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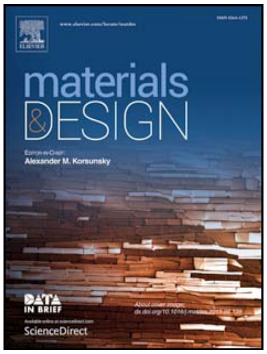

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Effect of cementation level on performance of rubberized cement-stabilized aggregate mixtures

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Abstract

An investigation and comparison is made of the effect of cement content on the performance of rubberized cement-stabilized aggregate mixtures and on cement-stabilized aggregate mixtures containing no rubber (RCSAMs and CSAMs). These materials are intended to be used as a base course for pavement structures. Three cement contents (3%, 5%, and 7% by dry weight of aggregate) were investigated. Rubberized mixtures were manufactured by replacing 30% of one aggregate fraction that has a similar gradation of crumb rubber. Performance was evaluated under static and dynamic testing. The investigated properties are unconfined compressive strength, indirect tensile strength, indirect tensile static modulus, toughness, dynamic modulus of elasticity, dynamic modulus of rigidity and dynamic Poisson's ratio. Increasing cement content increases strength of both types of mixtures, especially in the CSAMs. It is found that using crumb rubber at low cement content is more feasible than with high cement contents. Stiffnesses increased for both types of mixture as cement content increased but decreased on incorporation of crumb rubber. Energy absorption capacity was inversely related to stiffness. Mesostructural investigation revealed that the cracks were propagated through the rubber particles for all cement contents.

Keywords: Cement-stabilized aggregate; unconfined compressive strength; indirect tensile testing; rubberized cement-stabilized mixture; resonant frequency; static modulus of elasticity.

1. Introduction

Due to the expansion of the modern world, the number of waste tires stockpiled every year is increasing alarmingly. This has negative impact on both humans and the environment since these stockpiles can harbour vermin and represent possible combustion sites (Zheng et al. 2008). Over thirty years ago, different investigations have been conducted to evaluate the possibility of using rubber from waste tires as an aggregate in concrete mixtures. This would help protect the environment by reducing disposal impacts and save costs since using these tires as a replacement of aggregate will save natural resources. Researchers (Khatib and Bayomy 1999; Güneyisi et al. 2004; Papakonstantinou and Tobolski 2006; Balaha et al. 2007; Zheng et al. 2007; Khaloo et al. 2008; Taha et al. 2008; Zheng et al. 2008; Topçu and Bilir 2009; Nguyen et al. 2010; Pelisser et al. 2011; Najim and Hall 2012; Eiras et al. 2014) have studied the use of waste tire materials in different types of concrete mixtures as an aggregate replacement in the form of fine, coarse or fine and coarse fractions simultaneously. The results of their assessment indicated, in general, a reduction in mechanical properties, improvement in the energy absorption capacity, reduction in stiffness and enhancement in impact toughness. The degree of decline or improvement of the mentioned properties was different depending on the size of rubber and whether coarse or fine fractions or both were replaced. Based on their findings and justifications, others (Güneyisi et al. 2004; Pelisser et al. 2011; Najim and Hall 2013) attempted treating the rubber particles with sodium hydroxide or using silica fume to enhance their interaction with the other constituents of the mixtures. Their investigations claimed better performance because these treatments improved the bond between rubber and the surrounding cement matrix.

However, very little has been documented about the effect of cement content on the performance of the mixtures in which rubber particles were used. In addition, limited research was found in the literature regarding use of crumb rubber in cement stabilized mixtures typically used as a base course or subbase course in the pavement structure in spite of a long history of investigation for these waste materials in civil engineering applications. These layers' potential to consume large quantities of natural resources as compared with other civil engineering applications (Cao 2007; Barišić et al. 2014). To fill these gaps in the literature, the authors investigated the effect of cement content on the performance of cement-bound aggregate mixtures (CSAMs) and rubberized cement-bound aggregate mixtures (RCSAMs).

This paper reports this investigation and develops an understanding of the interaction between cement and rubber i.e., investigating of the effect of the relative stiffness of the rubber and the surrounding matrix on the overall performance of the mixture. This, in turn, can be considered as an exploratory step for studying the effect of other sizes and proportions of rubber so as to validate its use in a more sustainable "green" pavement structure.

2. Cement-stabilized materials

Cement-stabilized mixtures are normally used as base or subbases course within pavement structures so as to improve the structural capacity of pavement structure in terms of strength and stiffness. (Lim and Zollinger 2003) described cement-stabilized mixtures as a mixture of aggregate and Portland cement moisturized with small quantities of water for compaction and cement hydration purposes. Additionally, the Portland Concrete Association (PCA 2005) has classified cementitious materials into four types depending on their water and cement contents. Roller-compacted concrete and normal concrete are the mixtures in which high cement levels are normally used. However, the method of construction is different due to low water content in the first type as compared with the latter. Flowable fill and cement stabilized materials, on the other hand, have low cement contents but different water content.

3. Objectives and motivations

The motivation of this research is to understand the behaviour of cement-stabilized aggregate modified with crumb rubber extracted from post-consumer tires under different degrees of stabilization. This will help to make beneficial reuse of the tire rubber which, in turn, may ensure conservation of natural resources as well as reducing the environmental problems of disposal. Another motivation is to achieve cement-stabilization of granular materials that have less sensitivity to cracking than the stiff mixtures conventionally obtained, thereby reducing fatigue failure (Wu et al. 2015). Furthermore, reflection cracks in overlying pavement layers may be reduced. So, studying how the cement may affect the performance of rubberized mixtures might lead to improve stabilized aggregates from economic and practice points of view. Thus, the purpose of this paper is to study the effect of cement content on the properties of rubberized cement stabilized mixtures, mainly in terms of tensile performance, and to compare this with conventional stabilized mixtures. It also seeks to develop an understanding of the mechanisms of their failure. Tensile performance was selected because the stabilized pavement layers are normally designed based on critical tensile stress at their bottom. Limited information, even for rubberized concrete, could be found regarding the investigation of the mesostructure, of the failed samples to reveal how the cracks propagated

4. Experimental methodology

4.1 Materials

In this study, a crushed limestone aggregate with maximum size of 20 mm was used. This was collected, dried and stored at different fraction sizes (i.e., 20mm, 14mm, 10mm, 6mm and less than 6mm (dust)). The gradations of both natural aggregate and crumb rubber were performed based on BS EN 933-1:2012.The gradation of the different fraction sizes is presented in Figure 1. The physical properties of the crumb rubber are shown in Table 1.There were insignificant quantities of tire-derived steel or textile in the rubber, these having been removed by the processing. Portland cement CEM I 52.5 N confirming to BS EN 197-1:200 was used to stabilize the aggregate mixtures. Tap water was used to hydrate the mixtures.

4.2 Mixture design

Different aggregate fractions were combined together in different proportions in order to secure the [CBGM2-0/20] gradation as stated in BS EN 14227-1:2013 and hence to eliminate any variability in aggregate gradation. This was necessary so as to produce comparable mixtures due to the high dependency of strength on mixture density (Williams 1986) which is governed, to large extent, by the aggregate gradation. The proportions used were 11%, 20%, 11%, 13% and 45% for 20mm, 14mm, 10mm, 6mm and dust, respectively. The final gradation after blending the above five sizes is illustrated in Figure 2 with appropriate specification limits.

Three cement contents were used in this investigation. These are 3%, 5% and 7% of the dry weight of aggregate. These were selected based on previous studies (Thompson 2001). ((Drnevich et al. 2007) and (Chilukwa 2013) recommend vibratory compaction for granular material as the method most simulative of field compaction. Consequently, the optimum water content for each aggregate-cement mixture was estimated in accordance with BS EN 13286-4:2003 utilizing the vibratory compaction procedure. The optimum water content for each cement content is shown in Table 2. Given the small volume of rubber in overall mixture and the low water absorption of both rubber and natural aggregate, difference in water absorbability after natural aggregate replacement make no significant difference to water demand for compaction or cement hydration.

Cement-bound aggregate mixtures have a similarity with normal concrete where both of them are cementitious materials and also a similarity with asphaltic mixtures since both of them are compacted mixtures. Consequently, it was decided to try a small amount of rubber replacement as used in asphaltic mixtures (Hassan 2012) to avoid affecting compaction characteristics. To constitute the rubberized mixtures, 30% of the 6 mm fraction size was replaced by the same volumetric percentage. This size was selected due to the similarity between the gradations of crumb rubber and the 6 mm fraction size which, in turn, should secure the same packing skeleton. Owing to the considerable differences between specific gravities of natural aggregate and crumb rubber, proportioning on a weight basis was ruled out. To do so would add a significantly extra volume of 6 mm size particles, meaning that the packing in the CSAMs and RCSAMs were no longer comparable. Cement is normally added by the dry weight of aggregate but this would reduce after replacing the natural aggregate by the same volume of crumb rubber due to the low specific gravity of the latter. Similarly, the water required for compaction would also reduce, since this is normally expressed as a percentage of the weight of aggregate and cement. Accordingly, volumetric proportioning of rubber, water and cement was practiced for the rubberized mixtures. Thus, volumetric proportions were kept constant, as used in the control mixture. The easiest way to do so is to keep the quantities (per unit volume of mix) of water and cement in the rubberized mixtures the same as to that used in their corresponding reference mixtures.

Different mixtures are designated by two letters, to indicate cement and rubber, and each one is followed by a number to indicate corresponding percentage. For example, C7R30 describes a mixture stabilized with 7% cement and with a rubber replacement level of 30%.

4.3 Samples preparation and curing

The mixing process was performed as follows: dry granular material, with particle size of less than 6 mm, was mixed with cement first until, subjectively, a uniform colour was achieved. This was added to the rest of aggregate (including the crumbed rubber in those mixtures so designated) and mixed thoroughly for one minute. Then, followed adding the designed water content, a further two minutes of mixing was conducted.

Two different samples sizes were used: 100 mm x 100 mm cylindrical sample and prisms of 100mm x 100mm x 500mm dimensions, manufactured in split steel moulds and standard prismatic steel moulds, respectively. On completion of mixing, the mixture was compacted in three layers inside the lubricated moulds using a vibrating hammer. In accordance with BS EN 13286-51:2004, the compaction time was 60s per layer. Initial investigations revealed difficulty in achieving smooth and level surfaces, which are necessary for testing and fixing instrumentation. To deal with this problem, samples were manufactured in such a way as to achieve a slightly greater height which was then trimmed by saw to obtain the required dimensions. For prismatic moulds, a removable mould extension was fabricated in order to manufacture prisms of higher than 100 mm. Three samples were manufactured for each mix. Once the compaction was completed, samples inside their moulds were covered with wet paper and polythene sheets to prevent moisture loss. After 24 hours, the specimens were demoulded and wrapped with nylon film and placed in wet polythene bags and closed tightly and cured in the humid room at 20° C and relative humidity of 90% for 28 days.

4.4 Procedures and analysis approach

4.4.1 Unconfined compressive strength and indirect tensile strength

Although cement-stabilized base courses within pavement structure are normally designed based on tensile stress at the bottom of this layer, unconfined compressive strength (UCS) is one of the widely adopted methods to characterize cement-stabilized mixtures due to its simplicity and their established correlations with other properties (Piratheepan et al. 2009; Jitsangiam and Nikraz 2011). Moreover, this test has been adopted by European specification BS EN 14227-1:2013 as one of the primary means by which to classify cement-bound mixtures. In this study, the test was conducted in accordance with BS EN 13268-41:2003 using a 2500 KN testing machine. Three cylindrical samples of dimensions 100 mm dia. x 100 mm height were manufactured based on BS EN 13286-51:2004. The Indirect Tensile

Strength (ITS) was performed in accordance with BS EN 13286-42:2003. A 200 KN capacity Instron universal testing machine was used. ITS, in MPa, was estimated using the following equation:

$$ITS = \frac{2P}{\pi \mathrm{hD}} \tag{1}$$

Where P is the ultimate load (N), h is the sample thickness (mm) and D is the diameter of the sample (mm). To study the effects of curing age on both UCS and ITS, both tests were conducted at 7, 28 and 365 days.

4.4.2 Static modulus of elasticity

The modulus of elasticity, E, was determined in parallel with the ITS test at 28 days. In order to obtain load-deformation relationships and hence estimate the static modulus of elasticity, two linear variable differential transducers (LVDTs) were glued on both sides of samples to measure the lateral deformation. These were mounted using manufactured LVDT blocks. The test set-up is depicted in Figure 3. Each test was conducted under deformation control of 0.5 mm/min. Due to low strain levels developed in cement-stabilized mixtures during the test, accurate instrumentation is recommended by (Scullion et al. 2008). So a gluing jig was manufactured and used as reported by (Wen et al. 2014) to ensure accurate alignment of LVDTs blocks on both faces of the sample as shown in the latter figure. The readings from the two LVDTs were averaged to represent lateral displacement for each load application. The static elastic modulus was estimated from load-deformation relationships based on 30% of the maximum load and corresponding lateral displacement according to BS EN 13286-43:2003. However, because of the difference between LVDT arrangements (gauge distance) employed compared to the arrangement specified in BS EN 13286-43:2003, the formula recommended by (Solanki and Zaman 2013), as shown in Equation below, was used in lieu of the equation provided in the specification.

$$E_{it} = \frac{2P}{\pi . D . t . \Delta H_T (D^2 + D_g^2)} \left\{ (3 + \upsilon) D^2 . D_g + (1 - \upsilon) \left[D_g^3 - 2D\left(D^2 + D_g^2\right) tan^{-1} \left(\frac{D_g}{D} \right) \right] \right\} \quad (2)$$

Where E_{it}= indirect tensile static modulus of elasticity, P= 30% of ultimate load; D=diameter of sample; t= sample thickness; ΔH_T=lateral deformation corresponding to 30% of ultimate load; D_g=LVDT gauge distance and υ = Poisson's ratio.

4.4.3 Load-deformation relationships and toughness

To evaluate the post-peak bearing capacity, energy absorption capacity or toughness of the mixture, the area under the load-deformation curve was calculated. The estimation of toughness in this manner may include the improvement in strength and ductility due to rubber incorporation as stated by (Sobhan and Mashnad 2000). However, as a result of rubber inclusion, a reduction in the mixture strength is expected which makes it necessary to normalize the tensile load relative to its ultimate value so as to evaluate the toughness improvement due to enhanced stress at break. This is also logical since, in mechanistic pavement design, the stress is usually normalized and the stress ratio is principally used in the appropriate transfer function to calculate the number of permissible load applications. The methodology used by (Huang et al. 2005; Modarres 2013) was adopted to calculate toughness indices from the indirect tensile normalized load-deformation curves as follows

$$\text{Toughness index} = \frac{\mathrm{A_D - A_p}}{\mathrm{D - D_p}} \quad (3)$$

where A_D and A_p is area under normalized load-deformation curve up to a specific deformation (D) and deformation at peak load (D_p), respectively. D and D_p are the specific deformation at which the toughness index was calculated and the deformation at peak load, respectively. The former deformation is larger than the latter one. For comparable results, toughness indices for all mixtures were calculated at same deformation (Huang et al. 2005). This was 1.2 mm which was selected on the basis that all mixtures reached this deformation value after their failure and hence permit to compare between load-carrying capacities after failure. However, the C7R0 showed a very slight defamation after failure i.e., much less than 1.2 mm which make it incomparable with other mixture and considered as a brittle mixture.

4.4.4 Dynamic properties through resonant frequency testing

Dynamic modulus of elasticity, measured by resonant frequency, can be used for pavement analysis and design (Nunn 2004; Lav et al. 2006). Dynamic properties were measured nondestructively in accordance with (ASTM C215-02) using a resonant frequency tester. In this investigation, dynamic properties were evaluated in terms of dynamic modulus of elasticity (E_d), dynamic modulus of rigidity (G_d) and dynamic Poison's ratio (υ_d). In this test, the sample was supported at its centre on the equipment bench and clamped using the available clamping arrangement. Depending on the property to be measured, the driver and pick up parts were placed at different locations. Dynamic modulus of elasticity and dynamic modulus of rigidity are measured repeatedly then the dynamic Poisson's ratio is computed from these two moduli. Using the manufacturer's recommended frequency range and starting from a low frequency, frequency was increased gradually until the output meter showed the maximum value which indicates the fundamental resonant frequency of the mixture. Based on this frequency, dynamic modulus of elasticity (E_d) and dynamic modulus of rigidity (G_d) were computed. The dynamic Poisson's ratio (ν_d) was estimated as:

$$\nu_d = \frac{E_d}{2G_d} - 1 \tag{4}$$

4.5 Failure patterns

In an attempt to understand how the cement content affects the failure mechanism and to provide some explanation of the macroscale behaviour, the internal structure at mesoscale level of a failed ITS samples was scanned utilizing an X-ray CT machine with a mini focus system of a 300 kV X-ray source and a linear detector. Two scans were performed for each sample at the top and bottom of the middle third of sample. The resolution of the current scan is 0.065 mm/pixel.

5. Findings and discussion

5.1 Effect of cement content on UCS and ITS

Figure 4 illustrates the effect of cement, rubber and time on the UCS of the investigated mixtures. As can be seen from that figure, the general trend is an increase in UCS value as cement content increase which is expected since cement will increase the strength of material's matrix and the bond between particles due to increase in the hydration products. In addition, there was an improvement in this parameter with curing time, since hydration is a time-dependent process. The development rate of UCS, in general, is proportional to the amount of cement because the more cement in the mixture the more the hydration products (Barišić et al. 2015) and hence the more the strengthening and binding effect.

Regarding the combined effect of cement and rubber on the UCS, it was observed from the same figure that the UCS declined due to the partial replacement of natural aggregate with crumb rubber. Furthermore, interestingly, the decline in the UCS value due to rubber incorporation increased as cement content increased, although the increase was less marked as the cement content increased from 5% to7%. The latter behaviour can be explained as follows: the aggregates in compacted cement aggregate mixture are interlocked and bonded by the cement matrix to each other which make them resist the applied loading like an indeterminate structure, i.e. the "structure" carries the applied load in such a way that each element in the "structural system" carries part of that load in proportion to its relative stiffness. As cement content increases, the stiffness of the surrounding materials must increase while the stiffness of the rubber particles must remain unchanged. Hence, stresses will be shed from the compliant rubber particles toward the stiffer surrounding materials which will thus absorb more load than the rubber particles. If the mismatch between stiffness of the rubber and surrounding matrix become large, the rubber inclusion will act similarly to a void- which is, in effect, as inclusion having zero stiffness. This will result in greater stress concentrations in the matrix surrounding the rubber. On the other hand, in the case of low cement content this stiffness difference is lower, which will maximize the role of rubber particles in this structural system. This leads to the conclusion that the void-like behaviour depends, to large extent, on the relative stiffness between rubber particles and surrounding matrix.

In terms of indirect tensile strength, it was observed, as shown in Figure 5, that the ITS value increased proportionally with higher amounts of cement and/or long curing period. Similar to the UCS, the reduction in ITS is more obvious at higher cement level than at low contents for the same reasons as stated above.

Figure 6 shows the relationship between UCS and ITS values for different mixtures at different ages. From this figure, we can infer that the ITS value is around 10% of the UCS applicable for all investigated mixtures at all curing age. This means that the relationship between UCS and ITS is a unique relation regardless of mixture composition (aggregate type, degree of cementation and curing period). (Ji et al. 2015) in their study, for different natural aggregate/recycled asphalt pavement aggregate (RAP), recycled cement base aggregate blends stabilized with different cement contents concluded that there was a linear relationship in which the UCS=9.786 x ITS. (Arellano and Thompson 1998) reported a ratio of between 10-15%. Thus the current results confirm these earlier findings.

5.2 Effect of cement content on static modulus of elasticity

The effect of cement content on the static modulus of elasticity of virgin and cement-stabilized mixtures is illustrated in Figure 9. It can be said, based on the results depicted in this figure that the greater the cement content the greater the stiffness of the mixture. It can be inferred that for control mixtures, because the stiffness of aggregate is the same for all mixtures having different cement contents, the stiffness of mixtures is controlled, to a large extent by the stiffness of the matrix (fines plus cement) and its bond with aggregate particles. On the other hand, a drop of the stiffness was observed due to rubber inclusion which can be attributed to the replacement of stiff particles (natural aggregate) by soft particles (rubber). As the stiffness of mixtures depends on the stiffness of their individual components, it is logical for decrease to occur when the natural aggregate is replaced by the crumb rubber.

5.3 Effect of cement content on load-deformation relationship and toughness

Figure 7 demonstrates the load-deformation relationships for different investigated mixtures. From these curves, toughness indices were estimated (Section 4.4.3) as presented in Figure 8. It is clearly seen that inclusion of more cement caused a reduction in the toughness or energy absorption capacity. However, an improvement occurred in the toughness value after modification with crumb rubber at all cement levels. Improved enhancement was observed at higher cement contents. This leads to the conclusion that as far as the toughness of the materials is of concern, incorporating rubber in the cemented mixture at high cement content will be beneficial for improving the energy absorption capacity of the material. However, in spite of this, both conventional and rubberized mixtures of low cement content are still tougher than those with high cement contents.

It is suggested that the mechanism of toughness increase is by lengthening the crack propagation path for both virgin and rubberized mixtures. If an assumption (which will be checked later in this paper) is made that the crack always propagates through the weak points, then this may explain the toughness changes. In addition, this propagation through these rubber particles is also improve the toughness by stress relaxation at the tip of cracks. At low cementation levels, the bond between the aggregate particles and cement mortar (fines and cement) may be the weakest element in the internal structure of the mixture. Propagation through weak points (primarily around the aggregate particles) will lengthen the crack path and enhanced the toughness of the mixture.

5.4 Effect of cement content on dynamic properties

Similar to the static modulus of elasticity results, there was an increase in both dynamic modulus of elasticity and that of rigidity due to increase in mixture cement content, as depicted in Figure 10. This demonstrates the ability of the nondestructive testing to distinguish between different modified mixtures containing different amounts of cement and their high sensitivity to the small change in the aggregate structure due to incorporation of small amounts of rubber. Figure 11 demonstrates the effect of cementation on the Poisson's ratio of both virgin and rubberized mixtures. A decline in Poisson's ratio occurred for both mixtures because the higher stiffness due to high cement content is usually accompanied by less deformable behaviour.

5.6 Effect of cement content on failure patterns

Figure 12 illustrates the failure pattern in ITS and UCS specimens. In terms of ITS, virgin samples tend to fail in a brittle manner resulting in a complete separation of sample halves. The latter failure mode is more obvious in mixtures of high cement content. In contrast, the rubber modified mixtures at all cement contents did not experience such a failure pattern. Instead, these, after testing, looked intact with a narrow crack opening. Regarding the failure pattern of UCS samples, similar behaviour was observed where the reference mixtures at all cement contents tended to show severe crushing. In contrast, rubberized mixtures show less crack width and seem to be intact. This might be because the cracks propagated as a 3 dimensional network through rubber particles since these represent cracking initiation sites. These findings, in turn, explain the ductile behaviour due to rubber incorporation at all cement contents. The practical implication for use of the material as a base course in a pavement structure is less differential settlement and better load transfer in cracked material. At the same time this may reduce the possibility of reflection of these cracks into the surface course of the pavement which is due to stress concentration in the upper layer where it rests layer on a cement-stabilized base course having wide cracks. Similar behaviour was also reported by (Duarte et al. 2015) when they investigated the failure pattern of normal concrete samples.

5.7 Overall discussion regarding fracture mechanism

Theoretical studies conducted by (Duarte et al. 2015) and (Eldin and Senouci 1993) for rubberized concrete revealed that the cracks initiated near the rubber particles due to the stress concentration at these locations. Furthermore, (Duarte et al. 2015) findings revealed that damage and cracking is more concentrated in the concrete mixtures containing no rubber, but that is not the case for the rubberized concrete. There the damage is more widely distributed. In the present paper, examining the failure pattern and observing the internal structure through the X-ray images of the failed specimens reveals that regardless of the cement content, the cracks tend to propagate through or adjacent to the rubber particles (Figure 13). They tend not to run through the surrounding matrix when there is a rubber aggregate nearby. It is believed that this behaviour is related strongly to the void-like behaviour (mentioned earlier) of the rubber particles. Therefore, rubber particles embedded inside a stiff matrix behave like a void which attracts the crack to propagate across or adjacent to it. Another explanation of the crack routing could be the denser structure and lower heterogeneity (since the difference between the stiffness of the conventional aggregates and the surrounding cementitious matrix will be minimized as cement content increases) of highly cemented mixtures. This would means that the rubber particles were then the most significant defect inside such a mixture and hence stress would be concentrated more adjacent these particles. When this happens, cracks will tend to propagate between rubber particles and the latter will try to absorb and relieve the stress at the crack tip. Such an understanding explains why more toughness was observed at higher cement contents. At moderate cement level, toughness was also improved for the same reasons. However, comparing and contrasting the mixture behaviour at high and moderate cement contents reveals the degree of toughness improvement is higher at 7% cement content as compared that at 5% cement. This is probably because, at 5% cement content, the less dense matrix may already contain micro-voids that delay crack propagation since these micro-cracks consumes a part from energy due to the micro-crack shielding phenomenon defined by Shah (1995) as cited in (Löfgren 2005). Furthermore, the weaker bond between aggregate and surrounding matrix contributes to deflection of the crack and its propagation through the conventional aggregate-cement matrix interface. The latter process also consumes some energy.

6. Conclusions

The influence of cement content on the mechanical properties of virgin and cement-stabilized aggregate was investigated in this paper. The following conclusions can be drawn:

1. Indirect tensile strength increased as cement content increases. Furthermore, an improvement in this property also occurred as curing age increased. However, the reduction in the ITS of mixtures due to rubber replacement is more obvious for mixtures of high cement contents (7%) than these of low cement contents (3%). Therefore, from a strength point of view, using crumb rubber in mixtures of low cement content is the most sustainable solution since this will ensure saving of natural aggregate while maintaining better strength.

2. As expected, unconfined compressive strength is found to improve with cement content and curing age for both types of investigated mixes.

3. There was a reduction in the toughness of the investigated mixtures when more cement is used. However, an improvement due to rubber inclusion was observed. Greater enhancement occurred at high cement contents.

4. Non-destructive investigation confirmed that rubber replacement of some aggregate produce less stiff materials. The same behaviour was seen in static modulus of elasticity measurement, proving the ability of this test method to characterize the cement-stabilized materials containing different amount of cements and small changes in aggregate composition.
5. It is recommended to use low cement contents to stabilize rubberized mixtures since the reduction in the material strength is lower than at high cement content. This is considered as the more economical option.

6. Evaluation of the performance of the rubberized mixtures, especially under dynamic loading, is essential to validate their use.

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Figure Captions

Fig.1. Gradation of different fraction sizes including crumb rubber.

Fig.2. Final gradation of cement-stabilized mixtures.

Fig.3.Indirect tensile testing details: a. manufactured gluing jig; b. gluing LVDTs holders and c. test set-up.

Fig.4. Unconfined compressive strength for different mixtures at 7, 28 and 365 days.

Fig.5. Indirect tensile strength for examined mixtures at 7, 28 and 365 days.

Fig.6. UCS and ITS correlation for examined mixtures at indicated curing periods.

Fig.7. Load-diametrical deformation curves for different replacement levels: a. C3R0; b.C3R30; c. C5R0; d.C5R30; e. C7R0 and d. C7R30.

Fig.8. Effect of replacement on toughness indices.

Fig.9. Effect of cement content on static modulus of elasticity.

Fig.10. Effect of rubber replacement on dynamic elasticity and rigidity moduli.

Fig.11. Effect of rubber replacement on dynamic Poisson’s ratio.

Fig.12. Failure patterns due to UCS (a) and ITS (b) testing for different mixtures.

Fig.13. Mesostructural illustration for different mixtures: a. C3R30, b. C5R30 and c. C7R30 (Red arrow indicates the rubber particles)

Table 1: Physical properties of crumb rubber (Najim and Hall 2012)

Property	Value
Specific gravity	1.12
Apparent density	489 kg/m3
Thermal conductivity	0.11 W/k m
Tensile resistance	4.2–15 MPa
Speed of combustion	Very low
Water absorption	0.65 (negligible)

Table 2: Cement contents, optimum water contents and maximum dry density.

Cement content, %	Optimum water content, %	Maximum dry density, Kg/m^3
3	4.5	2392
5	4.6	2396
7	4.7	2403

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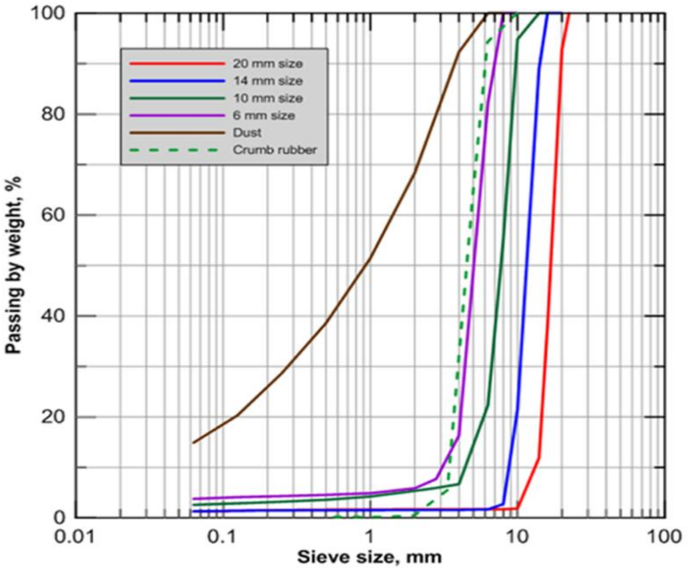

100
80
60
40
20
0
Passing by weight, %
0.01
0.1
1
10
100
Sieve size, mm
20 mm size
14 mm size
10 mm size
6 mm size
Dust
Crumb rubber

Figure 1

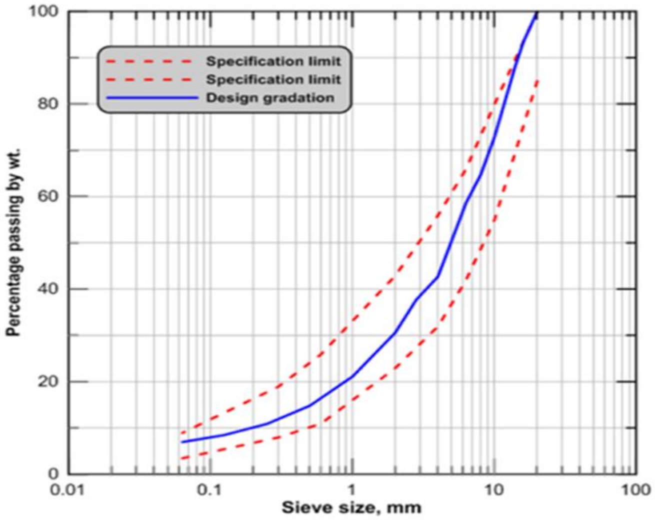

Specification limit
Specification limit
Design gradation
Percentage passing by wt.
0
20
40
60
80
100
0.01
0.1
1
10
100
Sieve size, mm

Figure 2

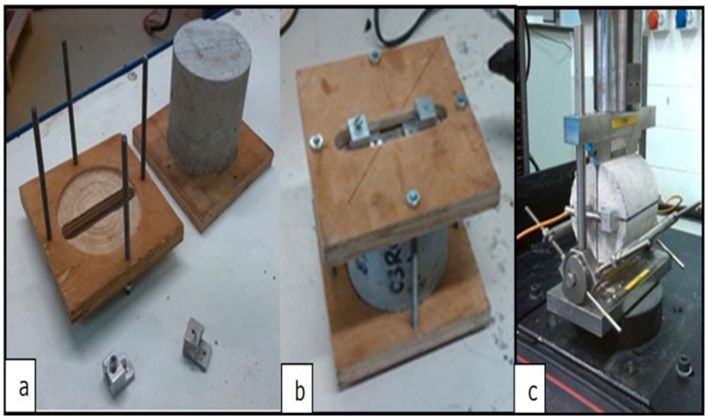


Figure 3

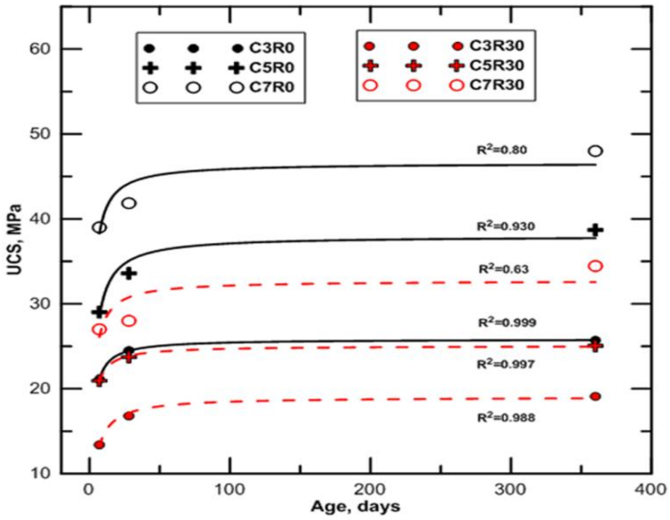

C3R0
C5R0
C7R0
C3R30
C5R30
C7R30
R²=0.80
R²=0.930
R²=0.63
R²=0.999
R²=0.997
R²=0.988
UCS, MPa
Age, days
10
20
30
40
50
60
0
100
200
300
400

Figure 4

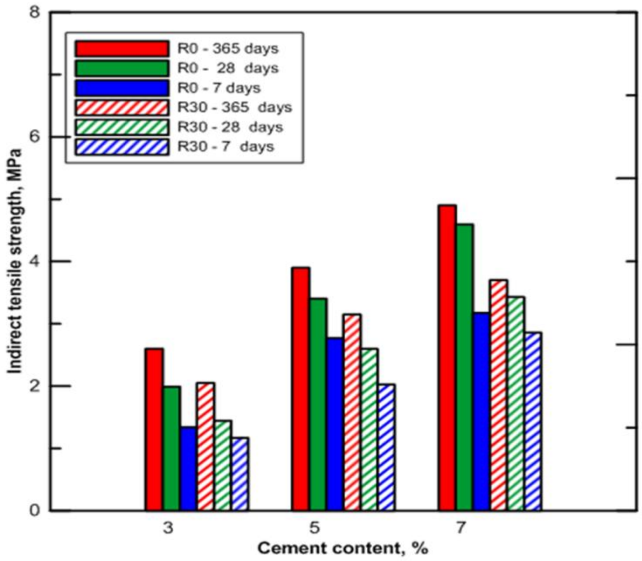

R0 - 365 days
R0 - 28 days
R0 - 7 days
R30 - 365 days
R30 - 28 days
R30 - 7 days
Indirect tensile strength, MPa
0
2
4
6
8
3
5
7
Cement content, %

Figure 5

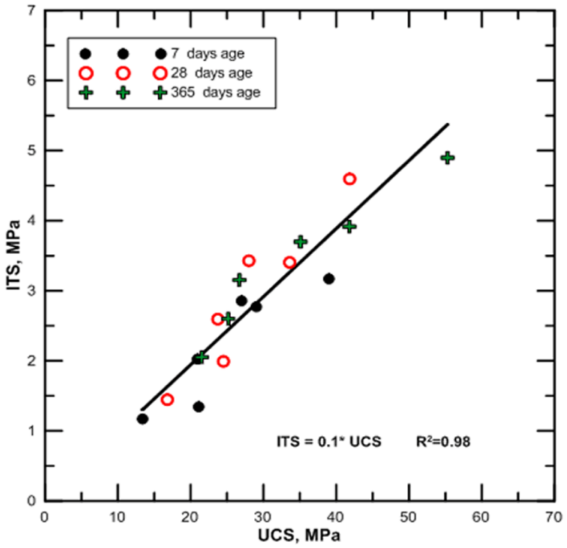

7 days age
28 days age
365 days age
ITS = 0.1* UCS
R^2=0.98
ITS, MPa
UCS, MPa
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70

Figure 6

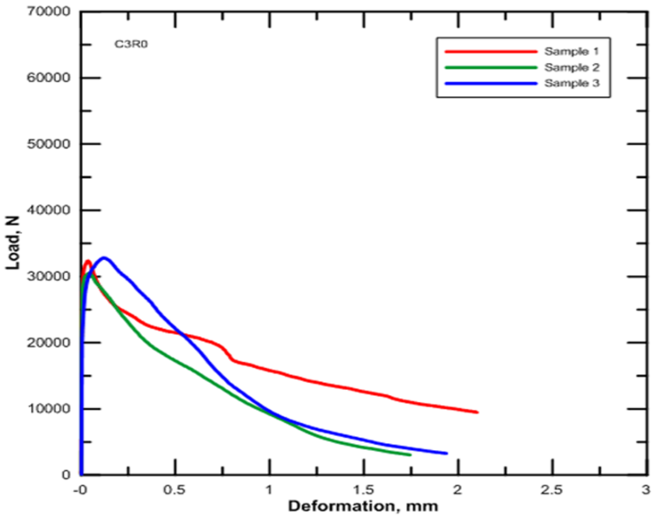

C3R0
Sample 1
Sample 2
Sample 3
Load, N
70000
60000
50000
40000
30000
20000
10000
0
-0
0.5
1
1.5
2
2.5
3
Deformation, mm

Figure 7a

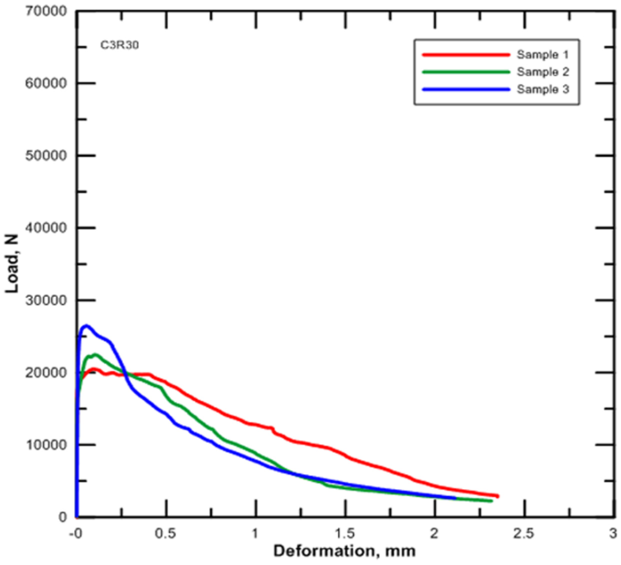

C3R30
Sample 1
Sample 2
Sample 3
Load, N
70000
60000
50000
40000
30000
20000
10000
0
-0
0.5
1
1.5
2
2.5
3
Deformation, mm

Figure 7b

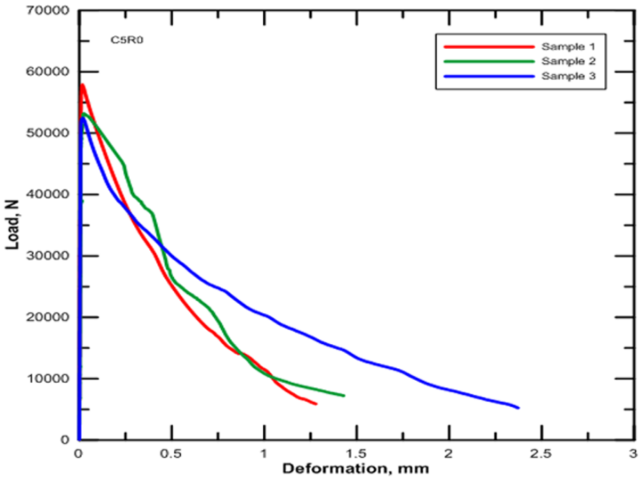

C5R0
Sample 1
Sample 2
Sample 3
Load, N
70000
60000
50000
40000
30000
20000
10000
0
0
0.5
1
1.5
2
2.5
3
Deformation, mm

Figure 7c

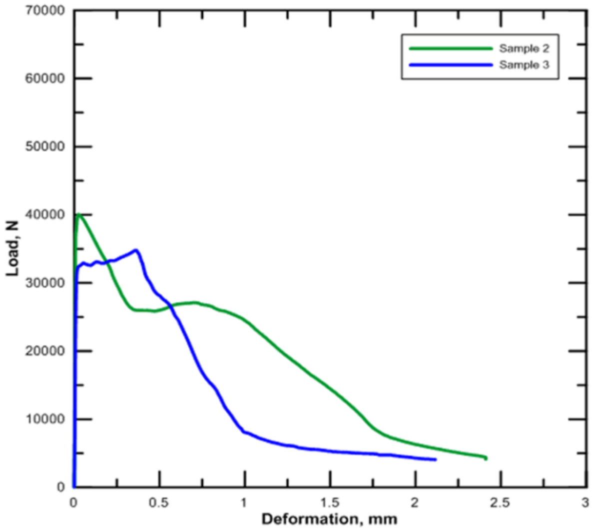

Sample 2
Sample 3
Load, N
0
10000
20000
30000
40000
50000
60000
70000
0
0.5
1
1.5
2
2.5
3
Deformation, mm

Figure 7d

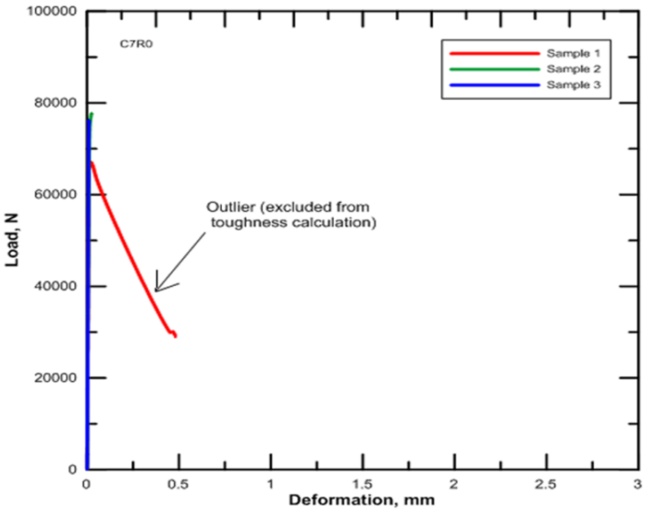

C7R0
Sample 1
Sample 2
Sample 3
Outlier (excluded from toughness calculation)
Load, N
100000
80000
60000
40000
20000
0
0
0.5
1
1.5
2
2.5
3
Deformation, mm

Figure 7e

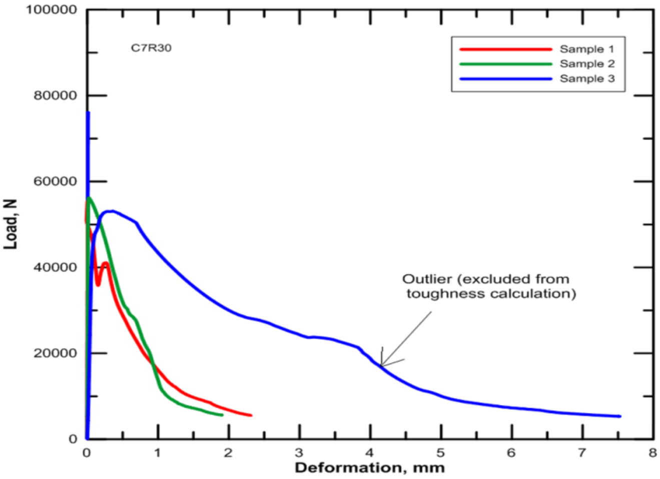

C7R30
Sample 1
Sample 2
Sample 3
Outlier (excluded from toughness calculation)
Load, N
0
20000
40000
60000
80000
100000
Deformation, mm
0
1
2
3
4
5
6
7
8

Figure 7f

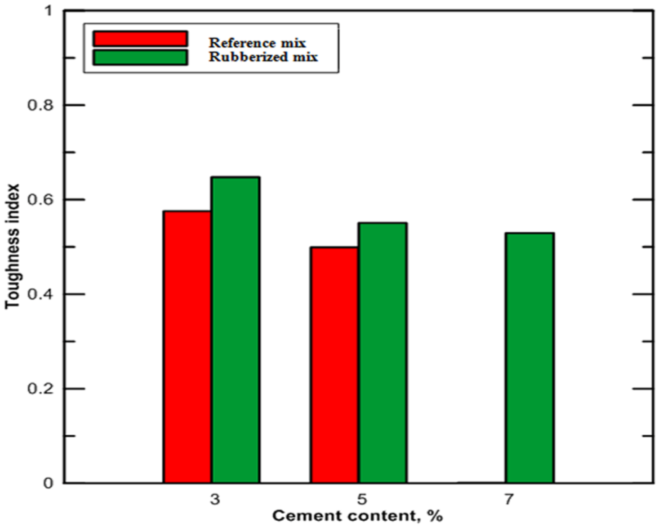

Reference mix
Rubberized mix
Toughness index
1
0.8
0.6
0.4
0.2
0
3
5
7
Cement content, %

Figure 8

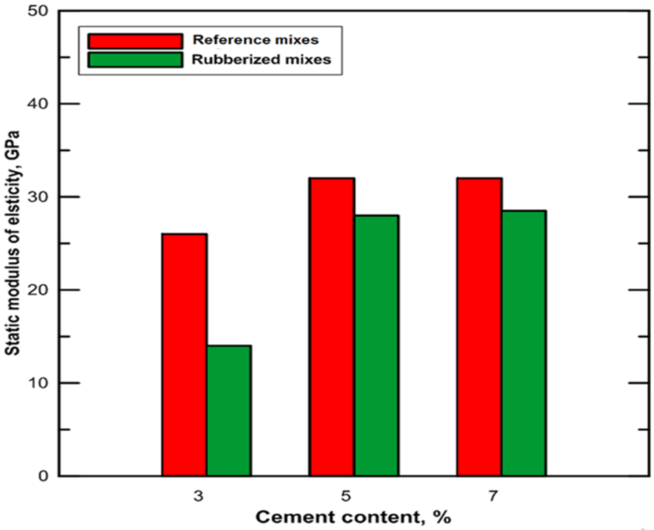

50
40
30
20
10
0
Static modulus of elsticity, GPa
Reference mixes
Rubberized mixes
3
5
7
Cement content, %

Figure 9

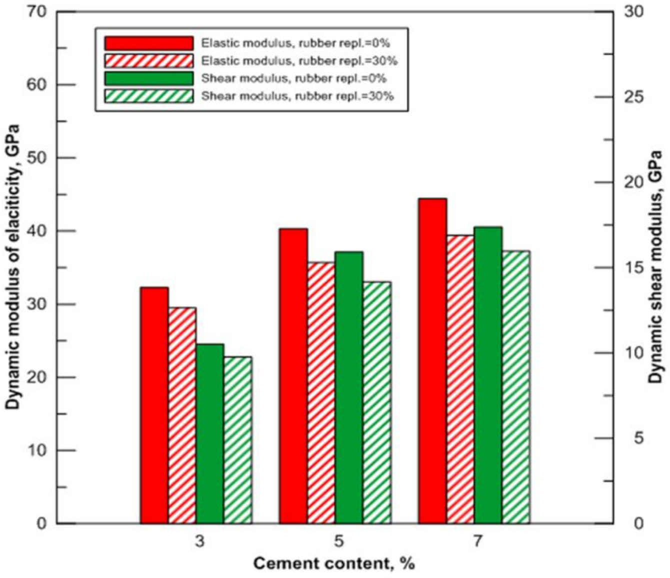

Elastic modulus, rubber repl.=0%
Elastic modulus, rubber repl.=30%
Shear modulus, rubber repl.=0%
Shear modulus, rubber repl.=30%
Dynamic modulus of elaciticity, GPa
Dynamic shear modulus, GPa
Cement content, %
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
3
5
7

Figure 10

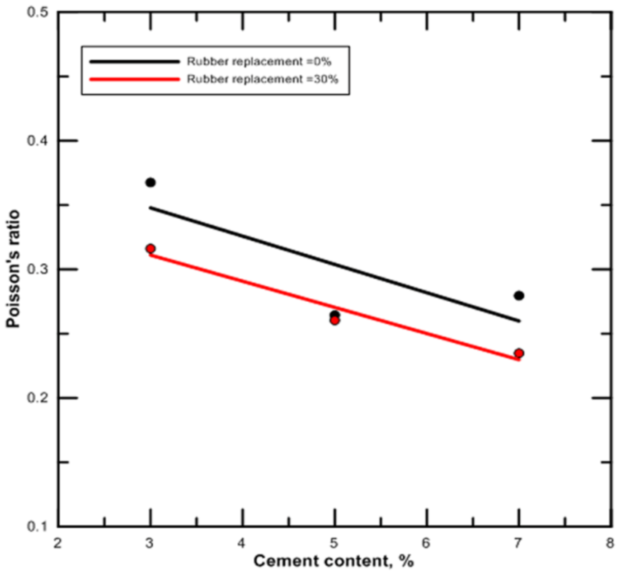

Rubber replacement =0%
Rubber replacement =30%
Poisson's ratio
0.5
0.4
0.3
0.2
0.1
2
3
4
5
6
7
8
Cement content, %

Figure 11

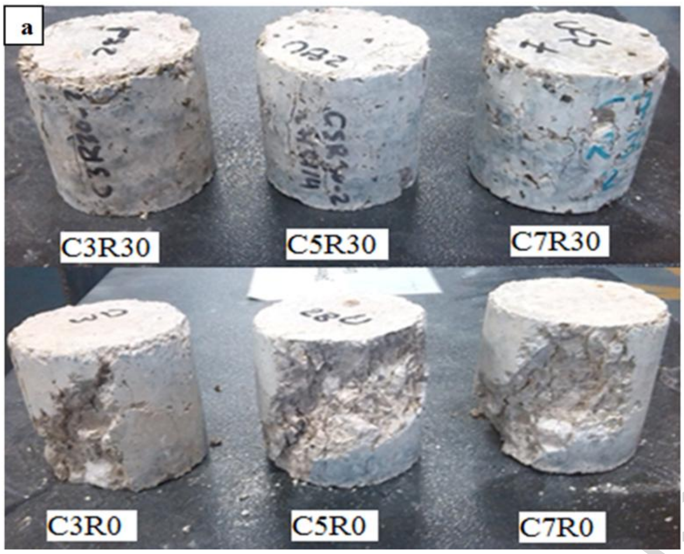


Figure 12a

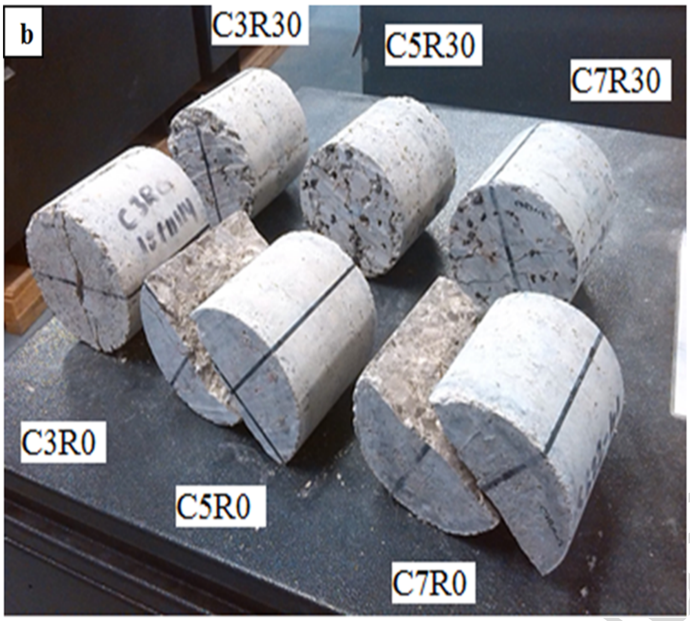


Figure 12b

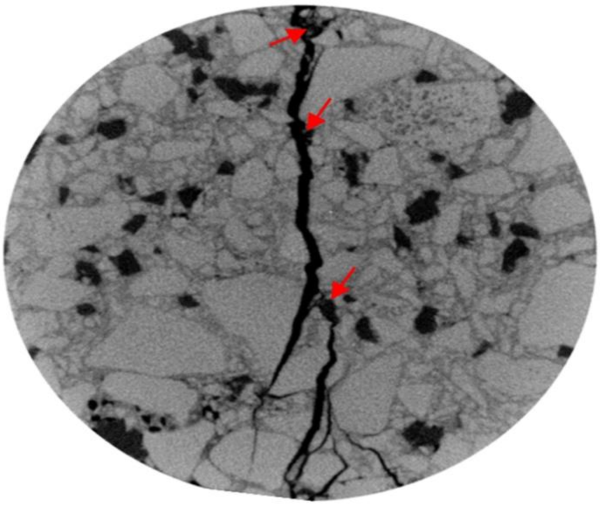


Figure 13a

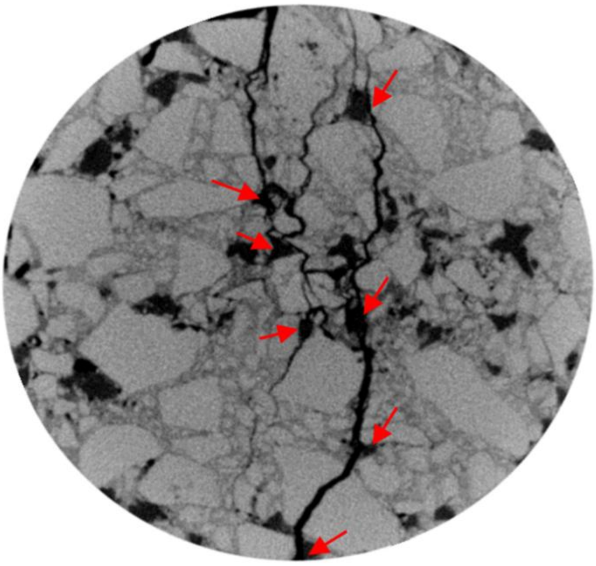


Figure 13b

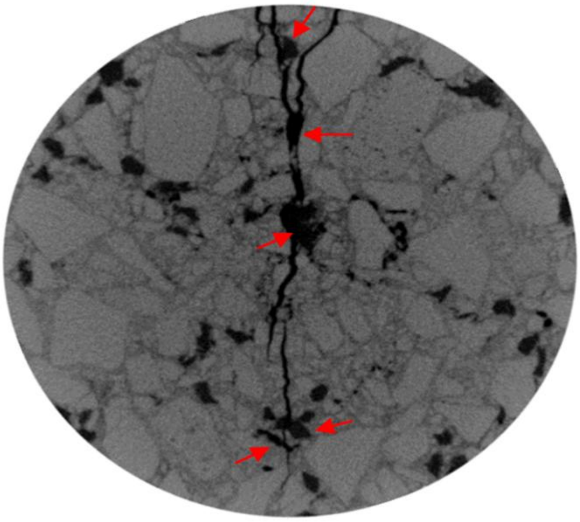
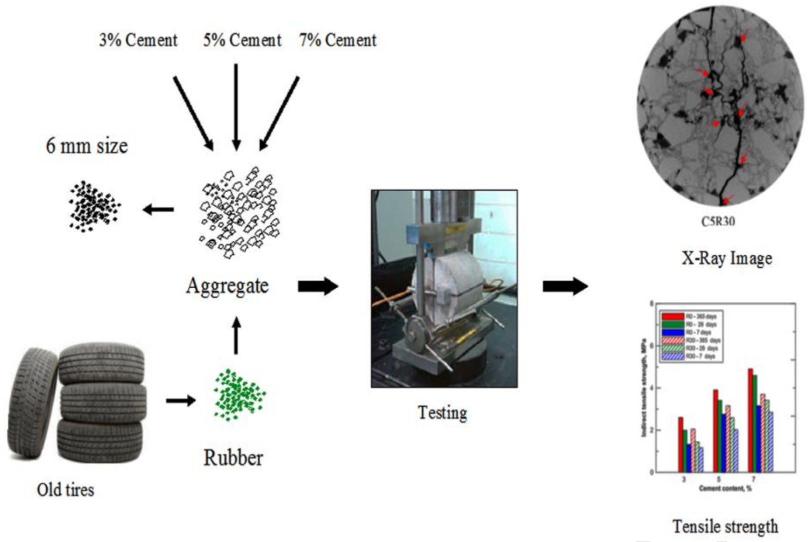


Figure 13c



Graphical Abstract

Research Highlights

- Increasing cement content in cement-stabilized mixtures containing crumbed rubber generates greater tensile strength.
- Reduction in cement-stabilized mixtures strength due to rubber inclusion is more obvious at high cement content.
- Toughness improvement and stiffness reduction confirm more ductile behaviour due to rubber incorporation at all cement contents.
- Cracks in rubberized cemented mixtures propagate through the rubber particles at all cementation levels.
- Overall performance of rubberized cement-stabilized mixes depends on the relative stiffness between rubber and surrounding matrix.