Damage propagation rate and mechanical properties of recycled steel fiber-reinforced and cement-bound granular materials used in pavement structure

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Abstract

Cement-bound granular mixtures (CBGMs) represent an attractive option to increase load-carrying capacity and sustainability in highway construction. However, reflection cracking of overlying pavement layers due to the low tensile strength of CBGMs represents an important obstacle limiting their use. This study is undertaken to investigate how incorporation, in CBGMs, of recycled steel fibers extracted from old tires, at different cement levels may affect their tensile properties related to pavement design. A combination of three levels of cement (3%, 5% and 7% by wt. of aggregate and fiber) and two reinforcement contents (0% and 0.5 by volume of aggregate) was investigated. To comprehensively quantify the benefits of fibers in the presence of variable cement contents, time-dependent fracture and damage propagation were examined quantitatively utilizing a combination of macro-surface cracks, fractal analysis and both image monitoring and processing techniques. The results indicated better tensile strength and toughness after cement and fiber inclusion. Furthermore, increasing the amount of cement accelerates the crack propagation and damage dispersion rate while these two parameters reduced significantly in the case of fiber-reinforced cemented aggregate. All benefits gained from fiber usage are more evident at higher cement contents.

Keywords: fiber-reinforced cement-stabilized mixture; recycled steel fibers; tensile testing; fractal analysis; crack propagation speed; damage propagation rate

1. Background

Cement stabilized aggregate mixture is a cementitious material that consists of aggregate, cement and a small amount of water. Over the years, researchers have attempted to use other stabilizers such as lime (Mohammadinia et al. 2017), flyash (Mohammadinia et al. 2017), kiln dust (Arulrajah et al. 2017) and geopolymers (Arulrajah et al. 2016). To save natural resources and to encourage sustainable solutions, many investigations have been conducted to replace the natural aggregate by recycled aggregate such as recycled concrete aggregate RAC (Li et al. 2010) and recycled asphalt pavement RAP (Taha et al. 2002, Puppala et al. 2017) or including waste aggregate such as a mix of construction and demolition waste CDW (Xuan et al. 2012) and glass materials (Arulrajah et al. 2015).

Cement stabilization of granular materials, intended to be used as a main structural layer within semi-rigid pavements, has been proved as an effective technique giving better protection of weak subgrades and enhanced support for the surface hot mix asphalt layer. However, the inherent crack susceptibility of this layer, either due to shrinkage or due to low tensile capacity, might forms an obstacle that reduces the benefits of the technique. The crack networks that develop normally affect these stabilized layers detrimentally since they reduce the structural integrity, contributing negatively to load-carrying capacity, and most importantly increase the possibility of reflection cracking, especially in the case of wide cracks.

Many attempts have been made to overcome the disadvantages that accompany application of cement stabilization in pavement construction. Thompson (2001), Shahid (1997) and Coni and Pani (2007), for example, tried to use industrial steel fibers as a reinforcement and investigated how such reinforcement might affect the mechanical properties of cement-stabilized aggregate mixtures. Their results indicated the better mechanical behavior of the composite. Different types of fiber have also been used in many applications to improve the properties of different types of chemically stabilized soils (Mirzababaei et al. 2012, Chen et al. 2015, Balkis 2017, Cristelo et al. 2017) . Coni and Pani (2007) claimed that the initial cost of this industrial fiber might make it an uneconomic option while Sobhan and Mashnad (2002) and Sobhan and Mashnad (2003) justified their design in the light of other benefits such as longer fatigue life and reduced layer thickness. Nevertheless, they later attempted to use the waste fibers extracted from old milk containers to reduce the initial cost of the fibers and hence reduce the pavement construction cost while ensuring better performance and a sustainable pavement structure. In their study, Zhang et al. (2013) used polypropylene fibers as a low price reinforcement in CBGMs. Improvement in fracture properties was the main outcome of their investigation. More recently, Farhan et al. (2015) and Farhan et al. (2016) used rubber particles from recycled vehicle tires as replacement for fine aggregate to modify the aggregate mixture and hence ensure better mechanical and cracking behavior. These rubber particles, as their results indicated, affect many of the mechanical properties detrimentally but achieve better cracking characteristics.

In order to improve mechanical properties while ensuring reduced cost and maintaining a sustainable pavement structure, an attempt is made in this paper to use recycled steel fibers from old tires as a reinforcement. Despite the recent use of this recycled reinforcement in different types of concrete as reported in many investigations (Aiello et al. 2009, Angelakopoulos et al. 2015, Caggiano et al. 2015), the use of recycled steel fibers has never been attempted in cement-stabilized aggregate at relatively low cement contents.

Investigation of damage propagation and cracking patterns is of the utmost importance since it will help in the understanding of damage and hence failure mechanisms which will eventually lead to more optimized mixtures (Silva et al. 2009). For concrete mixtures used in different civil engineering structures, many studies have been conducted to examine the crack propagation speed in both plain and fiber-reinforced concretes. Mindess (1995) conducted a study to show how fiber inclusion in normal concrete mixtures affects the crack propagation speed. He reported a decline in crack speed after steel fiber inclusion. Pyo et al. (2016) noted that the number of studies to characterize crack propagation in fiber-reinforced concrete is very limited compared to those performed for plain concrete and, accordingly, they studied the effect of fiber and loading rate on crack propagation speed in ultra-high strength concrete. Their findings indicated a drop in the crack propagation speed due to fiber reinforcement.

To the best knowledge of the authors, all of the above-mentioned studies to investigate the impact of fibers (either industrial or recycled) have focused on the mechanical properties only and no study has so far been conducted to investigate crack propagation in either plain or fiber-reinforced cement-stabilized mixtures. Furthermore, the role that cement content might play in this process is still unclear. Therefore, this study has been undertaken to investigate how fiber inclusion at various cementation levels might affect the mechanical properties and to understand the effect of fiber inclusion on the crack propagation process in cemented aggregate, as a time-dependent phenomenon.

2. Experimental methodology

2.1 Materials

A limestone aggregate from Tunstead Quarry, Derbyshire, UK was used in this study. The gradation is shown in Figure 1 together with specification limits.

To reduce the cost and increase the sustainability of highway pavement construction, recycled steel fibers (Figure 2) were incorporated to reinforced cement-stabilized aggregate mixtures. These were extracted from old vehicle tires by a shredding process. The maximum fiber volumetric content attempted in cement-bound granular materials (CBGMs) is 1% as documented in previous literature (Shahid 1997, Thompson 2001). Trial investigations at the start of the current experimental program showed there was difficulty in achieving uniform fiber dispersion due to fibers balling at 1% volumetric content. To ensure uniformity of fiber dispersion, a 0.5% volumetric content was selected.

Portland cement (CEM I 52.5 N) was used for the purpose of stabilization and binding the mixture components. To examine the effect of stabilizer content on the performance and effectiveness of fibers in CBGMs, three different stabilization levels, 3%, 5% and 7% by dry weight of aggregate and fibers were used. These cement contents, together with design water contents, were chosen based on the results of a previous investigation (Farhan et al. 2016).

2.2 Mix design

First, aggregate fractions were combined to produce CBGM 2-0 (BS EN 14227-1:2013 (British Standards Institution 2013)). To avoid any variability in aggregate gradation, each specimen was batched, mixed and compacted individually.

In this paper, a combinations of two fiber contents (0 and 0.5% by weight of dry aggregate) and three cement contents (3%, 5% and 7% by weight of dry aggregate plus fibers) were evaluated. For these fiber-reinforced CBGMs mixtures (i.e. FCBGMs), water contents were proportioned by the weight of dry aggregate, cement and fibers. Although a volumetric basis should be logically used to determine the required amount of water, using weight proportions resulted in negligible error due to the small amount of fibers used. Table 1 shows the investigated mixture designations and proportions.

2.3 Mixing, manufacturing and curing

The aggregate was mixed first with cement for a minute. Then, the design water content was added and mixed for two minutes. Lastly, the steel fibers were added and mixed for another one minute with the wet cemented aggregate. The mixing process was conducted manually.

The fresh cemented aggregate-fiber mixture was compacted in lubricated steel molds using a Kango 638 vibratory hammer. All compacted specimens were kept molded for the rest of the day then demolded, wrapped, and stored in wet plastic bags for 28 days. After the curing period, specimens were trimmed to obtain 100 mm x 100 mm cylindrical samples. As can be observed in Figure 3a, even for lower cement content, specimens looked intact and no pulling out of fibers was noticed, which suggests good interaction and bonding with aggregates.

2.4 Indirect tensile testing setup

CBGMs are normally classified through system II of European standards BS EN 14227-1:2013 based on their tensile strength. Adopting tensile strength comes from the fact that all cementitious stabilized layers within semi-rigid pavement structures are designed to resist the tensile stresses generated at lower boundary. Therefore, in this paper, tensile properties were utilized to evaluate the investigated mixtures. Indirect tensile testing was conducted on specimens at 28 days using a UTM-Instron with 200 kN capacity by applying a diametrical compression on the specimen. The application of this load was achieved through a curved steel plate. The latter step was preceded by marking of the specimen center to avoid eccentricity of loading. Indirect tensile strength (ITS) was calculated as $ITS = \frac{2P}{\pi \mathrm{hd}}$, where P= Peak load, N; h= specimen thickness, mm and D= specimen diameter, mm. Density was measured using the water-displacement method.

2.4.1 Stress- strain curves, absolute toughness and ductility

During vertical load application, horizontal strains were captured using non-contact equipment. This system is a video-based 2D measuring tool, called “Video Gauge”, for observing a face of a specimen under test. It consists of a lighting source and a high-resolution camera. The measurement is conducted by employing a digital image correlation (DIC) algorithm provided in the accompanying software. Figures 3b & 3c illustrate the testing setup and instrumentation system used in this investigation. Specimen faces were first speckled by application of a thin white matt paint followed by a thin black paint as shown in Figure 3a, c. The test was performed at a rate of 0.5 mm/min.

The load-carrying capacity or material toughness was calculated as the area under the stress-strain (Shahid 1997). For all investigated mixtures, this area was calculated up to strain of 2.5%. This approach evaluates the effect of both ductility and strength on material toughness due to steel fibers inclusion (Sobhan and Mashnad 2000). The formula due to Park (2011) was used to evaluate material ductility in terms of deformability index (Di) which can be calculated as, $D_i = \Delta_{fibrous}/\Delta_{nonfibrous}$, where $\Delta_{fibrous}$ and $\Delta_{nonfibrous}$ are the horizontal strains at peak stresses of fibrous and non-fibrous specimens, respectively.

3. Results and explanations

3.1 Combined effect of cement and fibers on indirect tensile strength and density

In general, the observed trend (Figure 4) is that the ITS value increases as cement content increases for both CBGMs and FCBGMs. This is logical in the light of the improvement occurring in the bond between aggregate particles with increase of cement content which, in turn, increases hydration products after curing. This will ensure, at the same time, better bond with fibers which increases the tensile strength. This is because the fibers inside the specimen will carry part of the load and also might prevent crack propagation and hence ensure intactness of the specimen. For this reason, the improvement in ITS value after fiber incorporation seems, as shown in Figure 4, most obvious at higher cement content. The inclusion of fibers at 3% cement content does not have any effect on ITS whereas the percentage improvement in ITS value is 16% and 40% due to fiber incorporation at 5% and 7% cement content, respectively.

Except for lightly cemented mixtures, densities rose after fiber reinforcement as presented in Table 1. This is because the specific gravity of the added fibers is much higher than the natural limestone aggregates.

3.2 Combined effect of cement and fiber on stress-strain curves and toughness

The stress-strain relationships for the mixtures investigated are shown in Figure 5. In all CBGMs with different cement contents, strain-softening occurs following initial cracking whereas this is not the case for fiber-reinforced mixtures. FCBGMs showed a strain-hardening zone after first crack initiation enabling them to carry an additional tensile load before reaching their ultimate capacity. The presence of enough cement (≥ 5%) allows the reinforcement system to carry the applied tensile stress after yielding of the cemented aggregate. After reaching their ultimate strength, all mixtures at all cement and fiber contents showed strain-softening. However, the degree of softening differed depending on cementation and reinforcement levels.

In terms of toughness improvement (Figure 6), the more the cement content the better the toughness of both reinforced and unreinforced mixtures. Furthermore, toughness improvement after reinforcement depends, to a large extent, on the cement content. In heavily cemented mixtures, fiber addition improves toughness significantly compared to lightly cemented mixtures; increases of 129%, 247% and 429% after 0.5% fiber incorporation are seen at cement contents of 3%, 5% and 7%, respectively. This might be attributable to a lower rate of crack propagation because the presence of fibers arrests the cracks and the degree to which crack propagation is inhibited is largely governed by the bond strength (i.e., the amount of cement) between the fibers and surrounding materials.

3.3 Combined effect of cement and fibers on ductility

Strain at peak stress generally decreases in CBGMs as the amount of cement increases as shown in Figure 7. This is because, as is well-known, the addition of more cement increases the brittleness of the mixture which may lead to failure with little deformation. In contrast, after 0.5% fiber reinforcement, the strain at peak increases substantially. This improvement, as was obtained from other findings, also seems to be governed by the cement content. Consequently, the trend of deformation index, due to fiber inclusion, is for significant improvement as cement content increases, with a deformability index increase of 16 and 11 times after fiber addition at cement contents of 5% and 7%, respectively compared with that at 3%. It seems that the presence of fibers in a highly cemented "environment" causes an increased restraint which in turn reduces the deformation of the specimens. This may explain the reduced deformability of fiber-reinforced mixtures at 7% cement content compared to 5%. Enhancement in ductility due to fiber reinforcement was also reported by Kim et al. (2010), who studied the effect of fibers on ductility of concrete. The effect of restraint was also noticed in their investigation where the largest reported ductility was at a lower fiber content, 0.25%.

4 Time-dependent fracture damage propagation

One of the most important problems, representing a serious challenge to the application of cement-bound granular mixtures is their sensitivity to cracking, either from bottom-up fatigue or from shrinkage. If they are wide, these cracks contribute to a reduction of the load-carrying capacity of the stabilized layer and load transfer capacity across the cracks, and most importantly cause reflection cracks (Adaska and Luhr 2004). The latter cracks occur in the surface asphaltic course and contribute to a gradual deterioration of the pavement structure. Logically, the rate of such deterioration is largely governed by the rate of which the main structural layer (CBGM layer in this case) deteriorates. Thus, studying how incorporation of fibers might affect the cracking process in the main structural layer (stabilized base course) is an important issue that needs to be clarified in order to understand the damage process and failure mechanism. In addition, this will contribute to explaining and understanding the relationship between cracking features at the meso-scale level and macro-scale properties.

In concrete, which is a different cementitious material, some researchers have studied, quantitatively, the cracking patterns of fiber-reinforced mixtures and attempted to relate them to mechanical properties. For example, Stang et al. (1990) and Yan et al. (2002) studied the cracking patterns of concrete mixtures reinforced with different types of fiber. Their conclusions indicated that a relationship existed between cracking pattern and mechanical properties. To understand the failure sequence of different types of composites, others (Curbach and Eibl 1990, Pyo et al. 2016) have attempted to monitor the formation of cracks in concrete specimens during load application as a time-dependent process by evaluating the crack propagation speed.

This paper represents the first attempt to investigate the time-dependent fracture of fiber-reinforced and cement-stabilized aggregate mixtures intended to be used as a base layer within a semi-rigid pavement. This was conducted in terms of crack propagation speed and crack diffusion rate. Both of these parameters were characterized, quantitatively, by monitoring the propagation of damage during load application. As is well known, the failure of a pavement structure is a time-dependent process; therefore, the idea of this part of the study was also to investigate how stabilizer (cement) affects the damage process of FCBGMs and to compare this with CBGM behavior, which will eventually lead to understanding of the feasibility of fiber reinforcement in a pavement structure. Such studies, as reported by Stang et al. (1990) and Silva et al. (2009), may also provide essential information to develop models to help simulate the cracking process of such materials.

4.1 Crack propagation speed

To monitor the development of the cracks during tensile loading, the non-contact DIC technique described earlier was used to capture videos at a rate of 1000 fps. These videos were used to obtain images (at selected stages of loading) which were then used to estimate the crack lengths. Figure 8 shows samples of captured images at various loading stages for some of the investigated mixtures. Crack propagation speeds were calculated by averaging the crack length-time curves as adopted by Pyo et al. (2016). To estimate the crack lengths, the latter authors used the Canny edge detector algorithm to extract a map of the cracks. In this paper, however, another approach is suggested and has been implemented to calculate the crack lengths. This is due to the nature of the speckled testing surface that makes both cracks and dots appear the same in the image after binarization. Such appearance in the testing surface makes it impossible to extract the cracking patterns using the available thresholding algorithms (Figure 9 a, b). In the suggested methodology, the captured images were inserted into a CAD system, then these images were scaled up to make a meaningful comparison. After that, these cracks were digitized (Figure 9c) using software facilities. Total crack lengths were measured through the CAD software tools. To reduce the processing time, these images were selected at equal time intervals, which depended on the testing time of the specimens. Figure 10 illustrates samples of estimated crack length-time relationships which were used to calculate the crack propagation speed of the investigated mixtures.

A summary of crack propagation speeds for different mixtures is presented in Figure 11. As is clear from this figure, the addition of more cement to CBGMs accelerates the propagation speed of cracks which might indicate that the rate of deterioration is higher in the case of stiff materials and also ductility decreases because the cracks propagate rapidly before showing further deformation. Using steel fiber reinforcement, in general, reduces the crack propagation speed as shown in the previous figure. This is because the presence of fibers arrests and bridges the cracks and hence reduces their propagation speed. This finding is consistent with outcomes of the studies conducted by Mindess (1995) and Pyo et al. (2016) which confirmed a reduction in the crack speed due to fiber inclusion.

Another interesting new finding is the clarification of the role that cement content plays in crack propagation speed. Figure 11 indicates that incorporation of higher cement content in the case of FCBGMs is found to decelerate the propagation of the cracks significantly compared to mixtures with low cement content. Crack speed decreased 3.6, 7.6 and 14 times due to incorporation of 0.5% steel fiber at 3%, 5% and 7% cement content, respectively. This can be attributed to the higher bond level between the fiber and the adjacent materials that accompanied the higher cement content which enables these fibers to be more effective in crack arresting-bridging and hence reduces the speed of crack propagation.

4.2 Rate of damage (diffusion of cracks)

In addition to the crack propagation speed, another important parameter that affects performance of a stabilized layer is the diffusion rate (or the degree of dispersion) of the cracks inside the body of the cemented layer. The idea of this part of the study was to evaluate diffusion rate (i.e., the rate of damage) as a time-dependent process. This will be achieved through implementation of the fractal geometry concept conducted in terms of fractal dimension by monitoring the evolution of fractal dimension during the load application. Another objective is to estimate the fractal dimension at the end of the test to evaluate the amount of damage that has occurred. Higher fractal dimension indicates, generally, more disordered cracks, which means higher damage (Carpinteri and Yang 1996). Less cracks diffusion or localization of cracks is expected to accelerate the formation of reflection cracks whereas more diffused cracks may help to reduce the potential reflectivity of cracks due to reduced stress concentrations. Logically, fractal dimension should increase with the load application process which means that the damage increases as load increases. However, an interesting question in this regard is: to what extent the fiber might affect the damage rate and the final damage of the cemented aggregate and what is the role that the amount of cement might play in this process.

To answer this question, the evolution of fractal dimension was estimated during the load application stages for both FCBGMs of different cement content and these were compared with the matching unreinforced mixtures. The following methodology was suggested and implemented: as was conducted in the previous part (Section 4.1), the cracks were extracted at each stage of load application. Next, the fractal dimension was determined using the box-counting method (Chiaia et al. 1998, Hassan 2012, Erdem and Blankson 2013). Then, the fractal dimension-time relationship was constructed and the slope of this curve was computed as the damage evolution rate of the mixture. Figure 12 shows samples of the estimated fractal dimension-time relationships.

A summary of the damage rate results is illustrated in Figure 13. It can be observed from this figure that, for CBGMs, the rate of fractal dimension propagation (i.e., the rate of damage) increases for the stiffer mixtures as compared with less stiff materials. The rate of damage for FCBGMs, on the other hand, decreases as a consequence of the fiber incorporation at all cement contents. Interestingly, there was a greater reduction in the rate of damage when the fiber-reinforced mixtures were heavily cemented. The rate of damage decreased by a factor of 4, 4.4 and 14.6 times upon the addition of 0.5% fiber reinforcement at 3%, 5% and 7% cement contents, respectively.

These findings, in fact, also reveal the mechanism behind the toughening process of fiber-reinforced mixtures. As can be seen from Figure 14, the reduction in damage correlates well with toughness improvement. In other words, the mixtures of higher toughness have normally had less damage rate (and, of course, lower crack speed) which means that these mixtures are able to carry the additional load after their peak because they are relatively intact and the fibers carry the greatest part of the tensile loads.

To evaluate the possible mitigation of reflection cracking due to the reduction of crack localization in the FCBGM layer, the fractal dimensions were calculated at the end of testing as stated earlier. Figure 15 illustrates the fractal dimensions for the different mixtures. The general trend is an improvement in the fractal dimension values due to fiber reinforcement which confirms greater crack diffusion inside unreinforced CBGMs. Although this improvement is only about 9%, using higher fiber content will ensure higher dispersion of damage. Furthermore, in combination with the bridging effect this may reduce the reflectivity of the cracks significantly. In their study, Yan et al. (2002) reported that the tensile strength of fiber reinforced concrete, measured through the flexural test, increased proportionally as fractal dimension increased. The fractal dimensions in this paper are also found to have some relationship with the indirect tensile strength as shown in Figure 16.

5 Horizontal strain rate

Figure 17 shows a sample of the horizontal tensile strains developed during the application of vertical diametrical compression (applied at a rate of 0.5 mm/min.). The slopes of these average straight lines are considered as the rate of applied horizontal strain. Figure 18 illustrates a summary of these horizontal strain rates. The latter figure indicates that the horizontal strain rate increases with the addition of more cement to the CBGMs while in FCBGMs, an inverse trend can be noticed. The highest reduction in developed horizontal strain occurred at high cement levels, where inclusion of 0.5% fiber-reinforcement in the highly cemented mixture reduced the strain rate 20 times compared to 3 times at low cement content. Most of the developed tensile stresses are, in fact, absorbed by the fibers at both micro and macro scale levels since all cementitious materials are weak in tension. So, when the micro-crack first develops, all tensile stresses are taken by the fibers. Therefore, in this process, the presence of cement plays an important role since it will increase the bond strength of the fiber which in turn increases the tensile resistance.

Apart from the testing configuration, many researchers have found a relationship between the rate of strain and crack propagation speed. For example, a logarithmic relationship was reported in Pyo et al. (2016)'s study. John and Shah (1986) and Curbach and Eibl (1990) found that the logarithm of strain rate is related linearly with the logarithm of crack speed. In this paper, a logarithmic relationship was also found (Figure 19). This suggests that regardless of the nature of the cement-stabilized aggregate (i.e., the degree of binding and gradation of different cementitious materials), these mixtures behave in a similar way to that observed in concrete mixtures. The rate of damage seems also to be affected by the rate of strain and a logarithmic relationship is also found, as illustrated in the Figure 19.

Comparing and contrasting crack speeds (at each strain level) of both CBGMs and FCBGMs with those for plain and fiber-reinforced concrete mixtures (Zhang et al. 2015, Pyo et al. 2016) reveals that the cracking speed of the former mixtures is always less (for the same loading rates) than those of the latter concrete mixtures, as shown in Figure 20. This is, logically, attributable to the greater amount of cement that the concrete mixtures have, compared with those used in cement-stabilized aggregates. This might suggest that, from the crack propagation speed point of view, the use of cement-stabilized aggregate mixtures as reinforced layers within a pavement structure is better than that of fiber-reinforced concrete.

6 Conclusions

In order to optimize and exploit all recycled steel fiber properties, this paper has examined the effect of cement content on the behavior of fiber reinforced cement-bound aggregate mixtures and unreinforced mixtures as well. To understand this behavior, both macro-scale mechanical properties and time-dependent damage at a meso-scale level have been investigated interactively and in a synergistic way. Based on the findings of this study, the following main conclusions can be stated:

1. Using more cement generally improves the tensile strength of both reinforced and unreinforced cement-stabilized mixtures. Significant improvement was obtained at higher cement contents when including steel reinforcement. Therefore, to ensure longer pavement life and/or less pavement thickness, it would be sensible to consider use of fiber at higher cement contents.

2. Regarding the increase in toughness for the investigated mixtures (CBGMs and FCBGMs), a significant improvement occurred with highly cemented mixtures. Nevertheless, the

toughness increased after fiber inclusion at all cement contents. Also, cemented mixtures become more ductile after fiber reinforcement and this improvement is more obvious with 5% or more cement inclusion. The toughness of fiber-reinforced mixtures comes from a lower damage propagation rate (i.e., lower diffusion rate of cracks inside FCBGMs) which keeps them intact for a relatively long period compared to CBGMs.

3. Using of a greater cement content led to a higher crack propagation speed in the case of mixtures containing no fibers. This means there will be more pavement deterioration after reaching the peak strength of the materials which, in turn, would necessitate maintenance operations that may be expensive or unavailable. On the other hand, use of steel fibers (extracted from waste tires) in cemented mixtures reduces the crack propagation speed at all cement contents with the greatest reduction occurring at high cement contents. This would suggest only a gradual deterioration of the FCBGM until the pavement reaches its ultimate capacity and, even after this stage, would probably result in a lengthy period before maintenance application is needed.

4. The rate of crack diffusion increases as cement content of the CBGMs increases which means that a highly cemented pavement layer will deteriorate more rapidly compared with mixtures containing less cement. With high cement content, if necessary, the use of fiber will contribute to delaying the rate of crack diffusion and hence ensure longer pavement life. Unlike lightly stabilized CBGMs, increasing the amount of cement in FCBGMs effectively decreases the rate of damage propagation.

5. In the light of the benefits obtained from fiber incorporation at high cement content, it is recommended that this reinforcement should be used with a cement content not less than 5%.

By combining these results, it can be concluded that incorporation of recycled steel fiber reinforcement at high cement content is most beneficial in CBGMs since this will result in significant improvement of indirect tensile strength. In addition, it will delay the crack propagation speed and crack diffusion rate. The implications of these findings are a reduction in the required thickness of the stabilized layer and a delay in pavement failure. In addition, this reinforcement will also reduce the decay of the pavement after reaching its service life, which will provide more time before maintenance is required – important in cases of limited funds for such pavement projects.

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Figure Captions

Figure 1: Gradation of aggregate.

Figure 2: Appearance of the steel fibres extracted from old vehicle tires.

Figure 3: Sample preparation (a); Testing setup (b) and close-up view (c) of indirect tensile testing.

Figure 4: Effect of fiber reinforcement on ITS values.

Figure 5: Stress-strain curves for different fiber and cement levels: a. C3F0; b.C3F0.5; c. C5F0; d.C5F0.5; e. C7F0 and C7F0.5

Figure 6: Absolute toughness for different of fiber and cement contents.

Figure 7: Deformability properties for various investigated mixtures.

Figure 8: Selected crack propagation stages for some of the investigated mixtures: a. C3F0; b. C3F0.5; c. C7F0 and d. C7F0.5

Figure 9: Extracting cracking patterns: a. cracked section; b. image binarization; c. digitization of the cracks and d. extracted cracks.

Figure 10: Samples of crack length propagation versus time used to estimate crack propagation speeds.

Figure 11: Summary of crack propagation speeds for CBGMs and FCBGMs.

Figure 12: Samples of fractal dimensions against time, used to estimate fractal dimension propagation rate.

Figure 13: Summary of damage propagation rate expressed as fractal dimension evolution rate.

Figure 14: Toughness- damage rate relationship.

Figure 15: Terminal fractal dimensions for investigated mixtures.

Figure 16: ITS-Fractal dimension relationship.

Figure 17: Samples of horizontal tensile strain development during the application of vertical compressive displacement at constant rate.

Figure 18: Summary of developed horizontal tensile strains at different cement contents.

Figure 19: Relationship of cracking speed and damage rate with horizontal tensile strain.

Figure 20: Comparison with previous crack speed-strain rate relationships obtained for different types of concrete mixture.

Table 1: Mix designation, proportions and densities of different components

Mixture ID	cement content[1],%	Fibers content[2],%	Water content[3],%	Density, kg/m^3
C3F0	3	0	4.5	2534.90 (4.4)*
C5F0	5	0	4.6	2532.24 (2.2)
C7F0	7	0	4.7	2528.90 (3.9)
C3F0.5	3	0.5	4.5	2517.51 (6.6)
C5F0.5	5	0.5	4.6	2539.70 (2.1)
C7F0.5	7	0.5	4.7	2539.95 (7.3)

[1] by the weight of dry aggregate (and fibers for reinforced mixes).

[2] by the weight of dry aggregate.

[3] by the weight of dry aggregate, (fiber for reinforced mixes) and cement.

*the numbers in the bracket are standard error of the mean

Figure 1: Gradation of aggregate.

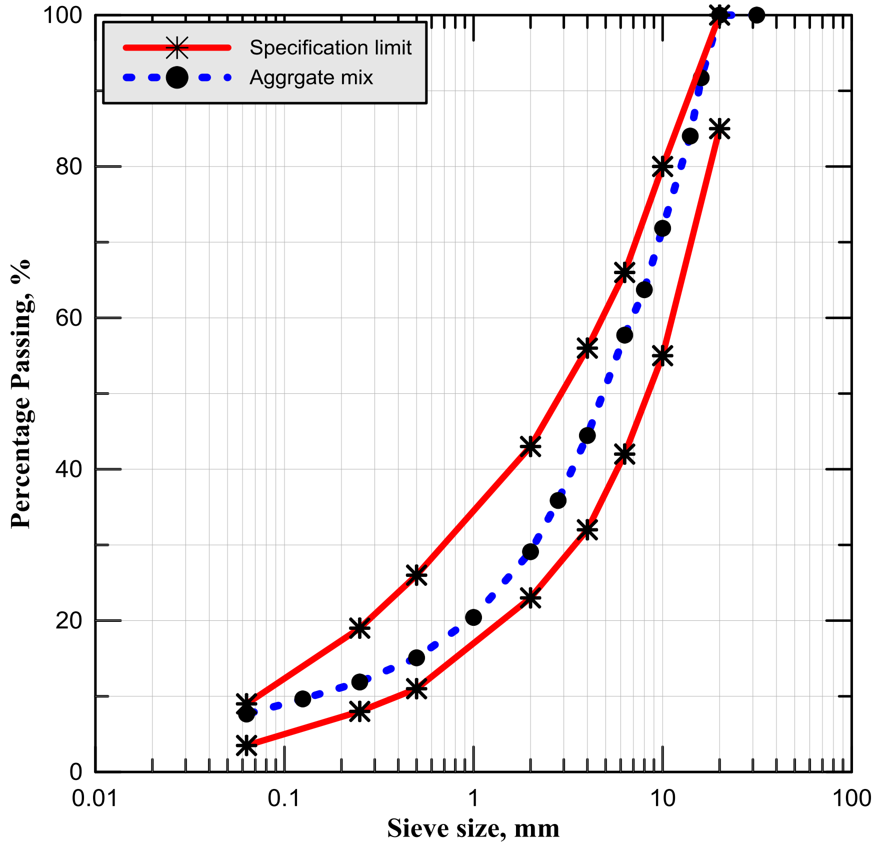
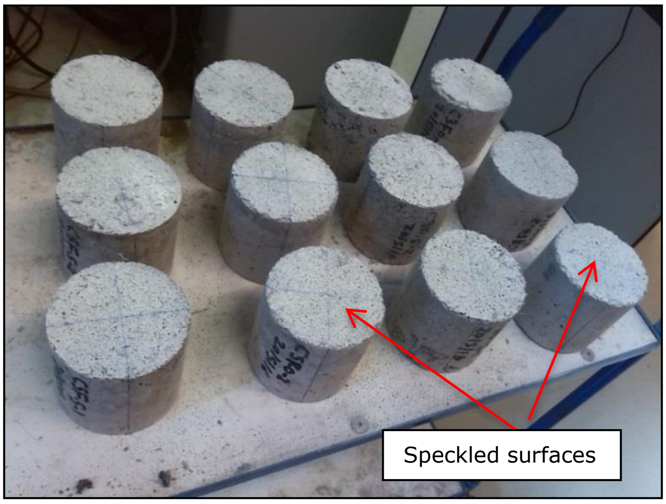


Figure 2: Appearance of the steel fibres extracted from old vehicle tires.

Figure 3: Sample preparation (a); Testing setup (b) and close-up view (c) of indirect tensile testing

a



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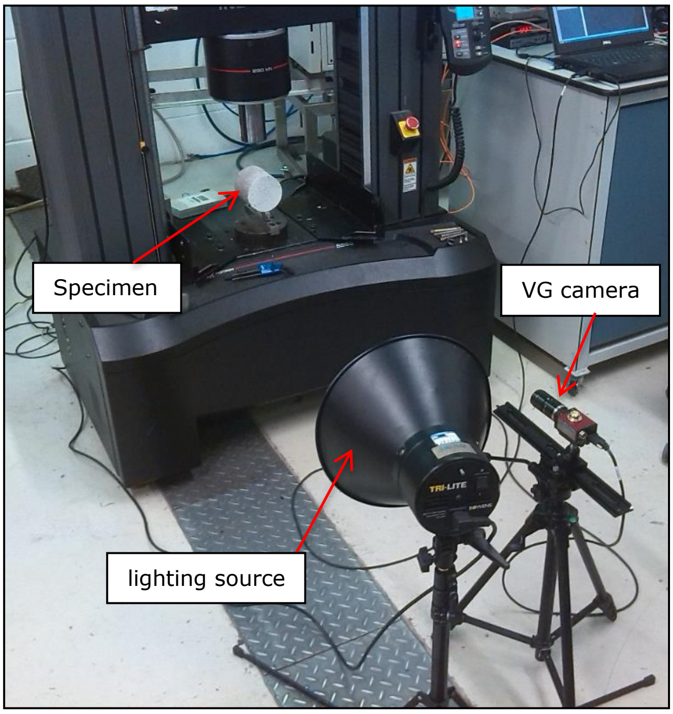

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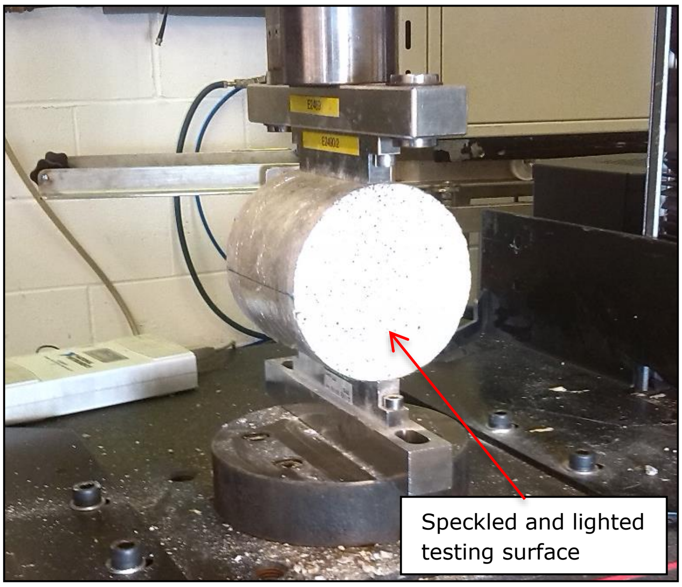


Figure 4: Effect of fiber reinforcement on ITS values.

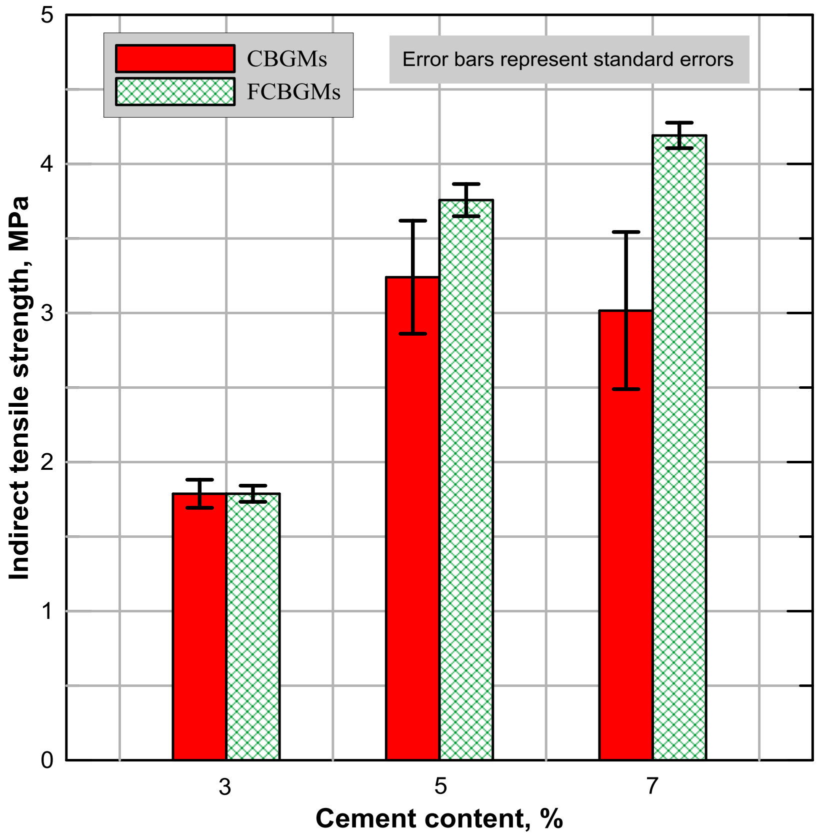


Figure 5: Stress-strain curves for different fiber and cement levels: a. C3F0; b.C3F0.5; c. C5F0; d.C5F0.5; e. C7F0 and C7F0.5

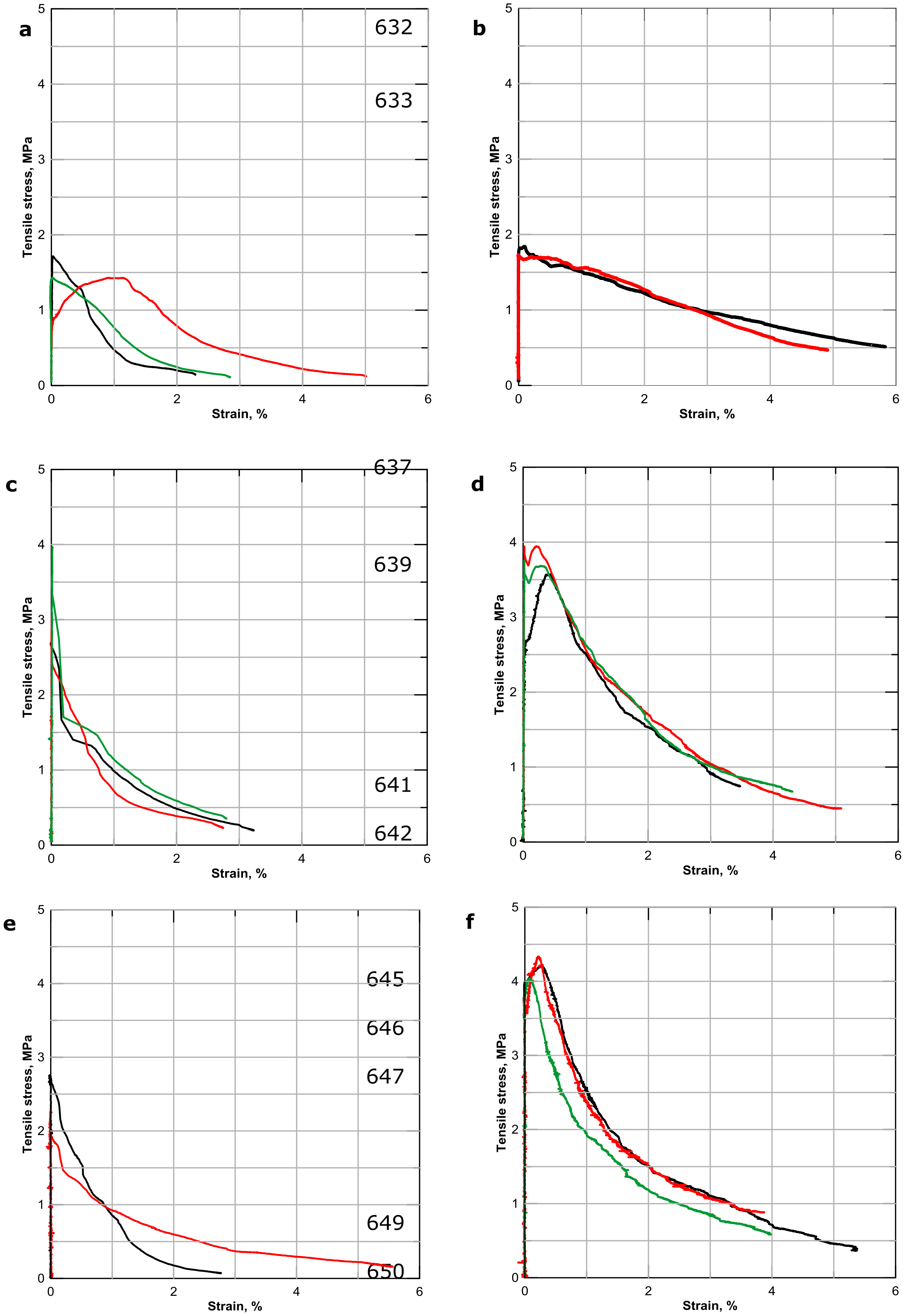


Figure 6: Absolute toughness for different of fiber and cement contents.

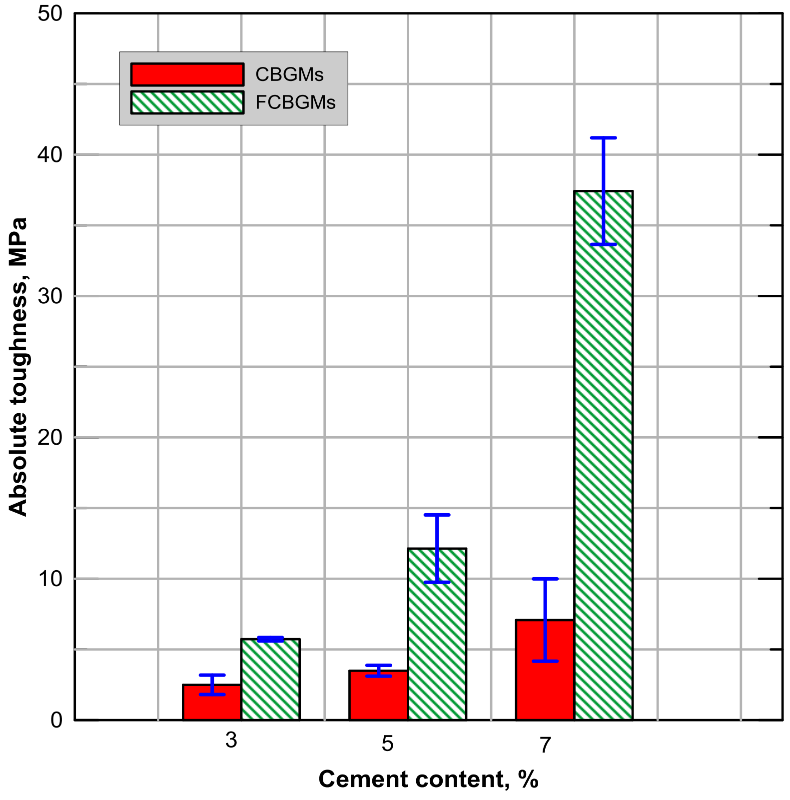


Figure 7: Deformability properties for various investigated mixtures.

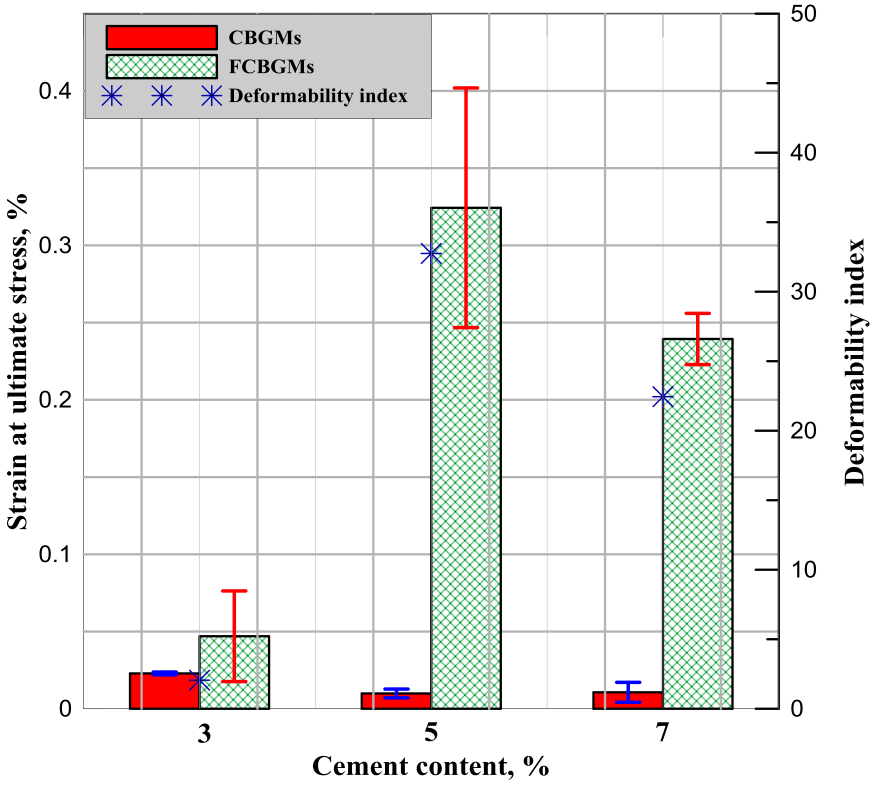


Figure 8: Selected crack propagation stages for some of the investigated mixtures: a. C3F0; b. C3F0.5; c. C7F0 and d. C7F0.5

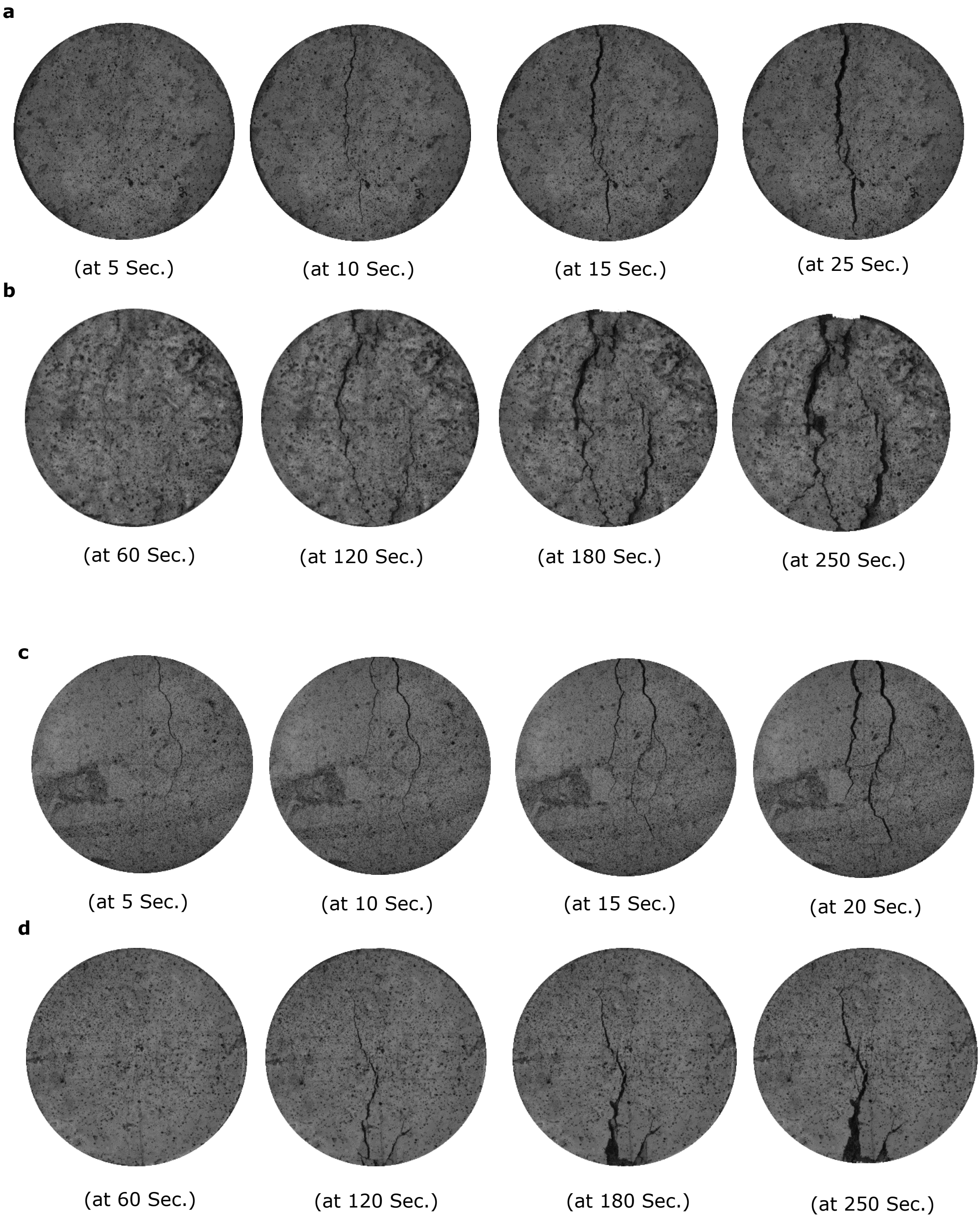


Figure 9: Extracting cracking patterns: a. cracked section; b. image binarization; c. digitization of the cracks and d. extracted cracks

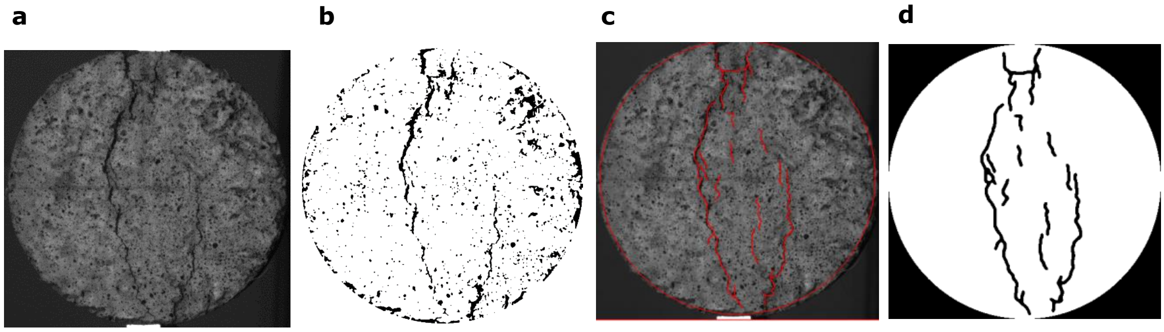
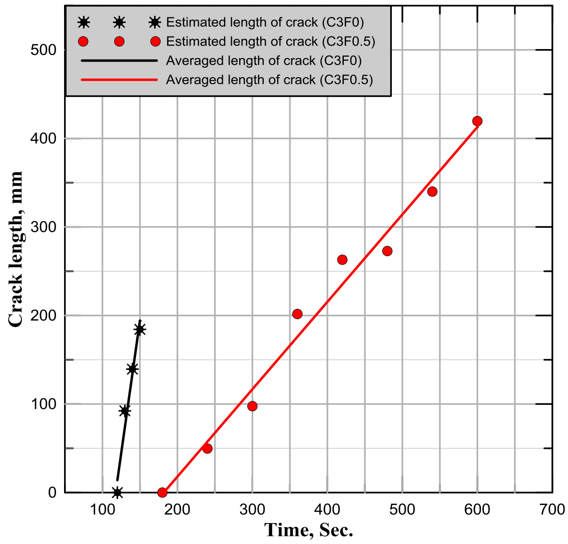
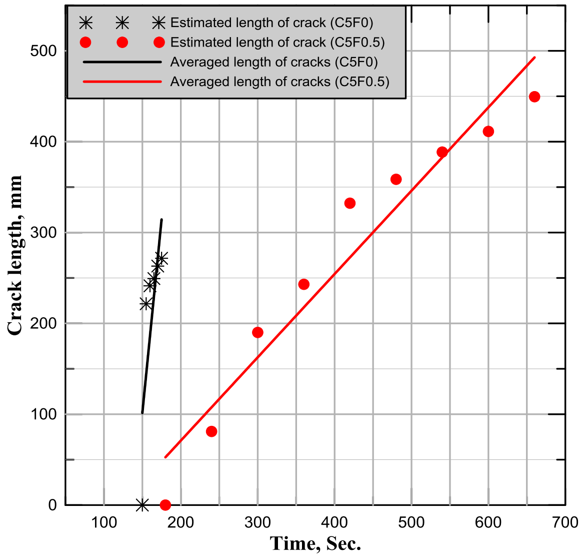


Figure 10: Samples of crack length propagation versus time used to estimate crack propagation

a



b



c

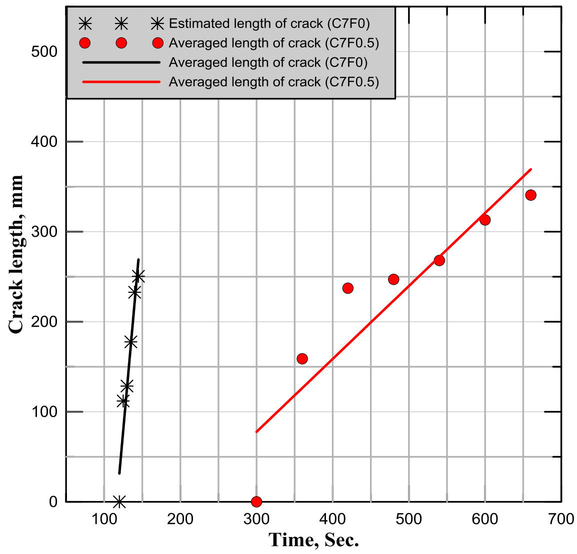


Figure 11: Summary of crack propagation speeds for CBGMs and FCBGMs

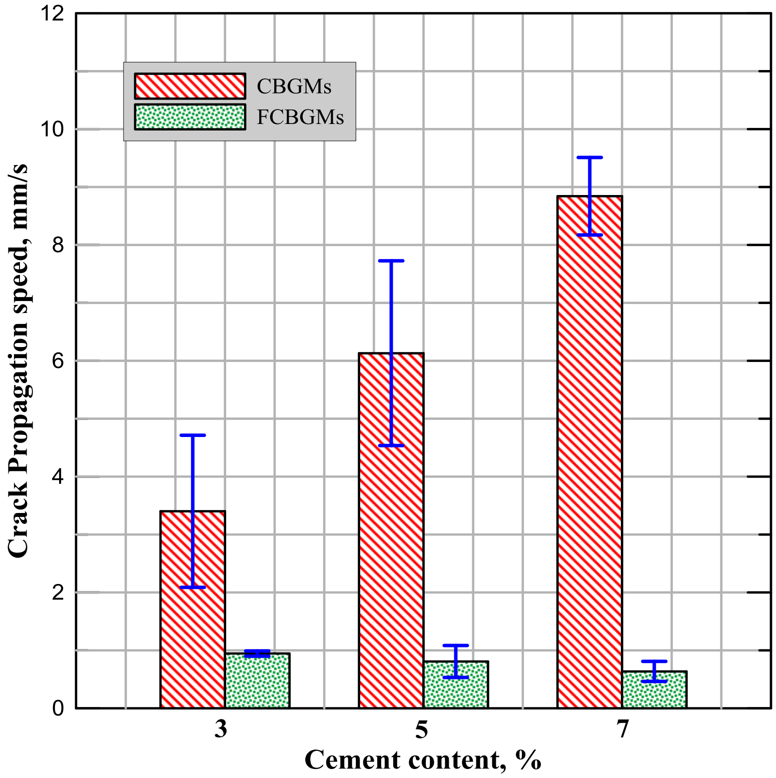


Figure 12: Samples of fractal dimensions against time, used to estimate fractal dimension propagation rate

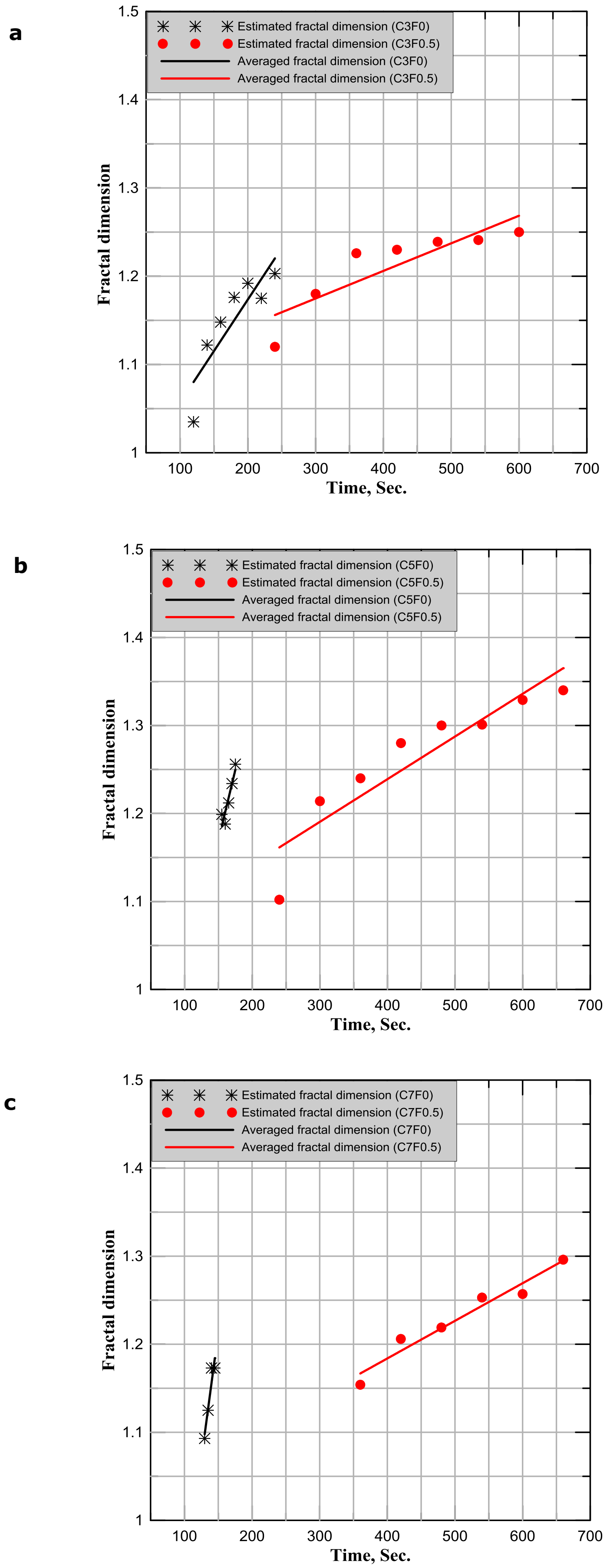


Figure 13: Summary of damage propagation rate expressed as fractal dimension evolution rate

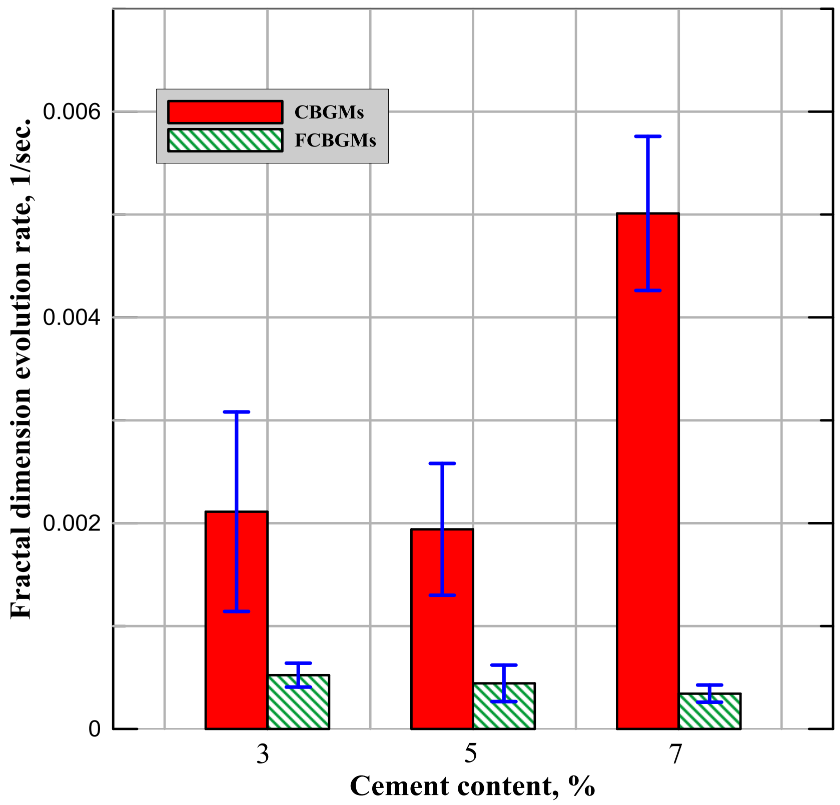


Figure 14: Toughness- damage rate relationship.

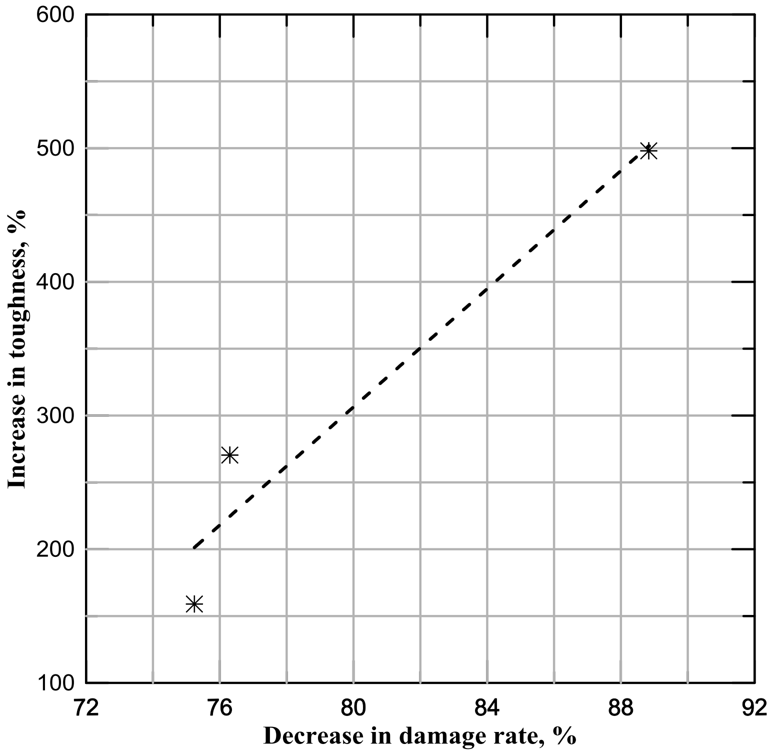


Figure 15: Terminal fractal dimensions for investigated mixtures.

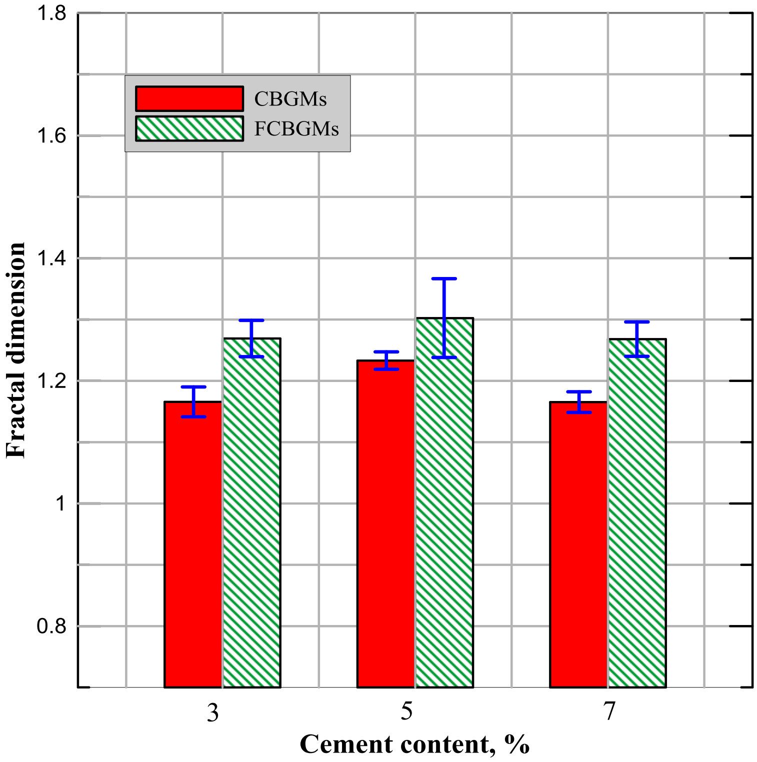


Figure 16: ITS-Fractal dimension relationship.

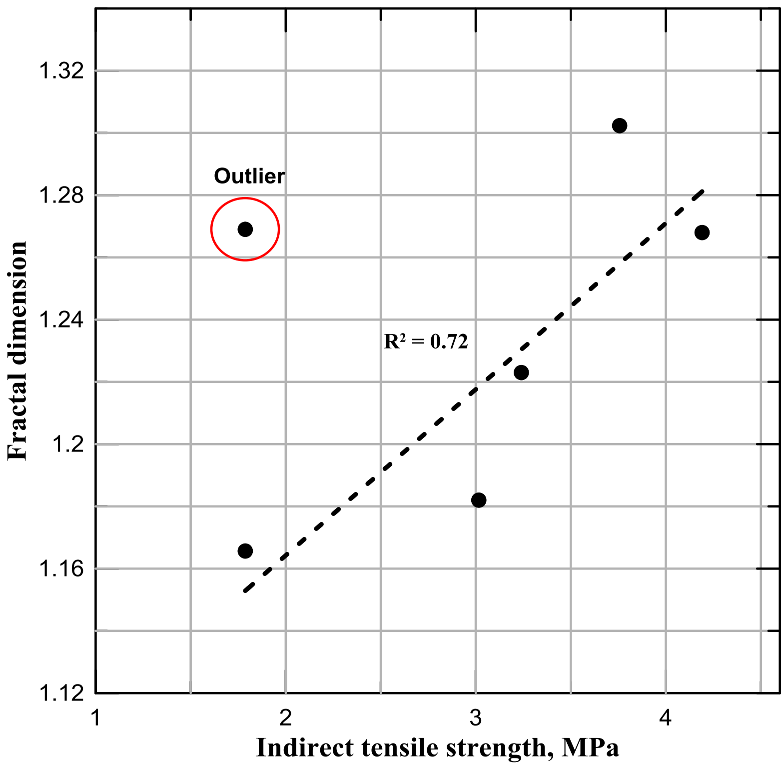


Figure 17: Samples of horizontal tensile strain development during the application of vertical compressive displacement at constant rate

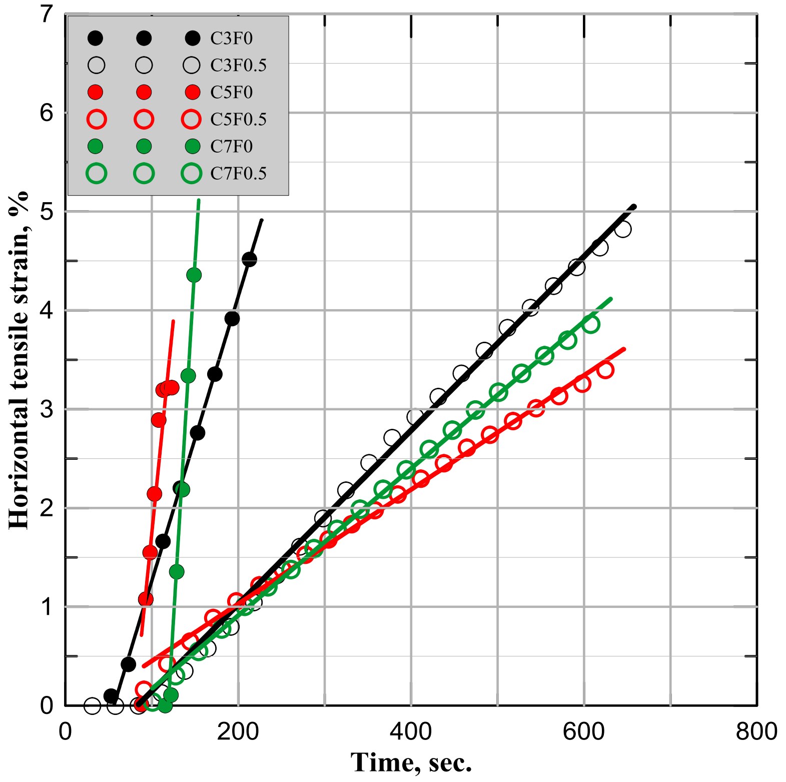


Figure 18: Summary of developed horizontal tensile strains at different cement contents.

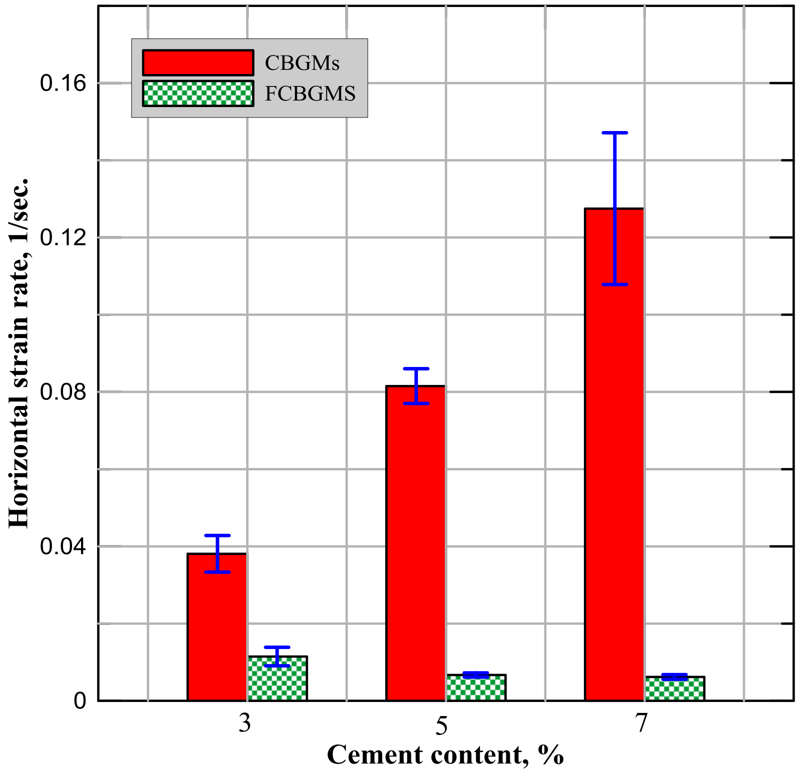


Figure 19: Relationship of cracking speed and damage rate with horizontal tensile strain.

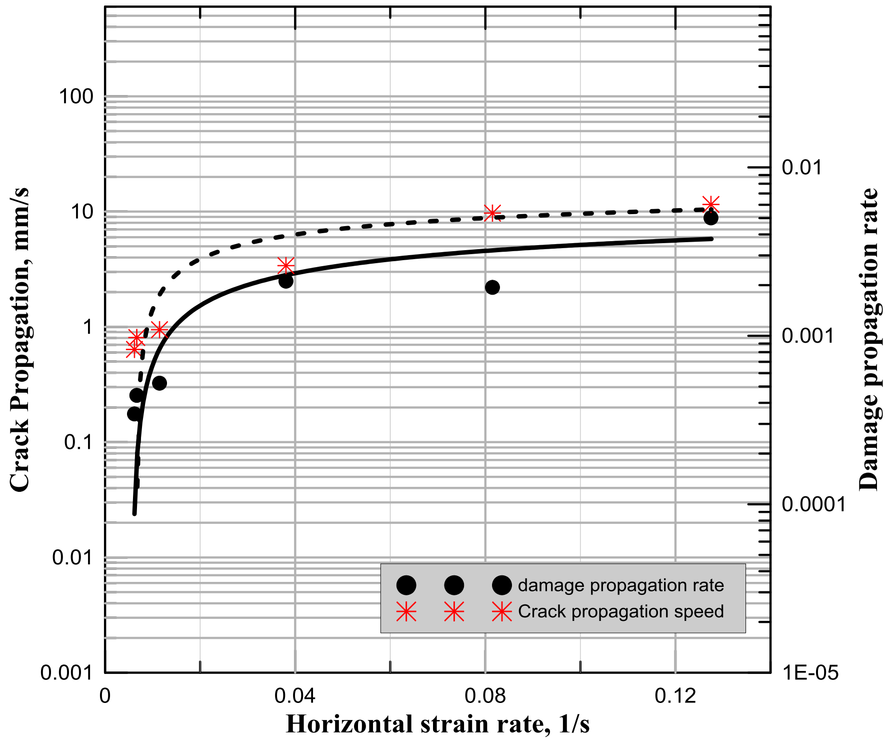
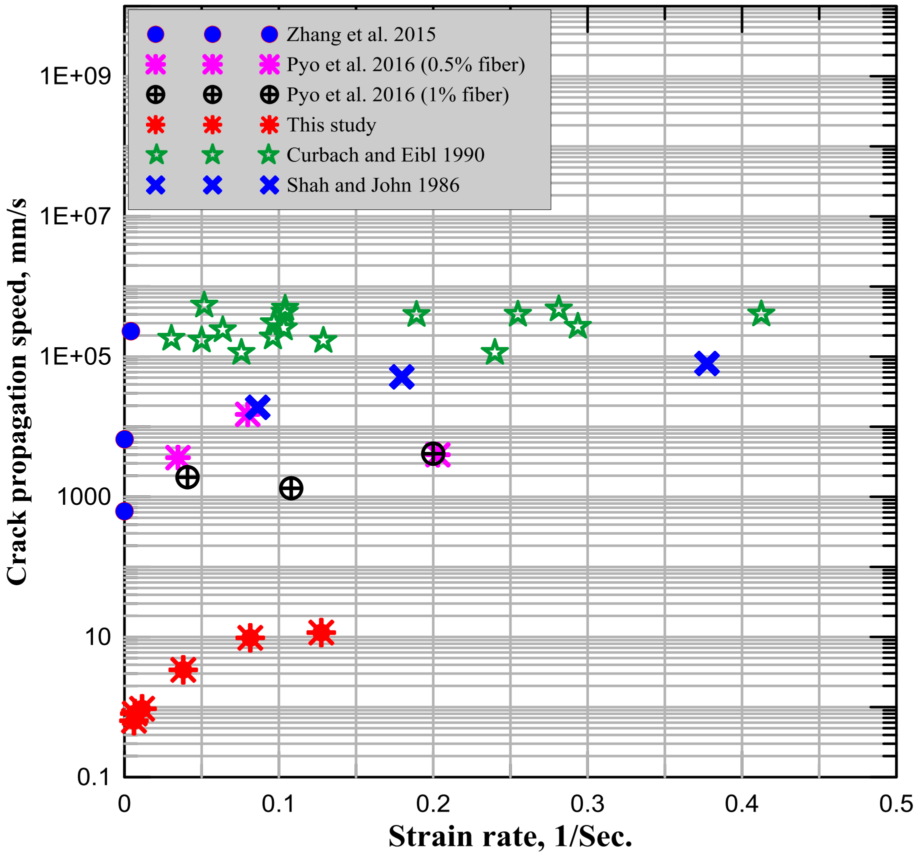


Figure 20: Comparison with previous crack speed-strain rate relationships obtained for different types of concrete mixture



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