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Characterization of rubberized cement bound aggregate mixtures using indirect tensile testing and fractal analysis

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Abstract

The main focus of this paper is to investigate the tensile properties of virgin and rubberized cement bound granular mixtures. This was conducted using indirect tensile testing with lateral displacement measurements, nondestructive resonant frequency testing, X-ray CT and quantitative assessment for cracking pattern using fractal analysis. The investigated properties were density, compacity, indirect tensile strength (ITS), indirect tensile static modulus, toughness, dynamic modulus of elasticity, dynamic modulus of rigidity, dynamic poison's ratio, fractal dimension and fracture energy. To keep the same aggregate packing, the natural aggregate was replaced by waste tyres' crumb rubber of similar gradation. Four volumetric replacement percentages (0%, 15%, 30% and 45%) of the 6 mm fraction size were utilized. This adjustment was observed to affect the material density not only due to the lower specific gravity, but because it also affects the compactibility of the mixture negatively due to the damping action of the rubber particles. In addition, strength was also affected detrimentally. However, material toughness was improved and stiffness was mitigated. The latter findings were supported by quantitative assessment of the cracking pattern which revealed more tortuosity and a higher fractal dimension as a result of rubber content increasing. A failure mechanism for this type of mixture was suggested and support by examining the internal structure of failed samples using X-ray CT. Overall, construction of cement-stabilized

aggregate base with a small percentage of added crumb rubber may ensure a more sustainable and environmental-friendly pavement material and, at the same time, improve the properties of stabilized layers. However, behaviour of these mixtures under cyclic loading and evaluation of their durability should be assessed to fully validate their use.

Keywords: cement-stabilized aggregate; waste tyres; rubberized cement bound mixture; indirect tensile; sustainable pavement; fractal analysis.

1. Introduction

Stockpiling waste materials and depletion of natural resources represent two accompanying problems in the modern world. One of the most common and continuously increasing waste materials is derived from the vehicle tires consumed every year. Over the years, many authors have attempted to make use of these waste materials to ensure proper disposal of these materials and to save natural resources. Authors (Khatib and Bayomy 1999; Güneyisi et al. 2004; Papakonstantinou and Tobolski 2006; Balaha et al. 2007; Gesoğlu and Güneyisi 2007; Zheng et al. 2007; Khaloo et al. 2008; Taha et al. 2008; Zheng et al. 2008; Güneyisi 2010; Pelisser et al. 2011; Najim and Hall 2012; Güneyisi et al. 2014) have investigated the feasibility of using waste tire materials in different types of concrete mixtures as a replacement of either fine or coarse aggregate or both. Others (Pincus et al. 1994; Cecich et al. 1996; Foose et al. 1996; Masad et al. 1996; Liu et al. 2000; Youwai and Bergado 2003; Kim et al. 2005; Humphrey 2007) studied the possible use of these materials in geotechnical applications as fill materials for embankments and behind retaining walls.

No doubt, highway construction consumes large quantities of natural materials as compared with other civil engineering projects (Cao 2007; Barišić et al. 2014). Therefore, studies have been conducted to investigate the possibility of using these waste materials within the pavement structure, specifically in asphaltic mixtures to modify the properties of the binder either through the wet or dry process (Chiu and Lu 2007; Fontes et al. 2010); (Cao 2007; Xiao et al. 2007; Chiu 2008). A very few studies were conducted to investigate the possibility of using crumb rubber within cement-stabilized aggregate mixtures typically used as a base and/or subbase courses in flexible composite pavement structure. The usage in this case might be more feasible than in asphaltic mixtures used as a base or surface course since the latter two layers usually have a limited thickness due to their high cost as compared with cement-stabilized layers. Cement-stabilized mixtures as defined by (Lim and Zollinger 2003) are a mixture of aggregate, Portland cement and a small quantity of water to facilitate compaction and to hydrate the cement. Cement-stabilized aggregate can be classified as a cementitious material. The Portland Concrete Association (PCA 2005) has classified these materials into four types depending on the amount of water and cement being used. Materials with high cement contents are roller-compacted concrete and normal concrete. However, the first one is constructed by rolling due to the low level of water as compared with the latter. On the other hand, flowable fill and cement-stabilized materials are the other types which contain low cement levels with first one being constructed by rolling due to its low water content.

2. Rationale and aims

The motivation of this research is to make use of the above waste materials which in turn should help to save natural resources as well as to reduce the environmentally detrimental effect of these materials. Another motivation comes from the fact that the use of Portland cement to stabilize granular materials usually produces stiff mixtures which are sensitive to cracking, overloading and fatigue failure (Wu et al. 2015). Furthermore, the reflection cracks mostly accompanying the cement-stabilization, especially at high cement contents. Consequently, an attempt was made in this paper to mitigate the above disadvantages by using the crumb rubber to modify some cement-stabilized mixtures. The purpose of this paper is to study the effect of crumb rubber particles on the properties of cement-stabilized mixtures, mainly in terms of tensile performance. The importance of this investigation comes from the fact that, in pavement structural design, tensile properties are the most influential factors since all bound layers (including cement bound granular mixture (CBGM) are designed based on the tensile stress / strain at the bottom of these layers. A review of literature indicated that there is no published study about the quantitative evaluation of cracking pattern of rubberized, nor even of conventional cement-stabilized materials. Therefore, another complementary objective of this paper is to use the fractal analysis concept to quantitatively study the cracking pattern of cement-stabilized aggregate containing different rubber contents and to investigate any possible correlation with macro-scale properties. This will help to better understand the failure mechanism of this type of modified mixture.

3. Experimental program and methodology

3.1 Materials and their properties

A crushed limestone aggregate of 20 mm maximum size is used across this study. To ensure the manufacture of comparable mixtures containing the same gradation and densities and hence investigating the effect of rubber alone, two steps were conducted. The first one was to use and combine different fractional sizes (20 mm, 14 mm, 10 mm, 6 mm and dust (less than 6mm)) in different proportions to constitute the required gradation and the second was to batch, mix and compact each sample individually. This was so as to ensure comparable strength since there is a high dependency of the strength on mixture density (Williams 1986). Different fractions of limestone aggregate were collected from Dene Quarry in Nottinghamshire in the UK. The gradations were assessed in accordance with BS EN 933-1:2012. The crumb rubber particles were sourced from J Allcock and Sons Ltd. in Manchester, UK. Its gradation is presented in Figure 1. Initial examination showed a similarity between the 6 mm aggregate fraction size and that of crumb rubber as shown in this figure. Consequently, it was decided to replace the former by the latter in order to ensure the same aggregate packing so as to enable study of the effect of elastic aggregate particles alone.

The specific gravity of the rubber was adopted as 1.12 as measured by (Najim and Hall 2012). CEM I 52.5 R Portland cement conforming to BS EN 197-1: 2000 was used for aggregate mixtures stabilization. Potable tape water was utilized to moisturize the cement- aggregate mixture.

3.2 Mixture design and samples production

The final gradation, after blending, of the CBGM was to specification BS EN 14227-1:2013 - [CBGM2-0/20]. It is illustrated in Figure 2. 5% cement, by dry weight of aggregate, was used. Optimum water content for aggregate-cement mixture was estimated as 4.6% (by the total dry weight of aggregate and cement) in accordance with BS EN 13286-4:2003. Regarding the degree of replacement by rubber, three volumetric replacement percentages was investigated and the resulting materials compared with mixtures contain no rubber. These are 15%, 30% and 45% of the 6 mm aggregate fraction volume. These are equivalent to 2.1%, 4.2% and 6.2% of the total volume of the aggregate, respectively. Because of the considerable differences between the specific gravities of natural aggregate and crumb rubber, proportioning on the weight basis is a misleading approach. This is because the cement is normally added by the dry weight of aggregate which will reduce after replacing with crumb rubber due to the low specific gravity of the latter. This in turn would cause a change in the cement content and accordingly water content for different replacement levels. Accordingly, volumetric proportioning was taken into consideration. All volumetric proportion was kept constant as used in the virgin mixture and the only variable was the rubber volume. This was simply done by keeping the weight of cement and water as that used in the virgin mix. For the purpose of designation, C5R0 was used to indicates the mixture containing 5% cement content and 0% rubber replacement i.e., virgin mix. On the other hand, C5R15, C5R30 and C5R45 were used to describe the mixtures containing 5% cement and 15, 30 and 45% replacement levels, respectively.

Regarding mixing sequence, cement and dust were mixed firstly until uniform colour was achieved. The cement- dust mixtures was added to the rest of aggregate sizes and mixed for a minute. After adding the appropriate water quantity, all materials were mixed thoroughly for another two minutes. All mixing was conducted manually. On completion of mixing, each mixture was compacted in three layers inside a lubricated spilt mould with diameter of 101.6 mm using a Kango 638 vibrating hammer. The compaction time was 60 sec. per layer as recommended by BS EN 13286-51:2004. Past experience with testing cement-stabilized samples predicted that a very low strain would develop during testing and that there would be a high sensitivity to the small unevenness in the surface which the loading platens touch, necessitating accurate instrumentation (Scullion et al. 2008). From initial investigations made during this study, the impossibility of achieving a smooth and level surface, which will make it is difficult to fix the instrumentations, had been observed. To overcome this problem, it was decided to manufacture the sample to achieve a height of about 115 mm and then trim it down to 100 mm. In addition, another set of samples was manufactured for resonant frequency testing using standard split moulds of 150 mm diameter and 300 mm height. Again, a removable mould extension was fabricated and used to ensure a specimen more than 300 mm tall which was then sawn down to 300 mm using a diamond saw. Three samples were manufactured for each mix. Once the compaction was finished, specimens were left inside their moulds and covered with wet paper and polythene sheets overnight to prevent moisture loss. On the next day, these were demoulded and wrapped with nylon film and placed in wet polythene bags and closed tightly and left in a humid room for 28 days.

3.3 Testing procedures and analysis performed

3.3.1 Compacity and density

It was observed that the performance of cement-stabilized aggregate mixture is greatly dependent on its density. (Williams 1986) has reported that a 5% reduction in mixture density causes 40-50 % reduction in the mixture strength. Thus, effective compaction can be expected to be critical for adequate performance. Accordingly, the British specification (BS EN 14227-1:2013) has introduced the compacity factor as a measure of the efficiency of compaction. It has been reported by the above specification that the compacity for cement-bound mixtures should be not less than 0.82. Critical analysis of this criterion shows that this is a movement towards the concept applied in asphaltic mixture to calculate the percent of air-voids. Compacity can be calculated as [100 - % air-voids]. In the current paper, due to the damping tendency of the rubber particles, these may affect the effectiveness of compaction negatively. Therefore, an investigation was carried out to evaluate if the rubber particle have a detrimental effect on the compactibility of the mixtures. Compacity in accordance with the above specification can be calculated using the following equation

$$\boldsymbol{C} = \left(\frac{\boldsymbol{\gamma m}}{\mathbf{100}}\right) \times \left(\frac{\boldsymbol{a}}{\boldsymbol{\gamma A}} + \frac{\boldsymbol{b}}{\boldsymbol{\gamma B}} + \frac{\boldsymbol{c}}{\boldsymbol{\gamma C}} \ldots\right)$$

where: C is the compacity factor, γm is the maximum dry density of the mixture and γA, γB, γC, are particle densities of material A, B and C, respectively. a, b, c represent the percentages of material A, B, C in the total mixture. Dry density of the specimens was measured after curing by drying them in an oven at 105±5°C until constant weight, then using the water displacement method to measure the density.

3.3.2 Indirect tensile strength and static modulus of elasticity

This test was performed at 28 days in accordance with BS EN 13286-42:2003. A 200 KN capacity Instron universal testing machine was used. The indirect tensile strength (ITS), in MPa, was estimated using the following equation: ITS=2P/πhD where P is the ultimate load (N), h is the sample thickness (mm) and D is the diameter of the sample (mm). In order to estimate the static modulus of elasticity, deformation was measured utilizing two linear variable differential transducers (LVDTs) mounted using LVDTs' blocks. These were glued on the both faces of specimen. Figure 3 illustrates the indirect tensile testing configuration. To ensure accurate instrumentation, the gluing jig was manufactured and used as reported by (Wen et al. 2014) to ensure precise alignment of the LVDTs blocks on both faces of the sample. The average displacement value from these two LVDTs was used at each load application. Finally, the static elastic modulus was estimated for a load being 30% of the maximum load, and the corresponding lateral displacement according to EN 13286-43:2003. However, instead of using the equation provided in the latter specification, which assumes specific arrangement for the LVDTs, the following formula was used (Solanki and Zaman 2013):

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

Where: P= load; D=diameter of sample; t= sample thickness; ΔH_T=lateral deformation; D_g=LVDTs gauge distance and υ = Poisson's ratio.

3.3.3 Mesostructural investigation

To better understand the failure mechanism and to observe how the cracks propagated, failed specimens were scanned using an X- ray CT machine. This includes two systems located in the same cabinet. The first one is the mini focus system of a 300 kV X-ray source and a linear detector. The second system is a micro focus having a 225 kV with an area detector. To ensure sufficient power of X-ray for penetration through stabilized mixtures, the first system was used in this investigation. Two scans were done for each sample at the top and bottom of the middle third of sample. The resolution of the reported scan is 0.065 mm/pixel.

3.3.4 Toughness through indirect tensile test

To obtain the post-peak load-deflection behaviour and hence quantify toughness of the material, the test was performed at a deformation rate of 0.5 mm/min. The corresponding deflection was measured as mentioned earlier. To evaluate the post-peak loading bearing capacity enhancement, the area under the load-deformation curve can be used to compute the toughness or energy absorption capacity of the material. 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, due to the reduction in the strength of the mixture as a result of rubber inclusion, it is necessary to normalize the load to its ultimate value to evaluate the enhancement in terms of ductility only. This is also logical since in the mechanistic pavement design the stress is usually normalized with respect to the strength and the stress ratio is normally used.

3.3.5 Dynamic properties through resonant frequency

Dynamic modulus of elasticity represents an important input for pavement analysis and design. (Nunn 2004) in TRL615 report and (Lav et al. 2006) adopted dynamic modulus as determined from resonant frequency for pavement design. In the present paper, dynamic properties were measured nondestructively using a resonant frequency tester (ERUDITE) in accordance with (ASTM C215-02). In this test, dynamic properties were evaluated in terms of dynamic modulus of elasticity (E_d), dynamic modulus of rigidity (G_d) and dynamic Poisson's ratio (υ_d). During the test, the sample was supported at its centre on the equipment bench and clamped in place. The driver and pick up parts were placed at different locations depending on whether dynamic modulus of elasticity or dynamic modulus of rigidity is to be measured. For each dynamic modulus type, there is a different recommended frequency range as shown in the equipment manual. Using the recommended frequency range and starting from a low frequency, the frequency was increased gradually until the output meter showed the maximum value which indicates the fundamental resonant frequency of the mixture. The latter was used to calculate the dynamic modulus of elasticity (E_d) and dynamic shear modulus (G_d) as explained in the above specification. From these two moduli, dynamic Poisson's ratio was estimated as $\nu_d = (E_d/2G_d)$.

3.3.6 Damage quantification using fractal analysis and image processing

To provide better a understanding of the mechanism of failure of this type of mixture, the failure cracking pattern was characterized quantitatively using fractal analysis. This technique has been extensively used in normal concrete to quantify cracking patterns (Erdem et al. 2012; Farhidzadeh et al. 2014) and fractured surfaces (Issa and Hammad 1994; Carpinteri et al. 1999; Guo et al. 2007). However, no published study was found in literature regarding the quantification of surface cracks of cement-stabilized mixtures using fractal analysis. In this study, the fractal analysis was performed in terms of the fractal dimension. The latter was estimated using the box-counting method (Mihashi et al. 2006; Erdem and Blankson 2013). An initial investigation performed to extract topological information concerning the cracked area using image processing software, ImageJ, had difficulty in differentiating between the cracks and the rubber particles utilizing a grey thresholding process. For this reason it was decided to digitize the crack network using the following procedure: images of failed samples were firstly captured using a high resolution camera. These images were inserted into AutoCAD software and scaled up to reflect the actual dimensions. The cracks were digitized after that using the software tools. Then these were covered by imaginary meshes with rectangular grid sizes decreasing linearly (Figure 4). Then the number of grid squares required to cover the cracks was counted. Finally the fractal dimension was computed from the slope of the line joining the logarithm of number of grid squares encountered by the crack and the logarithm of the grid square dimension. From surface macro-crack fractal dimension, the fracture energy was roughly estimated based on the formula suggested by (Guo et al. 2007) which is $W_s/G_f=a*(\delta/a)^{1-D_{1-d}}$ where W_s is the energy dissipated at the surface of the crack, G_f is the fracture energy at the observation scale, a is the Euclidean length (equal to the diameter of the sample) and D_{1-d} is the fractal dimension computed previously.

4. Results and discussion

4.1 Density and compacity

Table 1 shows a reduction in the material density after rubber incorporation. This is logical since the specific gravity of natural aggregate is much higher than that of crumb rubber. However, unlike natural aggregate, rubber particles of high elasticity may absorb the energy, due to their damping characteristics, from a vibrating hammer. This could causes a reduction in the compaction efficiency and, hence in mixture density. As can be seen from Table 1, the maximum difference was at a rubber replacement of 45% where there is a 0.92% reduction in the compacity of the mixture (i.e, a decline in density). This can lead to the conclusion that it is not only the low specific gravity of rubber that is responsible for density reduction, but it is also the reduction in compaction efficiency, due to the damping action of the rubber particles, that affects the density of the mixture detrimentally. The practical consequence of the latter finding is to avoid high levels rubber replacement in compacted mixtures.

4.2 Indirect tensile strength

It is generally accepted that all cementitious materials (including concretes) are weak in tension and have low strain capacity. It was found that replacement of natural aggregate by crumb rubber has a negative effect on the indirect tensile strength (ITS) as shown in Figure 5. ITS decreased by 3% for each 1% of rubber replacement. This can be attributed, in addition to the lower modulus of elasticity, to the decrease in the number of contacts points between natural aggregate particles as a result of compacity drop and hence a reduction in the efficiency of aggregate interlock. This may affect the frictional resistance and accelerated mixture deterioration since frictional resistance is one of the main mechanisms for sustaining loads. The same decrease in ITS was observed at both 7 and 28 days for all mixes except C5R45 where there was no further reduction in this parameter, perhaps because of a specific rubber distribution.

4.3 load-deformation relationship, static modulus of elasticity and toughness

The load-deformation relationships for different mixtures are illustrated in Figure 6. From these curves, toughness index was calculated as shown in Figure 7. It is clearly seen, at all replacement levels, that there was an improvement in the energy absorption capacity of the mixtures. This improvement was around about 27%. Although many researcher reported similar behaviour when they investigated the effect of rubber on toughness of normal concrete, no clear reasons was reported to explain this behaviour. However, (Chiaia et al. 1998) claimed that the ductility improvement when using weak aggregates is due to a change in the mechanism of microcracking. The reasons behind ductility improvement due to rubber addition in cement-stabilized materials might be a) partly because the crumb rubber particles helped to delay crack propagation by relieving some induced local stresses b) and partly due to embedding of weak particles inside stiff media lengthening the crack path since the crack path tends to propagate through these weak points. In addition, since the cracks tend to be propagating as a main crack and branches rather than one main crack, especially for rich rubber mixtures, this would cause more energy dissipation as described by Shah et al. (1995) and (Erdem 2012). To clarify the mechanism of failure and to elucidate the above hypotheses, X-ray CT was utilized to investigate the internal structure of failed samples at mesoscale level. Part (b) of the suggested mechanism is evidenced in Figure 8 which shows how the cracks propagated for different mixtures containing different rubber contents. Examining these scans clearly supports the suggested failure mechanism as the cracks can be seen to connect rubber particles as indicated by the red arrows in the same figure and tend to avoid areas without rubber (as predicted by reason (b) above). Furthermore, the load-deflection responses and estimated improved energy absorption capacity clearly support the explanation (a) of the mechanism suggested as presented in Figure 7. This was also supported by the tortuous and complex crack pattern as highlighted in fractal analysis. No doubt the applicability of this proposed mechanism depends, to some extent, on the distribution of the rubber particles. The more uniform the rubber distribution, the more uniform the stress/strain distribution can be anticipated inside the mixture.

As the stiffness of the mixture depends, to a large extent, on the stiffnesses of its constituents, replacement of stiffer natural aggregate by softer crumb rubber particles reduces the stiffness of the mixture as shown in Figure 9. The increase in the stiffness of C5R45 relative to C5R30 might be because of the less uniform distribution of rubber particles in the mixture. Perhaps an accumulation of rubber particles caused a stress concentration and resulted in premature failure of the sample without large deformation.

4.4 Dynamic properties

Similar to the static modulus of elasticity results, there was a decrease in both dynamic modulus of elasticity and that of rigidity due to rubber replacement, as shown in Figure 10. This is because these two moduli depend on mixture density and type of aggregate. However, these parameters decreased linearly at all replacement levels. This, in fact, supports the above hypothesis regarding the possible rubber accumulation. As it known, during nondestructive testing, there was zero applied stress which eliminates the formation of micro-cracks and possible creep (Najim and Hall 2012). In other words, it depends on the mixture constituents and mixture fabrication alone. For this reason, it can be concluded that nondestructive testing does not depend, to a large extent, on rubber distribution as compared with sensitivity of destructive ones. With regard to dynamic Poisson's ratio, Figure 11 shows a decline in the value of this parameter as rubber content increase in the mixture. This is consistent with Goulias and Ali (1997) as cited by (Nehdi and Khan 2001)

4.5 Damage quantification

Figure 12 demonstrates the fractal dimensions and fracture energies for different rubber replacement levels. Generally, higher fractal dimensionality and fracture energy are observed as rubber replacement level increases. This means that as rubber content increases, more energy will dissipate to fracture the sample as suggested by (Guo et al. 2007) and (Erdem 2012). The possible explanation for this phenomenon is that when the cracks developed they propagated through the weak points (i.e., rubber particles), as noted previously. Before their propagation, the rubber particles tend to absorb energy developed at the crack tip when the tip reaches them, especially at the microcracking level. In addition, more energy will disperse since the cracks more easily propagate as branches rather than as one main crack, which agrees with (Yan et al. 2003) who attributed this to the disordered crack growth characteristics found in a mixture's internal structure during load application. This means that more energy was absorbed by the mixture before failure. Energy dissipation capacity improvement is one of the findings reported by (Atahan and Yücel 2012) when they investigated the effect of rubber on fracture energy of normal concrete during impact tests. The dissipated energy at the surface macro-crack based on fractal analysis correlated well (Figure 13) with the toughness of mixture calculated from the load-deformation responses. This supports the above explanation and confirms that a strong relationship exists between the cracking pattern, represented by the fractal dimension, and the toughness, a finding which is consistent with (Yan et al. 2002; Tang and Wang 2012).

5. Conclusions

The effect of replacement of natural aggregate by crumb rubber on the tensile properties and mechanism of their failure was investigated in this paper. This was done utilizing indirect tensile tests and fractal analysis. The following conclusions can be drawn:

1. Even though the reduction in density after replacement with crumb rubber is a logical finding due to the low specific gravity of rubber particles as compared with natural aggregate, this is not the only reason for density reduction. Evaluation of the compacity for different replacement levels revealed a decline in the effectiveness of

compaction as the rubber inclusion rate increased. This can be attributed to the damping effect that the rubber particles of high elasticity possess which may absorb some of the compaction energy during vibratory compaction.

2. Indirect tensile strength reduced due to the inclusion of rubber particles in cement-stabilized aggregates mixtures due to the weakness of these introduced particles. However, an increase was observed in the post-peak behaviour which caused an improvement in the toughness of the modified mixtures. In addition, the high stiffness of the original mixtures was mitigated after partial replacement with rubber particles.

3. By observing stress-strain responses and the failure pattern and examining the internal structure of the failed specimens, the failure mechanism for a rubberized compacted system has been proposed in this paper. It assumes that the crack propagates through rubber particles which are thought to be absorbing energy on the crack tip. In addition, due to the distribution of these weak particles, this may also lengthen the path of the crack. Both of these would improve the energy absorption capacity of the modified mixtures.

4. The Fractal analysis concept is found to permit quantitative distinguishing between different failure patterns of CBGMs. Findings indicate that there is an increasing fractal dimension due to rubber replacement. This also provides a support for the suggested failure mechanism.

5. Non-destructive investigation confirmed that added rubber produced less stiff materials. It is also proved the ability of this test method to distinguish between mixtures with low rubber contents and its suitability to assess the performance of these modified mixtures.

6. It is not recommended to use high content of rubber particles contents due to their negative effect on compactibility of the mixture and, accordingly, the strength of the

modified mixture. Evaluation of the durability of these mixtures and assessment of their performance under cyclic load is important to validate their use.

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Figure Captions

Fig.1. Grain size distribution rubber and 6 mm natural aggregate.

Fig.2. Grain size distribution for investigated material (specification limit as defined by BS EN 14227-1:2013).

Fig.3. Indirect tensile testing configuration.

Fig.4.Methodology of fractal dimension calculation.

Fig.5. Indirect tensile strength for examined mixtures.

Fig.6. Load-diametrical deformation curves for different replacement levels: a. C5R0; b.C5R15; c. C5R30; and d. C5R45.

Fig.7. Effect of replacement on toughness indices.

Fig.8. Sample scans of the failed specimens showing crack propagation through rubber particles: A and B represents the mixtures with 30% and 45% rubber replacement, respectively.

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

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

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

Fig.12. Fractal dimensions for virgin and modified mixtures with different replacement level.

Fig.13. Correlation between mechanical and fractal analysis results.

Table 1: Investigated mixtures, compacity and dry density

Mixture symbol	Compacity factor	Dry density, Kg/m^3	COV, %
C5R0	0.9198	2421.79	0.5
C5R15	0.9189	2395.21	0.65
C5R30	0.9165	2364.96	1.4
C5R45	0.9114	2327.70	0.8

Table 2: Fractal analysis result summary

Mix ID	Fractal dimension	W_s/G_f
C5R0	1.013	103.99
C5R15	1.166	164.40
C5R30	1.219	192.70
C5R45	1.214	189.67

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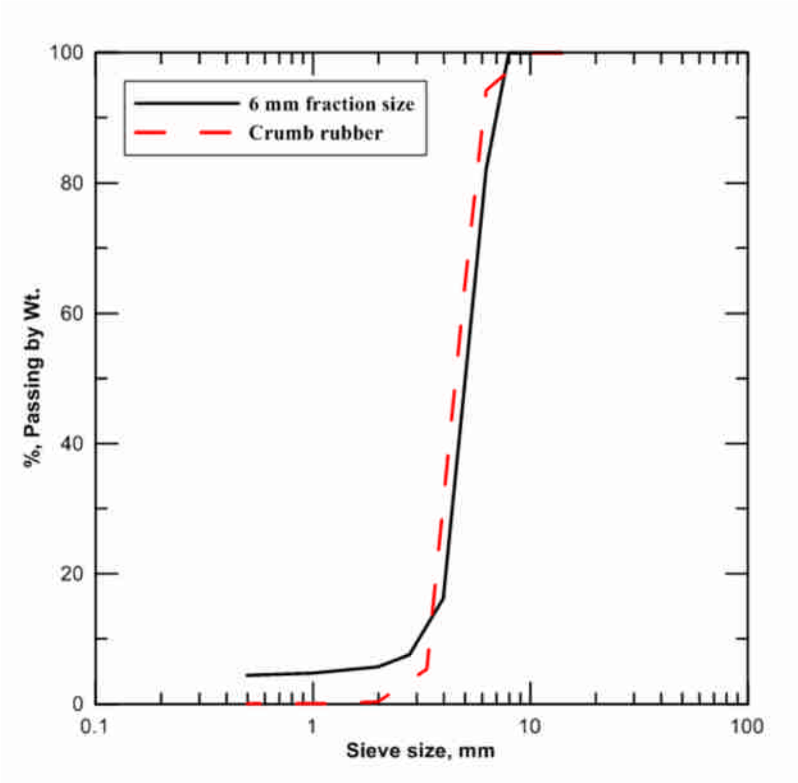

Figure 1: Grain size distribution rubber and 6 mm natural aggregate

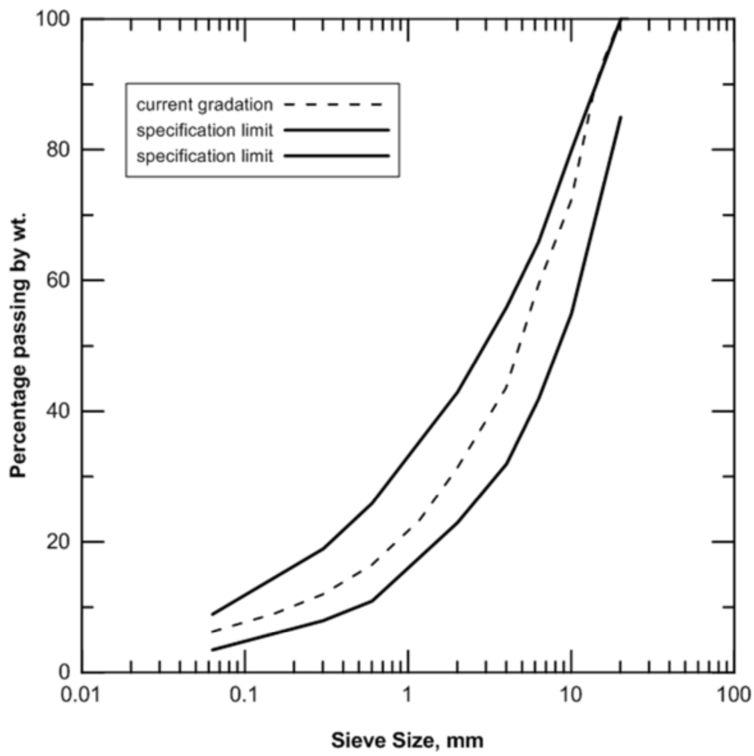

Figure 2: Grain size distribution for investigated material (specification limit as defined by BS EN 14227-1:2013)

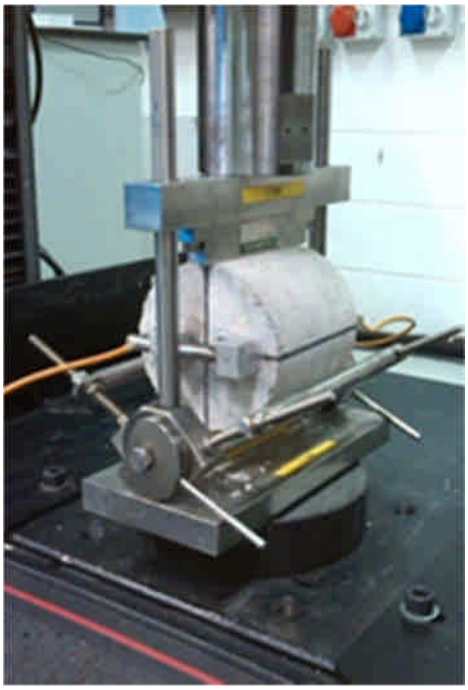

Figure 3: Indirect tensile testing configuration

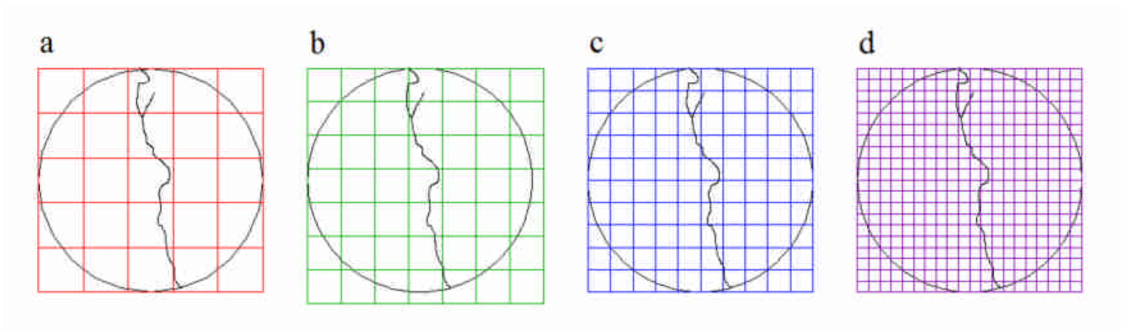

Figure 4: Methodology of fractal dimension calculation

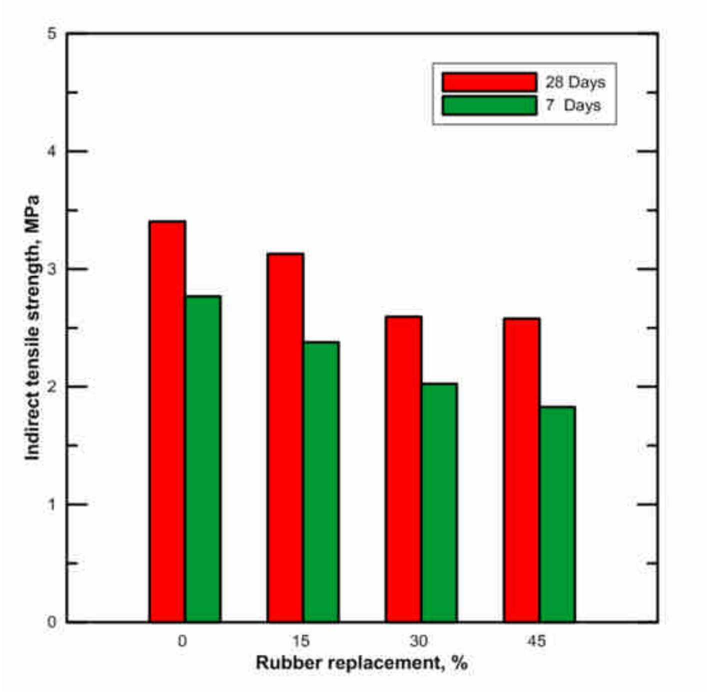

Figure 5: Indirect tensile strength for examined mixtures

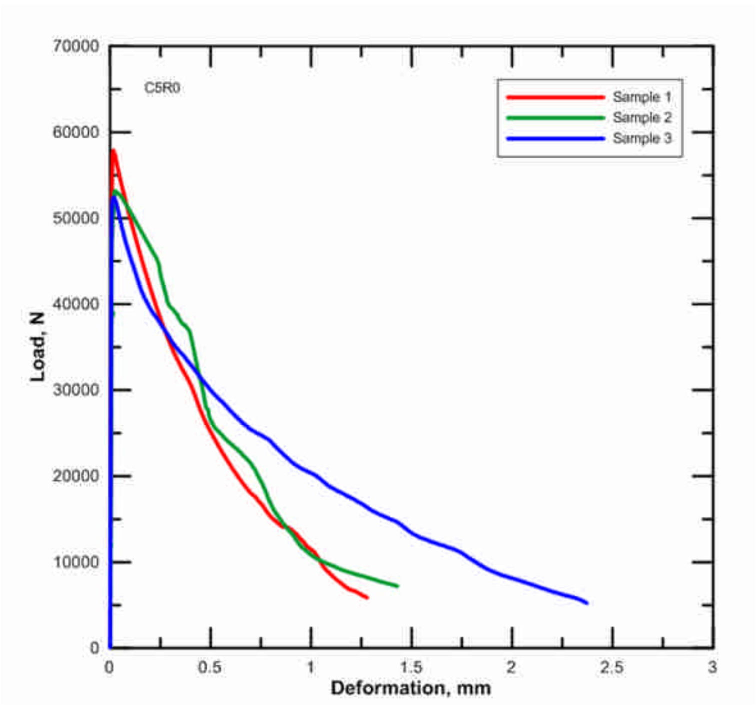

Figure 6: for different replacement levels: a. C5R0; b.C5R15; c. C5R30; and d. C5R45

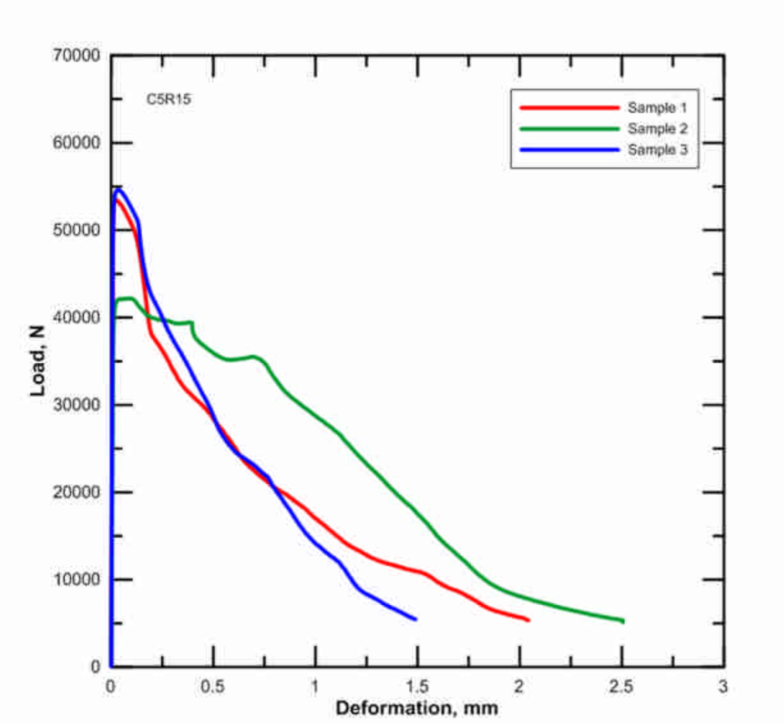

Figure 6: b

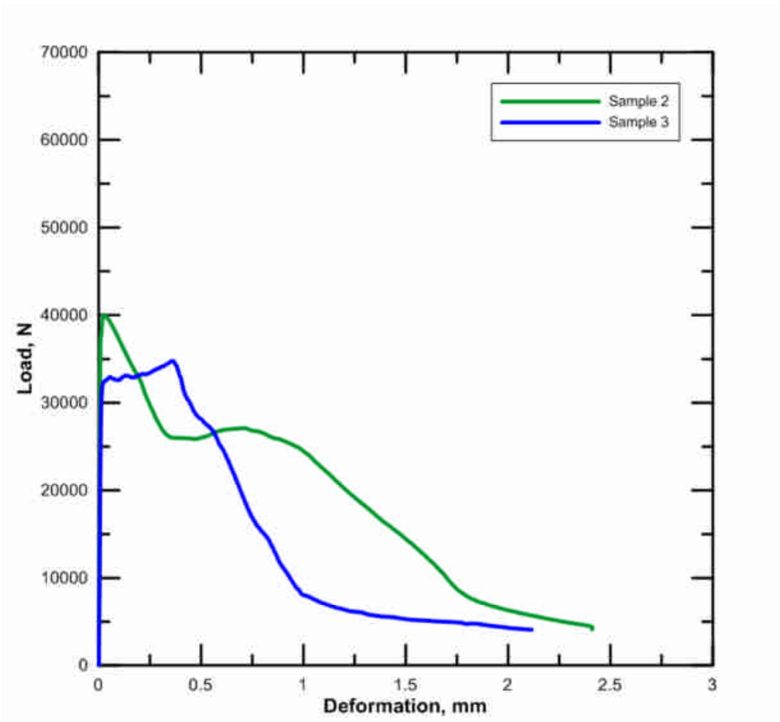

Figure 6: c

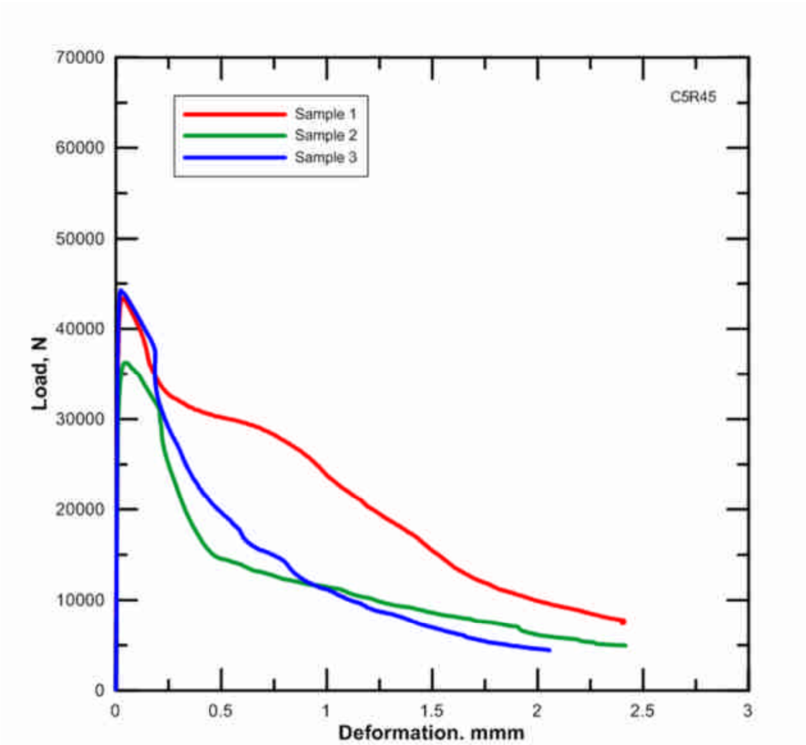

Figure 6: d

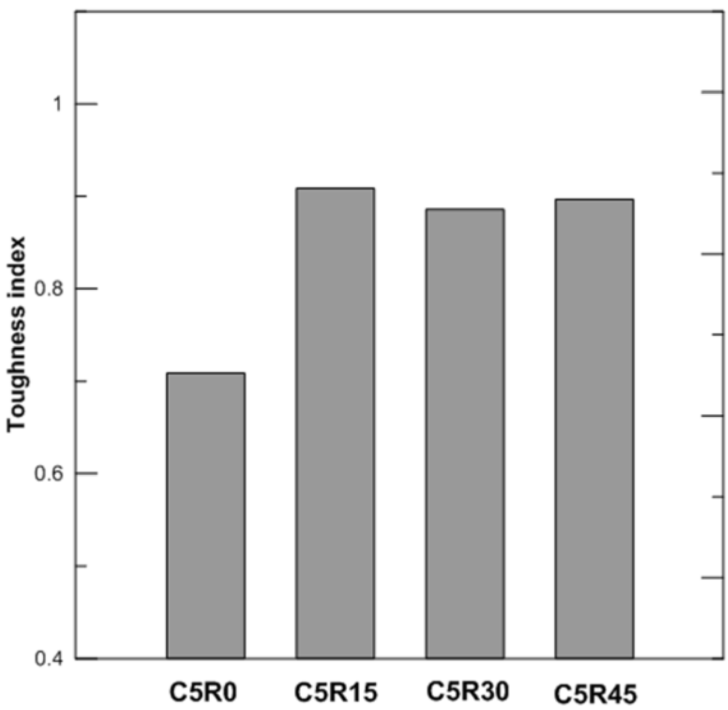

Figure 7: Effect of replacement on toughness indices.

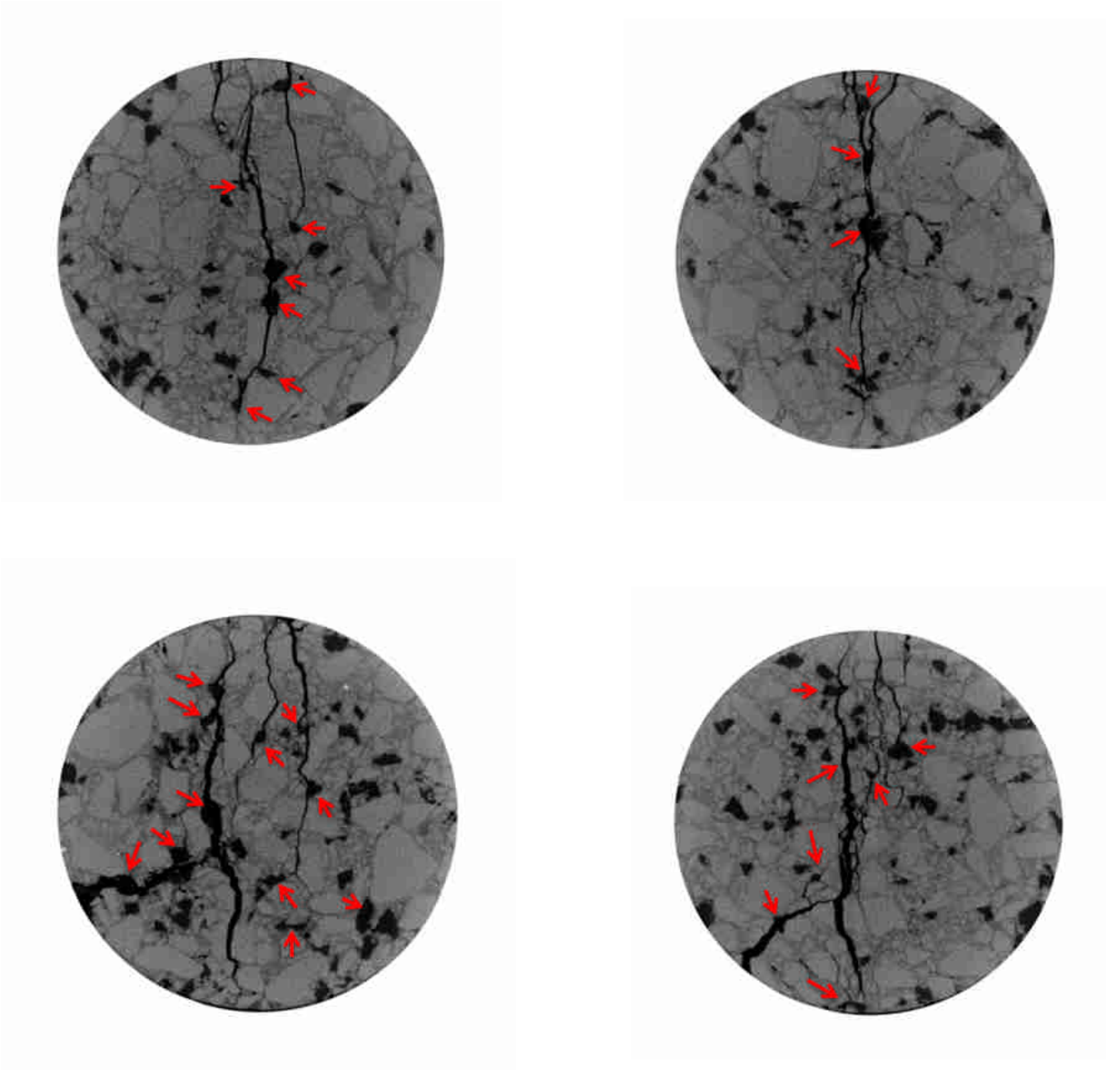

Figure 8: Sample scans of the failed specimens showing crack propagation through rubber particles: A and B represents the mixtures with 30% and 45% rubber replacement, respectively.

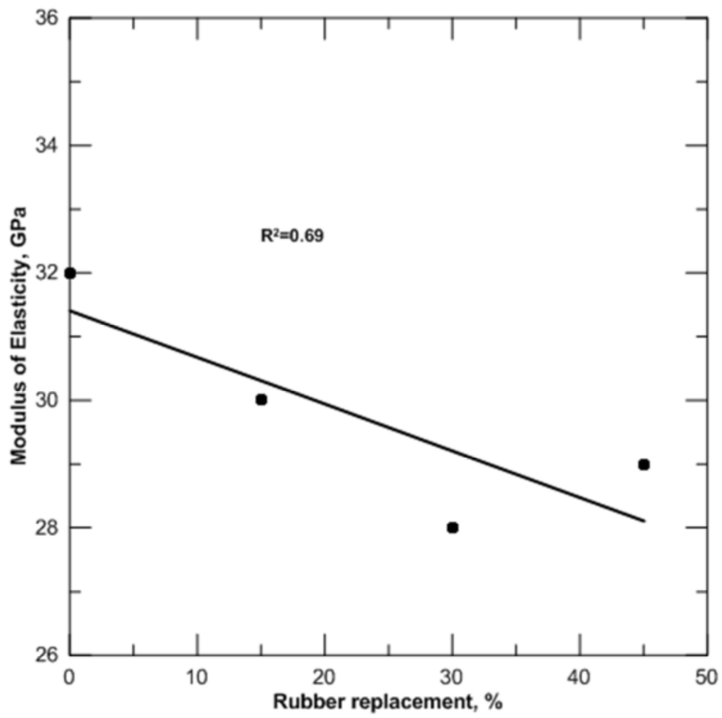

Figure 9: Effect of rubber content on static modulus of elasticity.

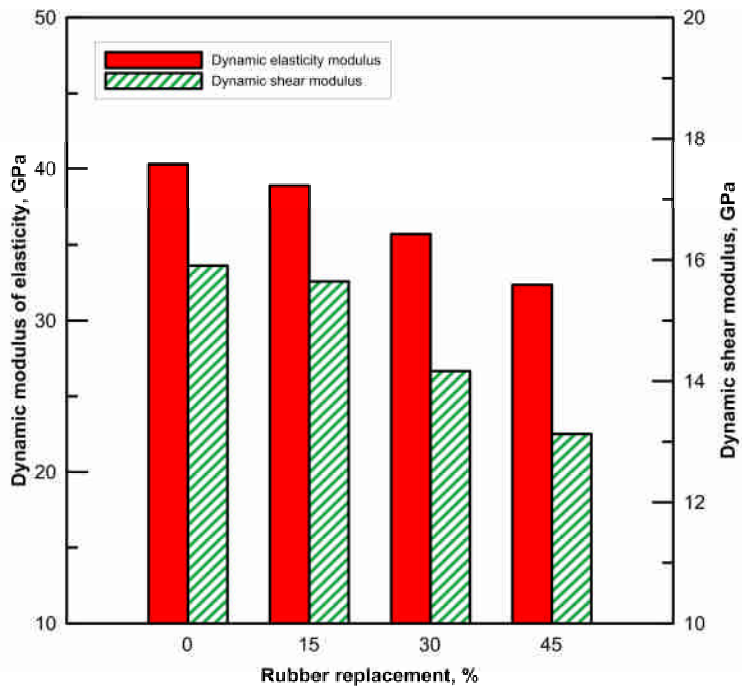

Figure 10: Effect of rubber replacement on dynamic elasticity and shear moduli

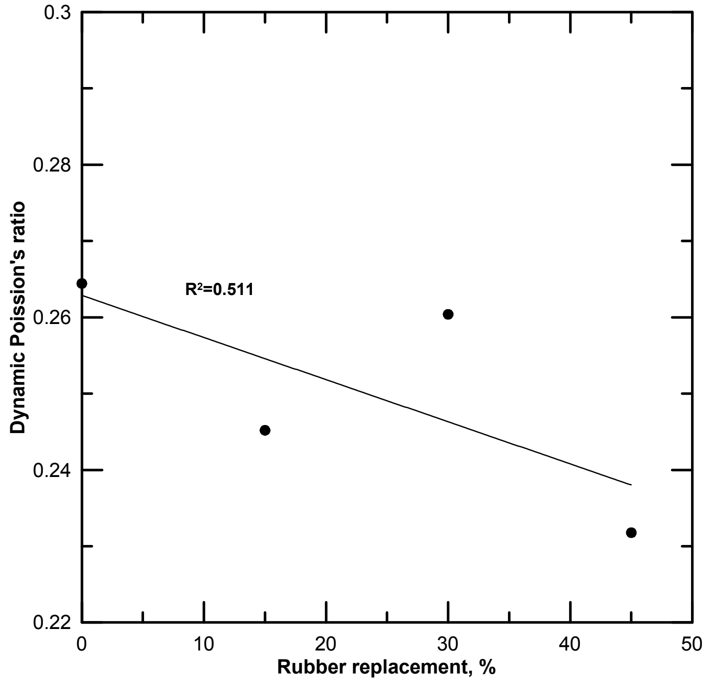

Figure 11: Effect of rubber replacement on dynamic Poisson's ratio

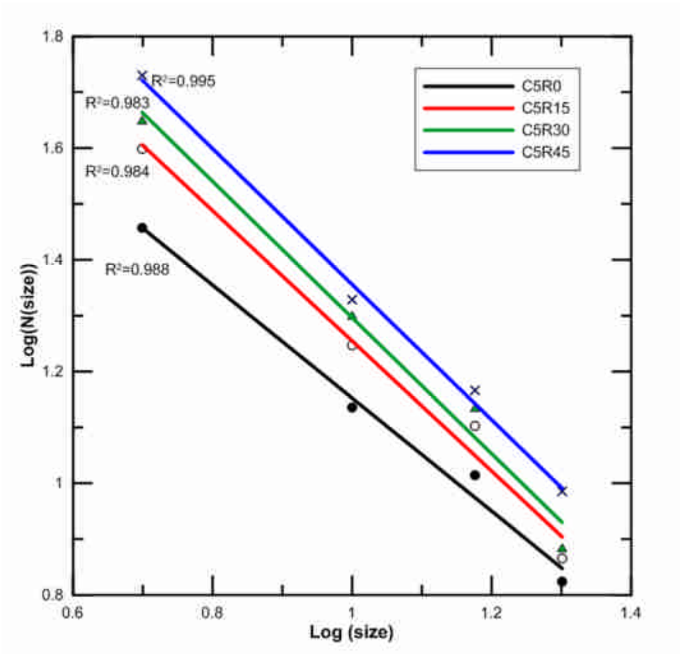

Figure 12: Fractal dimensions for virgin and modified mixtures with different replacement level

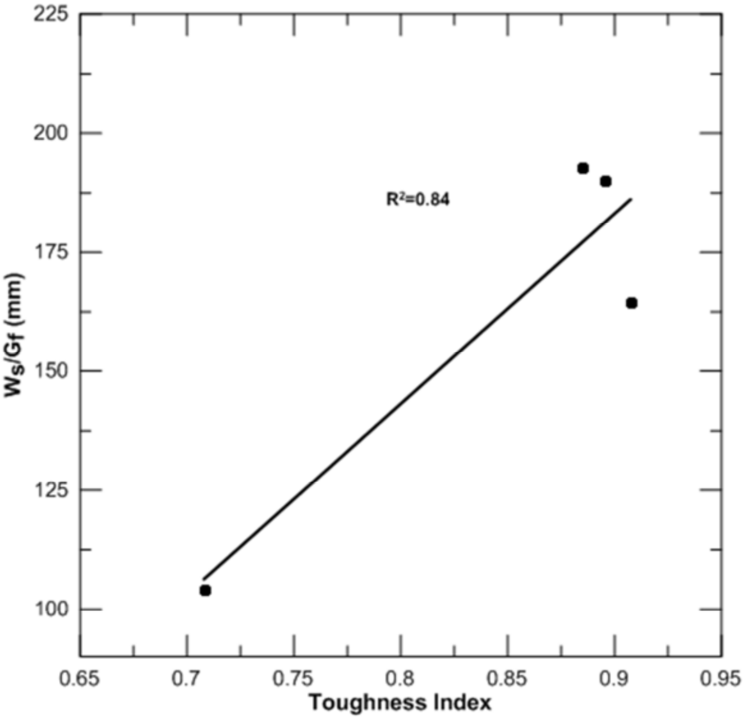

Figure 13: Correlation between mechanical and fractal analysis results