5-1
United Kingdom	7 days with 100% modified compaction	CBM1	CBM2	CBM3	CBM4
		2.5-4.5	4.5-7.5	6.5-10.0	10.0-15.0
China	7 days at 100% standard compaction	Highway or Primary Road		Secondary Road	
		Base	Sub-base	Base	Sub-base
		3.0-5.0	1.5-2.5	1.5-2.5	1.5-2.0

Note: 1) C1, C2, C3 and C4 are crushed stone or gravel designated in South African specification.
2) CBM1, CBM2, CBM 3 and CBM 4 are classified on basis of gradation in British specification

Criteria for the ITS have not been established yet, but investigations conducted in South Africa suggest the values shown in table 3 (Committee of State Road Authorities, 1986).

Table 3. South African Requirements for the ITS of Cement Treated Granular Materials.

Cemented material	Minimum ITS (MPa)
C3	0.20
C4	0.12

By means of eq. 8, eq. 10 and the data in Figure 7, UCS and ITS values have been estimated for different CTMiGr having different cement contents, masonry contents and degree of compaction. The estimated values are shown in table 4 and table 5. Both tables show that all three influence factors (masonry content, cement content and degree of compaction) are about equally important.

Table 4 and 5 also show that the strength requirements shown in table 2 and table 3, can be met even with 100% masonry in CTM_iG_r. Of course other criteria should also be taken into account such as effect of composition on shrinkage and retained strength after soaking.

Table 4. UCS after 7 days for CTM_iG_r with different Masonry Content (M), Cement Content (C) and Degree of Compaction (DC)

M (%)	DC (%)	UCS (MPa)		
		C =2.5%	C =4.0%	C =5.5%
100	97%	1.17	1.87	2.57
	101%	1.61	2.58	3.55
	105%	2.20	3.52	4.84
65	97%	1.43	2.28	3.14
	101%	1.97	3.15	4.33
	105%	2.69	4.30	5.91
35	97%	1.64	2.62	3.61
	101%	2.26	3.62	4.98
	105%	3.09	4.94	6.80
0	97%	1.80	2.88	3.96
	101%	2.49	3.98	5.48
	105%	3.40	5.43	7.47

Table 5. ITS after 7 days for CTM_iG_r with different Masonry Content (M), Cement Content (C) and Degree of Compaction (DC)

M (%)	DC (%)	ITS (MPa)		
		C =2.5%	C =4.0%	C =5.5%
100	97%	0.15	0.27	0.41
	101%	0.20	0.36	0.54
	105%	0.26	0.47	0.71
65	97%	0.18	0.33	0.50
	101%	0.24	0.44	0.66
	105%	0.31	0.57	0.87
35	97%	0.20	0.38	0.57
	101%	0.27	0.50	0.76
	105%	0.36	0.66	0.99
0	97%	0.23	0.42	0.64
	101%	0.30	0.56	0.84
	105%	0.40	0.73	1.11

6. CONCLUSIONS

The main findings and conclusions are summarized as follows:

1) The ratio of cement to water as well as the dry density or the degree of compaction influences the mechanical properties of CTMiGr. The masonry content in CTMiGr is another unique factor that determines the mechanical properties of CTMiGr.

2) A general model to estimate the mechanical properties (the compressive strength, the elastic modulus and the indirect tensile strength) of CTMiGr was developed. The model predicts the mechanical characteristics as a function of the ratio of cement to water, the masonry content, the degree of compaction and the curing time. Despite the natural variation in quality of the crushed masonry and concrete aggregates, the model has a good fit with the test results.

3) CTMiGr has good mechanical properties similar to those of cement treated natural aggregate materials.

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