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Title:

Investigation on the Use of Crumb Rubber Concrete (CRC) for Rigid Pavements

By:

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Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Iman Mohammadi

June 2014

Abstract

In many countries around the world, the adverse environmental impacts of stockpiling waste tyres have led to investigate alternative options for disposal of waste tyres. One option to reduce this environmental concern is for the construction industry to consume a high amount of recycled tyres accumulated in stockpiles.

There are different concerns regarding the introduction of rubber into concrete, which were addressed by previous studies. On the one hand, making a homogenous mix containing even distribution of rubber is a challenge. On the other hand, the severe reduction of concrete strength limits the rubber content. Moreover, replacing a portion of fine aggregates with low-stiffness rubber particles raises concerns regarding the generated shrinkage and cracking of rubberised concrete. This thesis investigates these concerns thoroughly and provides a comprehensive know-how of rubberised concrete characteristics, using crumb rubber.

In order to improve the strength of rubberised concrete different rubber treatment has been introduced by previous studies. A commonly applied rubber treatment method in the literature termed sodium hydroxide (NaOH) treatment has been assessed in this study. Numerous investigations examined using sodium hydroxide treatment of rubber. However, the level of improvement provided by different studies was not consistent. It was found that the sodium hydroxide treatment method is required to be optimised to achieve the most promising results. Two arrays of concrete specimens were prepared using different water cement ratios and a wide range of rubber contents. Then, the common fresh and hardened mechanical tests were conducted on the prepared samples. The results indicated that the duration of rubber treatment should be optimised based on concentration of the alkali solution and the type of recycled rubber. Consequently, the 24-hour treatment duration for crumb rubber resulted in the most suitable fresh and hardened concrete characteristics. Compared to untreated rubberised concrete, rubberised concrete produced with the optimised sodium hydroxide treated rubber, showed 25% and 5% higher compressive and flexural strength, respectively.

Based on a large number of tests, this research introduced a relationship between the strength of rubberised concrete and three key parameters including the water-cement

ratio (WC), the concrete age and the rubber content. Using this relationship enables concrete producers to have an accurate estimate of rubberised concrete strength.

In addition, this research investigated the effects of applying an innovative method of rubber treatment, named "water-soaking". Unlike the current methods of adding rubber into a concrete mix, which are conducted in a dry process, this research trialled introducing of rubber particles into the concrete mix in a wet process. Conducting the required sets of fresh and hardened concrete tests, number of mix series with a variety of rubber contents and water-cement ratios were evaluated. In order to measure the effectiveness of the introduced method, the properties of concrete containing water soaked rubber were compared with concrete containing untreated rubber. It was revealed that applying the proposed method resulted in considerable improvement of fresh and hardened properties. Applying the water-soaked method resulted in 22% higher compressive strength, and the formation of stronger bonds between rubber particles and cement paste compared to concrete made with untreated rubber.

The effects of using recycled tyre rubber on shrinkage properties of rubberised concrete were evaluated. It was observed that adding rubber into a concrete mix led to minimise shrinkage cracks, if only an optimised content of rubber was applied. Therefore, the optimised rubber content was determined based on the mix design properties, the early-age tensile strength, and the results of plastic and drying shrinkage tests. Accordingly, the early-age mechanical strength tests, toughness test, bleeding test, and the plastic and drying shrinkage tests were conducted. A semi-automated image processing method of crack analysis was introduced in this research. Average cracks width, length, and area were determined accurately by applying the introduced method. In addition, the experimental data resulted from drying shrinkage tests of rubberised concrete were crosschecked with the results of numerical shrinkage formula provided in the Australian Standard AS3600. It was found that the provided relationship in the Australian Standard AS3600 is a valid measure for estimating the drying shrinkage of rubberised concrete.

By considering the shrinkage characteristic and the acceptable mechanical performance of rubberised concrete, this dissertation concludes that the most promising results could be achieved for samples prepared with water-cement ratios of 0.45 and 0.40, and rubber contents of 20% and 25%, respectively.

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Finally, I wish to express my deep gratitude to my family for their support and encouragement.

LIST of Publications

During the course of this research, a number of publications have been made which are based on the work presented in this thesis. They are listed here for reference.

Mohammadi, I & Khabbaz, H 2013, "Challenges Associated with Optimisation of Blending, Mixing and Compaction Temperature for Asphalt Mixture Modified with Crumb Rubber Modifier (CRM)", Journal of Applied Mechanics and Materials, Vol. 256, pp. 1837-1844

Mohammadi, I, Khabbaz, H & Vessalas, K 2014, "In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements", Journal of Construction and Building Materials, Vol. 71, pp. 456-471

"Enhancing Mechanical Performance of Rubberised Concrete Pavements with Sodium Hydroxide Treatment" is submitted to the journal of "Materials and Structures (MAAS)"

"Shrinkage Performance of Crumb Rubber Concrete (CRC) Prepared by Water-Soaking Treatment Method for Rigid Pavements" is submitted to the journal of "Cement and Concrete Composites"

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List of Notations and Symbols

The symbols used in this report, including their definitions, are listed below:

Air Content	*AC*
Air Entraining Admixture	*AEA*
Gross Cross-Sectional Area of a Concrete Element	A_g
Untreated Rubber	*ARR*
Cement Concrete & Aggregates Australia	*CCAA*
Compacting Factor	*CF*
Crumb Rubber	*CR*
Crumb Rubber Concrete	*CRC*
Crack Reducing Ratio	*CRR*
Calcium Silicate Hydrate	*C-S-H*
Concrete Modulus of Elasticity	E_c
Characteristic Compressive Strength	f'_c
Characteristic Compressive Strength at 28 days	$f'_{c,28}$
Mean Compressive Strength of Concrete	f_{cm}
Mean Compressive Strength at Age of t	$f_{cm.t}$
Flexural Stress	f_{ctf}
Flexural Stress up to Net Deflection of L/150	$f^D_{T,150}$
Flexural Stress up to Net Deflection of L/600	$f^D_{T,600}$
Flexural Strength	f_P
Fibre Reinforced Concrete	*FRC*
Tensile Strength	f_t
Interfacial Transition Zone	*ITZ*
Linear Variable Differential Transducers	*LVDT*
Modulus of Elasticity	*MOE*
Modulus of Rupture	*MOR*
Mass per Unit Volume	*MPV*
Sodium Hydroxide	*NaOH*
Capillary Pressure	P_c
Peak Flexural Tensile Strength up to Net Deflection of L/150	P^D_{150}

Peak Flexural Tensile Strength up to Net Deflection of L/600	P^{D}_{600}
Peak Flexural Tensile Strength	P_P
Rubber Content	R
Radius of Menisci	r
Equivalent Flexural Strength Ratio up to a Net Deflection of L/150	$R^{D}_{T,150}$
Equivalent Flexural Strength Ratio up to a Net Deflection of L/600	$R^{D}_{T,600}$
Relative Humidity	RH
Styrene Butadiene Rubber	SBR
Specific Gravity	SG
Shrinkage Limited	SL
Stress Reduction Factor	SRF
Surface saturated Dry	SSD
Air Temperature	T_a
Concrete Temperature	T_c
Area Under the Load-Deflection Curve up to a Net Deflection of L/150	T^{D}_{150}
Area Under the Load-Deflection Curve up to a Net Deflection of L/600	T^{D}_{600}
Hypothetical Thickness of a Member	t_h
Exposed Perimeter of a Member	u_e
Water-Cement Ratio	WC
Water Reducer	WR
Surface Tension of Water	γ
Mid-Span Deflection	δ
Final Basic Drying Shrinkage Strain	ε^*_{csdb}
Final Autogenous Shrinkage	ε^*_{cse}
Shrinkage Strain of Concrete	ε_{cs}
Drying Shrinkage Strain	ε_{csd}
Chemical (autogenous) Shrinkage Strain	ε_{cse}
Shrinkage Strain	ε_s
Normal Compressive Stress	σ_{nom}
Tensile Stress	σ_t