In addition to the recycled aggregates, EN 42.5 Portland cement and tap water were used to prepare the test specimens.

2.2 MIXTURE DESIGN

Cement content and degree of compaction were selected as variables to prepare the CTM_iG_r mixtures. The mixture composite design was determined by using the central composite design method (Muraya 2007). Five levels were used for each variable. The cement content is based on the ratio of cement mass to the total mass of the aggregates and varied from 2.5% to 5.5%. The water content is determined by the One Point Proctor test, Annex B of EN 13286-2. The degree of compaction refers to the One Point Proctor density and varied from 97% to 105%. Figure 3 shows the mixture design method with two variables and five levels.

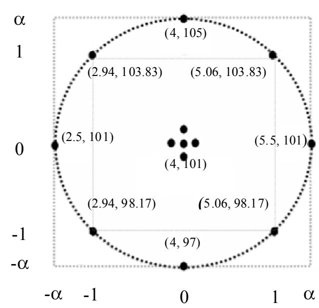


Figure 3. Coded test conditions in the central composite design.

2.3 MIXTURE PREPARATION

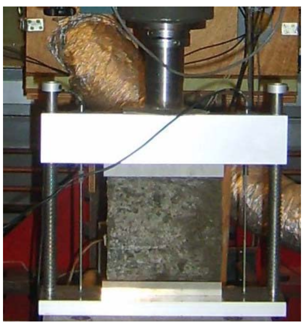
In the laboratory the CTM_iG_r mixture was firstly mixed by using a laboratory mixer. The fresh mixture obtained was compacted in three layers in the mould of Φ150×150 mm by using a Bosch vibrating hammer. The detailed compaction procedure is as follows:

- pour a specific mass of the fresh mixture in the mould of Φ150×150 mm, which was determined by the degree of compaction;
- distribute the material evenly to avoid the segregation;
- poke the fresh mixture a couple of times near the edge of the cylinder mould by using a screwdriver;
- pre-compact the mixture by using the hammer;
- compact each layer by the vibrating hammer (compacting time depends on the required degree of compaction);
- make the surface of the compacted layer rough by a screwdriver to ensure a good adhesion with the next layer;
- continue to finish three layers.

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 28 days, the specimens were ready for testing.

2.4 MEASUREMENT OF COMPRESSIVE STRENGTH AND INDIRECT TENSILE STRENGTH

The unconfined compressive strength (UCS) and indirect tensile strength (ITS) of the mixtures have been determined. The tests were done using a MTS actuator of 245 kN and 150 kN respectively in the displacement control mode. Displacements were controlled by linear variable differential transformers (LVDTs) along the axial deformation of the specimen. For UCS, a friction reduction system was used to obtain uniform radial deformations over the height of the specimen (Erkens 2002). The strain rate for UCS is 10^{-5}/second. The displacement rate chosen for ITS was 0.2 mm/second. The data of the force and the deformation are automatically recorded by a MP3 or Labview program. Figure 4 shows the experimental set-ups in the laboratory.



(a) Indirect tension test

(b) Unconfined compression test

Figure 4. Mechanical tests in the laboratory.

3. RESULTS AND DISCUSSION

3.1 MOISTURE-DRY DENSITY RELATIONSHIP

In accordance with the EN 13286-2 standard, CTM_iG_r with a cement content of 4% by mass was compacted in order to produce the conventional moisture-dry density curve. Figure 5 shows the moisture content-dry density curve of CTM_iG_r. It can be seen that when the masonry content decreases from 100% to 0%, the dry density of CTM_iG_r becomes higher. It means that the replacement of RMA by RCA results in an increase of the dry density of CTM_iG_r. This is attributed to the bigger density of RCA than that of RMA. Also note that in some cases, the maximum dry density of CTM_iG_r may be found, but the tendency is not obvious or the change of the dry density with the moisture content is very small as is shown by means of the two dashed lines. This proves that the optimum moisture content and maximum density can not be found or is not obvious for some materials in practice (Van Niekerk 2002; Molenaar 2005).

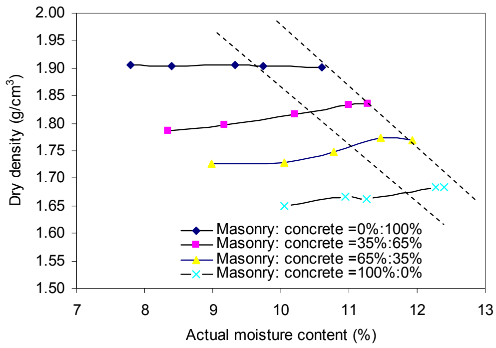


Figure 5. Moisture-dry density relationship of CTM_iG_r.

Meanwhile, it is found that when the masonry content increases, more water is needed to obtain a good workability. In this study, the cumulative water absorption of all fractions of masonry aggregates is approximately 10%. It was also observed that CTM_iG_r with RMA could not keep more water in the fresh mixture under the Proctor compaction when the water content is close to the optimum level. This is due to the porous nature of recycled aggregates, especially masonry. When adding more than 10%water, the 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 the loss of cement paste in the mixture as well. Because of these reasons, the reference density and moisture content in this study were determined by means of the standard One Point Proctor test according to Annex B of the European Standard EN 13286-2.

Table 1 lists the actual moisture content and dry density of CTM_iG_r after the One-Point-Proctor compaction. The moisture content of CTM_iG_r is over 9 % for a good workability. This value is higher than the normal optimum moisture content of cement treated natural aggregates (approximately between 5% and 8%) (Sherwood 1995).

Table 1. Actual moisture content and dry density of CTM_iG_r after the One-Point-Proctor compaction.

Ratio of RMA to RCA	Actual water (%)	Dry density (g/cm^3)	Appearance of fresh CTM_iG_r
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	

3.2 UNCONFINED COMPRESSIVE STRENGTH (UCS)

The UCS is a design index widely used to evaluate the performance of cement treated materials. Figure 6 shows the UCS of CTM_iG_r in relation to the cement/water ratio, the degree of compaction and the masonry content. The dry density is related to the degree of compaction according to the mixture design in Figure 3. One will observe that the UCS linearly increases with the ratio of cement (C)/water (W) and exponentially increases with the dry density or the degree of compaction (D). And, with the increase of the masonry content (M), the slopes of these curves increase as shown in Figure 6.

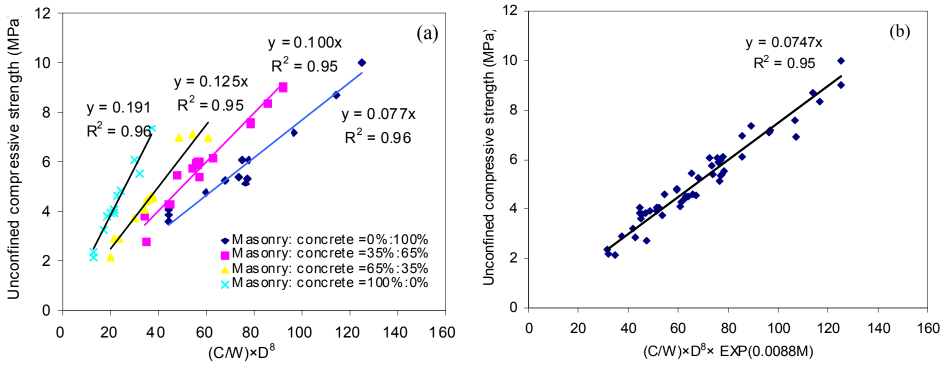


Figure 6. UCS of CTM_iG_r at 28 days.

Based on the experimental data, a model to estimate the compressive strength of CTM_iG_r has been developed:

$$f_c = 0.0747 \cdot \frac{C}{W} \cdot D^8 \cdot e^{0.0088 \cdot M} \quad (R^2 = 0.95, S=0.41 \text{ MPa}) \qquad (2)$$

Where, D is dry density, g/cm^3; C is the cement content by mass of aggregates, %; W is the water content by mass of aggregates, %; M is the masonry content by mass of the total aggregates, %. R^2 is the coefficient of determination; S is the standard deviation.

It is a well-known fact that the cement content and the degree of compaction of cement treated materials play important roles to improve the cohesiveness of cement-stabilized materials and their mechanical properties (Terrel et al 1979; TRH 13 1986; Williams 1986). It is more economic and efficient to achieve a high strength by good compaction rather than by trying to increase the cement content. The fact that a high density during compaction is the best way to ensure long-term durability is also recognized by others (Sherwood 1995). This study shows that the masonry content is another important factor to influence the mechanical performance of CTM_iG_r.

3.3 ELASTIC MODULUS (E)

The tangent elastic modulus is determined by the linear part of the stress-strain curve at the beginning of the compression test. Figure 7 shows the elastic modulus of CTM_iG_r related to material parameters. It is found that an estimation model for the elastic modulus of CTM_iG_r may also be established with the C/W ratio, the dry density and the masonry content.

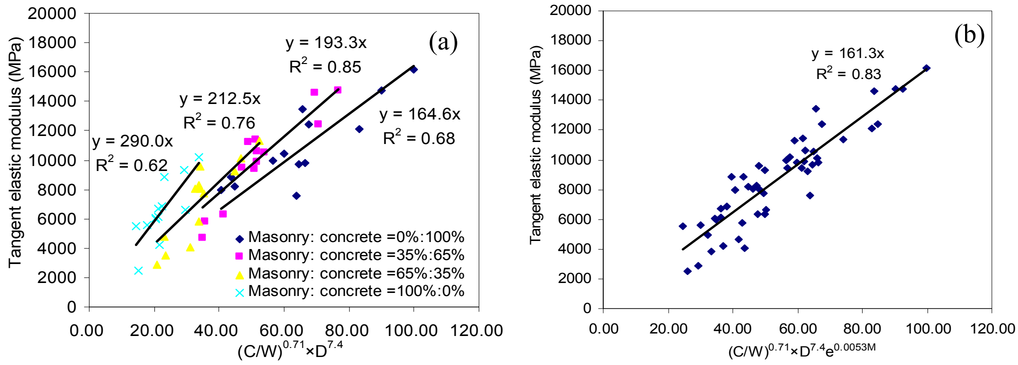


Figure 7. Tangent elastic modulus of CTM_iG_r at 28 days.

In previous researches, most of the prediction models for the elastic modulus are not related to material parameters, but to the compressive strength (Xuan 2009). However, as both strength and elastic modulus are controlled by the nature of the CTM_iG_r structure, an estimation model for the elastic modulus of CTM_iG_r may be established. In this study, it is given as:

$$E_{\tan gent} = 161.3 \cdot (\frac{C}{W})^{0.71} \cdot D^{7.4} \cdot e^{0.0053 \cdot M} \quad (R^2 = 0.83, \text{S=1317 MPa}) \quad (3)$$

3.4 INDIRECT TENSILE STRENGTH (ITS)

Figure 8 shows the influence of the C/W ratio, the dry density and the masonry content on the ITS of CTM_iG_r. A similar prediction model like that for the UCS (equation 2) can be derived. The ITS of CTM_iG_r is also proportional to the increase of the C/W ratio, the dry density and the masonry content. The dry density is the most important factor for the ITS.

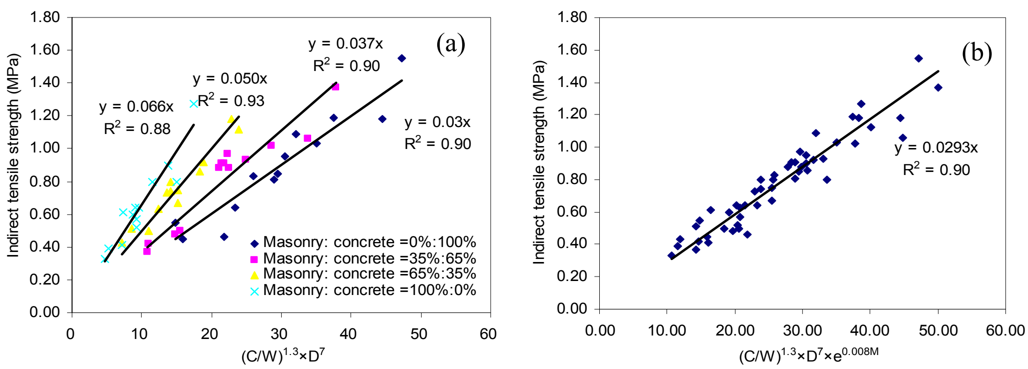


Figure 8. ITS of CTM_iG_r at 28 days.

So far the prediction models for the ITS of cement treated materials are mostly focused on the linear relationship with UCS (Williams 1986; Xuan 2009). Based on the experimental results in this research, the following estimation model for the ITS (f_{it}) of CTM_iG_r could be derived:

$$f_{it} = 0.0293 \cdot (\frac{C}{W})^{1.3} \cdot D^7 \cdot e^{0.008 \cdot M} \quad (R^2 = 0.90, S=0.09 \text{ MPa}) \quad (4)$$

4. CONCLUSIONS

This study was conducted to explore the mechanical properties of cement treated mix granulates with recycled crushed masonry and concrete aggregates from C&D waste. It has been found that the ratio of cement to water and dry density influence the mechanical properties of CTM_iG_r. The masonry content in CTM_iG_r is another unique factor to determine the mechanical properties of CTM_iG_r.

As both strength and elastic modulus are controlled by the nature of the CTM_iG_r structure, a prediction model for them may be put forward. On basis of the experimental results, this general prediction model and its parameters for strength and modulus at 28 days are listed in table 2.

Table 2. A model and its parameters for the strength and modulus of CTM_iG_r.

Model and Parameters	$A \cdot (\frac{C}{W})^{n1} \cdot D^{n2} \cdot e^{K \cdot M}$					
	A	n1	n2	K	R^2	S
f_c	0.0747	1	8	0.0088	0.95	0.41
f_{it}	0.0293	1.3	7	0.0080	0.90	0.09
E	161.3	0.71	7.4	0.0053	0.83	1317

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PERFORMANCE OF PRECAST CONCRETE PAVEMENTS

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ABSTRACT

Precast pavement technology is a new and innovative construction method that can be used to meet the need for rapid pavement repair and construction. Precast pavement systems are fabricated or assembled off-site, transported to the project site, and installed on a prepared foundation (existing pavement or re-graded foundation). The system components require minimal field curing time to achieve strength before opening to traffic. These systems are primarily used for rapid repair, rehabilitation, and reconstruction of asphalt and portland cement concrete (PCC) pavements in high-volume-traffic roadways. The precast technology can be used for intermittent repairs or full-scale, continuous rehabilitation. As part of the US Strategic Highway Research Program 2 (SHRP 2), a study (Project R05) is underway to develop tools for the design, construction, installation, maintenance, and evaluation of precast concrete pavements. As part of this study, testing was conducted to obtain field performance data from selected precast concrete pavement projects constructed throughout the US. This paper summarizes the field test data collected from intermittent repair projects as well as from continuous application projects and presents the findings of the data evaluation.

INTRODUCTION

Pavement rehabilitation and reconstruction, major activities for all U.S. highway agencies, have significant impact on agency resources and traffic disruptions because of extensive and extended lane closures. Traffic volumes on the primary highway system, especially in urban areas, have increased tremendously over the last 20 years, leading in many instances to an earlier-than-expected need to rehabilitate and reconstruct highway pavements. Pavement rehabilitation in urban areas is resulting in serious challenges for highway agencies because of construction-related traffic congestion and safety issues. A promising rehabilitation strategy is the effective use of precast concrete pavement systems, which provide for accelerated repair and rehabilitation of pavements and also result in durable, longer-lasting pavements. Precast concrete pavement systems are systems that are essentially fabricated or assembled off-site, transported to the project site and installed on a prepared foundation (existing pavement or re-graded foundation). These systems do not require field curing for the precast concrete panels and require only minimal time for system components to achieve strength before opening to traffic.

SHRP 2 Modular Pavement Study

The "Renewal" focus area of the US Strategic Highway Research Program 2 (SHRP 2) emphasizes the need to complete highway pavement projects rapidly, with minimal disruption to the users and local communities, and to produce pavements that are long-lasting. A goal of this focus area includes applying new methods and materials to preserve, rehabilitate, and reconstruct roadways. The effective use of precast concrete pavement technologies for rapid repair, rehabilitation, and reconstruction of pavements addresses this goal. One of the projects funded under SHRP 2 is Project R05, Modular Pavement Technology. The objective of this project is to develop tools for use by highway agencies to design, construct, install, maintain, and evaluate modular pavement systems.

The Phase I effort under Project R05 identified a serious lack of field performance data from installed precast concrete pavement systems. Because of this serious gap in available performance data, the project team contacted several highway agencies in the US to request support with the performance data collection effort, as part of Phase II effort under Project R05. This paper summarizes the field test data collected to date from several precast concrete pavement projects and presents the findings of the data evaluation.

BACKGROUND

The precast concrete pavement technology is gaining wider acceptance by North American highway agencies and contractors and precasters are beginning to seriously explore business opportunities related to precast concrete pavement applications. The precast concrete pavement technology is generally based on sound technical/engineering considerations and field installation processes appear to be workable given the severe working conditions for many of these projects. The application of precast concrete pavement technology can be classified as follows:

1. Intermittent repairs of concrete pavements - isolated full-depth repairs or isolated full slab replacement using precast concrete slab panels
2. Continuous concrete paving - full-scale project level rehabilitation (resurfacing) or reconstruction of asphalt and concrete pavements is performed using precast concrete panels.

Precast Pavement Systems

Several recently developed techniques are available in the US, as follows:

1. Precast prestressed concrete pavement (PPCP) developed at the University of Texas
2. Jointed precast concrete pavement, proprietary and generic systems:
    a. Fort Miller Super-Slab system (proprietary)

b. Kwik Slab system (proprietary)
c. Roman Stone system (proprietary)
d. Michigan system (generic)
e. Illinois Tollway system (generic)
f. La Guardia International Airport system (generic)

Discussion of the various systems and techniques is given elsewhere (Tayabji et al., 2009; Hall and Tayabji, 2008; Merritt and Tayabji, 2009).

Precast Pavement Use in the US

Since about 2000, many highway agencies in North America have expressed interest in considering use of precast concrete for intermittent repair or continuous applications in heavily trafficked urban areas where extended lane closures are difficult. The following U.S. and Canadian highway agencies have accepted the use of precast pavement for production work:

1. Caltrans
2. Illinois Tollway Authority
3. Iowa DOT (as an alternate for bridge approach slabs)
4. Ministry of Transport, Ontario
5. Ministry of Transport, Quebec
6. New Jersey DOT
7. New York State DOT
8. New York State Thruway Authority

The following U.S. agencies have investigated or are investigating use of precast pavement:

1. Colorado DOT
2. Delaware DOT
3. Florida DOT (demonstration project planned for construction, 2010)
4. Hawaiian Agencies
5. Indiana DOT
6. Michigan DOT
7. Minnesota DOT
8. Missouri DOT
9. Texas DOT
10. Virginia DOT
11. Airport Authorities
    a. Port Authority of New York and New Jersey
    b. Metropolitan Washington Airport Authority
12. US Air Force

In addition to the North American initiatives, the Netherlands, France, Russia, and Japan are actively investigating or are using the precast concrete pavement