3D mesoscale modeling and fracture property study of rubberized self- compacting concrete based on uniaxial tension test

DOI:

[10.1016/j.tafmec.2019.102363](https://doi.org/10.1016/j.tafmec.2019.102363)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Li, X., Chen, X., Jivkov, A., & Zhang, J. (2019). 3D mesoscale modeling and fracture property study of rubberized self- compacting concrete based on uniaxial tension test. *Theoretical and Applied Fracture Mechanics*, 104, 1-14. [102363]. <https://doi.org/10.1016/j.tafmec.2019.102363>

Published in:

Theoretical and Applied Fracture Mechanics

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

3D mesoscale modeling and fracture property study of rubberized self-compacting concrete based on uniaxial tension test

Xing Li^{a,b}, Xudong Chen^{a*}, Andrey P Jivkov^c, Jinhua Zhang^d

^aCollege of Civil and Transportation Engineering, Hohai University, Nanjing, 210098, P.R. China

^bCollege of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, P.R. China

^cDepartment of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, M13 9PL, UK

^dSchool of Civil Engineering, Southeast University, Nanjing, 210096, P.R. China

Abstract: Rubberized concrete is a new type of building material intended to utilise waste rubber with a potential for significant economic and environmental benefits. However, its strength is lower than the strength of ordinary concrete due to the introduction of rubber material, which might affect its application in practical engineering. To improve the mechanical performance of rubberized self-compacting concrete (RSCC), it is a necessary to study the internal mechanisms of strength formation, degradation and failure. Based on the uniaxial tensile test of RSCC, this work reports on the development and validation of a mesoscale model of RSCC, which accounts for its heterogeneity. RSCC is considered to be composed of mortar, coarse aggregate, rubber particles, aggregate-mortar interface transition zone (A-M ITZ), rubber particle-mortar interface transition zone (R-M ITZ), and initial defects. The mesoscopic model is validated by comparing the simulation results with test results.

*Corresponding author
E-mail: cxdong1985@hotmail.com

The model is then used to analyse the mechanical properties, crack generation and propagation, and expansion of self-compacting concrete (SCC) and RSCC are compared and analysed. Further, the effects of different volume fractions of rubber on the mechanical properties of RSCC are studied. It is found that the mechanical properties and final fracture surface morphology of RSCC with different rubber content are significantly different, and the causes of these differences are discussed.

Keywords: RSCC; R-M ITZ; Uniaxial tensile test; 3D mesoscale model; Fracture property; Crack morphology

1. Introduction

Nowadays, waste rubber, predominantly from used tires, has become the second-largest polymer pollutant and its disposal has attracted increasing attention across countries and governments. The treatment of waste rubber generally included physical processing, chemical decomposition, stacking, landfill, and combustion. Among these, landfill, burning, and chemical decomposition are very harmful to the environment, and natural placement cannot clear up the waste rubber for a short period. An effective method to deal with the waste rubber is by crushing used tires and adding them into rubberized concrete after physical processing. Rubberized concrete can effectively solve the problem of disposal of rubber products such as used tires and has unique advantages in environmental protection.

In the production process of rubberized concrete, rubber powder or rubber particles

44 are used to replace the coarse and fine aggregates inside the concrete by equal volume
45 or equal mass. The incorporation of rubber particles changes concrete properties from
46 the known properties of plain concrete. Eldin [1], Toutanji [2], Topcu [3], Guoqiang li
47 [4], F. Hernandez [5,6] demonstrated experimentally that with the increase of rubber
48 content, the compressive strength, flexural strength and tensile strength of concrete
49 specimens decreased, while plastic properties improved significantly. L.Zheng [7],
50 Feng Liu [8] studied the seismic performance of rubberized concrete by vibration test.
51 The test results showed that the damping ratio of rubber concrete was much higher than
52 the ordinary concrete, and the dynamic elastic modulus was lower than the ordinary
53 concrete. Wang her Yung [9] studied the durability of RSCC through experiments. The
54 results showed that the toughness and durability of RSCC could be significantly
55 improved when the rubber content was 5%. These scholars have made many
56 contributions to explore the property of rubberized concrete and expand the engineering
57 utilization of rubberized concrete. A common conclusion from their research is that the
58 incorporation of rubber can significantly improve the apparent density, durability, shock
59 absorption, impact resistance, heat insulation, sound insulation, and other properties of
60 concrete but at the same time its strength will decline substantially. To improve the
61 strength of rubberized concrete, the crack pattern and failure mechanism need to be
62 studied and understood in sufficient detail, e.g. via explicit representation of its
63 constituents using meso-scale models. However, little attention has been given to this
64 type of modelling of rubberized concrete[10]. One of the very few contributions is the

work by Feng Liu [11] who considered the rubberized concrete as a composite of aggregate, rubber and mortar, which however is quite different from the actual rubberized concrete where interfacial transition zones(ITZs) are known to control damage initiation and propagation. Another notable work is by ZH Xie [12], who analysed the mechanical properties of rubberized concrete by a 2D model, where the material contained four phases: aggregate, rubber, mortar, and aggregate-mortar interface. This work, however, omitted explicit representation of the phase with weakest mechanical properties, namely R-M ITZ. Furthermore, 2D analysis is not a reliable approach to studying the complex crack patterns forming in real materials. To the best of our knowledge, a study regarding rubberized concrete as a six-phases material composed of aggregate, rubber, mortar, voids, A-M ITZ, R-M ITZ, in a 3D mesoscale heterogeneous model has not been proposed to date. Such a study would allow for substantially more realistic representation of the rubberized concrete mesostructure and correspondingly more reliable analysis and discussion of its mechanical properties. In this paper, appropriate 3D meso-scale model is proposed and validated using uniaxial tensile tests. The model is used to investigate the crack formation mechanism and mechanical properties of rubberized concrete.

The paper is organised as follows. Uniaxial tension tests of rubberized self-compacting concrete with different rubber particle content are presented in Section 2. Based on the test results, a 3D mesoscale model of rubberized self-compacting concrete is established and presented in Section 3. The parameters and constitutive law of the

3D model are determined by the test results and trial calculations. Model validation is performed in Section 4, where comparison between simulations and experiments is shown. Section 5 presents parametric studies investigating the effects of rubber content on the strength, crack initiation, crack propagation and fracture morphology. Both test results and simulation results show that the toughness of RSCC is improved compared with that of SCC without rubber particle. The incorporation of rubber particles reduces the failure rate of the whole prism and controls the final fracture morphology of the uniaxial tensile cracks of RSCC.

2. Experiment programme

2.1 Materials

The exact mix proportions of RSCC used in this paper are shown Table 1. The materials used are listed as follows: P.O.42.5 plain Portland cement with a density of 2600 kg/m³ ; gravel with size distribution shown in Table 2; river sand; rubber particles with a density of 1050 kg/m³ ; fly ash; silica fume; highly efficient polycarboxylate water reducer; tap water. Fine rubber particles were produced by mechanical shredding of waste tire. These particles were sieved, and the particles with a size ranging from 3~5mm retained. The fine aggregate of concrete is replaced by the sieved rubber particles in the volume of 0%, 5%, 10%, and 15 %, respectively. The specimens with fine aggregates was replaced with 0%, 5%, 10%, 15% rubber particles were designated by RSCC-0, RSCC-5, RSCC-10 and RSCC15, respectively.

2.2 Specimen production

Prescribed amounts of material according to the mix proportion - fine aggregate, cement, fly ash and silica fume - were added and mixed for the 30s in the concrete mixer. This was followed by coarse aggregate addition and to thorough stirring. Finally, the tap water, water reducer and rubber particles were added and mixed for 3 minutes. The produced fresh concrete was discharged and poured into plastic molds with dimensions of $100\text{mm} \times 100\text{mm} \times 400\text{mm}$. The molds were removed after 24h. Then specimens were cured in water for 28 days. As mentioned before, four groups specimen with different rubber content were prepared.

2.3 Specimen processing

According to the previous studies [13,14], when the cross-section of a prism specimen is kept constant, the measured tensile strength of the prism decreases with the increasing of prism length of the prism due to size effect. However, when the aspect ratio of prismatic specimens is 3~4, the measured tensile strength tends to be a constant. At the same time, due to the clamping method used in this paper, the stress distribution in the test piece is very uniform for a specimen with a length greater than 200 mm. Thus, the length of the specimen was selected to be 300mm. Before the test, the specimens were taken out from the curing pool and their lengths reduced by cutting off 50mm from both ends. The specimens were cleaned up and steel plates with the same size were attached at both ends using adhesive glue. The tensile strength of the glue used is not less than

10MPa, which is higher than the tensile strength of the concrete specimen, ensuring that it will not be degummed during the tensile test. The steel plate was connected to the testing machine through the ball hinge, as shown in Fig. 1. The horizontal ruler was used for calibration in the process of pasting the steel plate to avoid the influence of eccentricity. The positioning hole on the pasted steel plate was located at the section centroid of the specimen to ensure the geometric alignment of the tensile test.

2.4 Experimental procedure

A 500kN MTS322 electro-hydraulic servo testing machine was adapted for loading, and the specimen was connected to the testing machine through ball hinge. The test machine was equipped with an extensometer (standard gauge 280mm, measuring range $\pm 2.5\text{mm}$), which could measure the deformation of the recorded test piece and could also be used to control the test loading process. The extensor installation diagram is shown in Fig. 1.

The deformation of the specimen was used as a control signal in the test loading to obtain the full tensile stress-strain tensile curve. During the test, the load sensor of MTS was used to measure the direct tension of the specimen, and the extensometer was adopted to measure the deformation of the specimen.

3. 3D mesoscale model generation process and numerical simulation

setup

3.1 CDP Constitutive model

Under the external load of the concrete, in addition to the stiffness degradation phenomenon caused by damage, unrecoverable permanent plastic deformation will also occur. In recent years, many researchers have applied the two theoretical frameworks of plasticity and damage to characterize the mechanical behavior of concrete, such as Grassl [15], Badel [16], and Kim et al. [17]. The plastic-damage model of concrete proposed by Lubliner et al. [18] and improved by Lee and Fenves [19] can not only characterize the permanent plastic deformation of concrete under external load but also describe the stiffness degradation caused by damage accumulation of concrete and the mechanical behavior of material softening after reaching peak strength. The main idea of the concrete damage model is to assume that the failure pattern of concrete is cracking during tension and crushing under compression. The isotropic damage variable is used to characterize the stiffness degradation and unrecoverable plasticity caused by a tensile fracture and compression failure of concrete. This is described mathematically by:

$$\sigma = (1 - D)D_0^{el}:(\varepsilon - \varepsilon^{pl}) \quad (1)$$

where D represents the isotropic damage variable; D_0^{el} is the initial linear isotropic elastic modulus; ε^{pl} represents the plastic strain tensor. The evolution of plasticity is

described by two hardening parameters, $\tilde{\epsilon}_t^{Pl}$ and $\tilde{\epsilon}_c^{Pl}$, where footers "t" and "c" respectively represent tension and compression. Figures 2 (a) and (b) respectively show the mechanical behaviour of concrete under uniaxial compression and tension. Under tension, the material is linear elastic before reaching its strength f_t , and the stiffness degradation occurs after exceeding the tensile strength. The softening stress-displacement relation characterizes the stiffness degradation behaviour. Under compression, the material is linear elastic before reaching a yield strength, typically 40%~60% of the compressive strength. When the stress is larger than the yield stress but less than the peak stress, the material is in a strain hardening regime. After exceeding the compressive strength (peak stress), strain softening, and stiffness degradation occur. Uniaxial tensile and compressive stress-strain relationships can be described in the form of stress and plastic strain, as follows:

$$\sigma_t = \sigma_t(\tilde{\epsilon}_t^{pl}, \dot{\tilde{\epsilon}}_t^{pl}, \theta, f_i) \quad (2a)$$

$$\sigma_c = \sigma_c(\tilde{\epsilon}_c^{pl}, \dot{\tilde{\epsilon}}_c^{pl}, \theta, f_i) \quad (2b)$$

where $\dot{\tilde{\epsilon}}_t^{pl}$ and $\dot{\tilde{\epsilon}}_c^{pl}$ is the equivalent plasticity strain rate of tension and compression, respectively; θ is temperature; f_i ($i = 1, 2, \dots$) is custom field variable.

Under uniaxial tension and compression, the stiffness degradation of concrete materials is defined by two independent uniaxial damage variables, namely the tensile damage factor d_t and the compression damage factor d_c . The stress-strain relationship of the material under uniaxial tension and compression conditions corresponds to Fig. 2, and the expressions are:

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \tilde{\varepsilon}_t^{pl}) \quad (3a)$$

$$\sigma_c = (1 - d_c)E_0(\varepsilon_c - \tilde{\varepsilon}_c^{pl}) \quad (3b)$$

3.2 Generation of RSCC 3D mesoscale model

Since the study of RSCC mesoscale model is uncommon, this paper attempts to simulate the RSCC uniaxial tension test with a 3D mesoscale model for the first time and explores other mechanical properties of RSCC through the established model.

The difficulty in establishing the 3D mesoscale model is that due to the incorporation of rubber particles, a transitional zone between the rubber and the mortar will be formed which is similar to the interface between the mortar and the coarse aggregate. The nature of the interface transition zone between mortar and aggregate has always been a hot topic of scholars. Nowadays, many scholars [17,20–24] regard the interface transition zone between mortar and aggregate as a material similar to mortar, but its porosity is much higher than mortar. Due to the existence of natural defects such as voids and pores, it has always been a weak area of the overall structure. According to the research of [5], the thickness of R-M ITZ is around 60 microns. And the thickness of A-M ITZ is about 10~50 microns [25–27]. Therefore, the thickness of the R-M ITZ is similar to that of the A-M ITZ. During the process of simulation, the most common way is to treat the A-M ITZ as a thin layer of a certain thickness outside the aggregate. Most scholars believed that the thickness of the A-M ITZ is fixed [21,23,28,29], while H. Chen [30] thought that the thickness of the A-M ITZ varies with the size of the

aggregate. The larger the aggregate size, the thicker the A-M ITZ. Since this paper aims to explore the mesoscale model of RSCC, the influence of the ITZ on the properties of the material is not the focus. Therefore, the thickness of A-M ITZ and R-M ITZ are all taken as 0.25mm to facilitate mesh generation and simulation calculation. In this paper, coarse aggregate and rubber are assumed to be linear elastic materials, while mortar, A-M ITZ, and R-M ITZ are defined as plastic-damaged materials, which all obey the CDP constitutive model described above albeit with different parameters [28,29].

Many scholars have explored the method of establishing the mesoscale concrete model [31–34] and used a variety of ways to generate aggregate particles and voids in the concrete matrix. Generally, there are two specific methods to build the mesoscopic model, one is a synthetic parameterization method, and the other is an image-based modelling method. In the first method, the particles are randomly placed in the space according to a pre-arranged particle distribution. The limitation of this method is the position and size distribution of the aggregate are different from the actual concrete specimen. But it has the advantage of an easy implement. The most significant advantage of the second method is that the model is generated by X-ray tomography (XCT) 2D image, and the created model has the same mesostructure with the test sample. This method can reconstruct a series of 2D images into a 3D structure, and further mesh and rebuild them into finite element models. The most significant disadvantage of the second method is time-consuming and expensive, and the reconstructed finite element model tends to be unable to perform further numerical

simulation and analysis due to a large number of elements. In this paper, the synthetic parameterization method is used to generate the model with insufficient aggregate and rubber particle distribution information, and then the generated 3D mesostructure is transformed into a pixel-based image. Finally, the finite element model is generated by an image-based method. The shape of the particles in this paper is all spheres to simplify the mesoscale model.

The aggregate in concrete can be divided into coarse aggregate and fine aggregate, only coarse aggregate is considered in the model, and fine aggregate is composed of mortar together with cement. The particle size distribution of the coarse aggregate in the model is consistent with the experimental gradation setting, as shown in Table 2. The rubber particles are also kept consistent with the experimental setup; all the rubber particle size is in the range of 3~5mm. Pores and voids are weak areas of concrete, and the presence of pores and voids can provide a channel for the development of cracks. Therefore, to fully reflect the mesostructure of concrete, the pores and voids should also be included in the mesoscopic model. According to the CT scan results [35], the pore size range is 1~2mm, and the porosity of SCC is 1%~3%. So, in this paper, the porosity of the mesoscale model is set as 1%. Similarly to Ref. [24], finite-thickness A-M ITZ and R-M ITZ elements are generated by enlarging aggregates and rubber particles before the model is tessellated into voxels. Enlargement by radius increment of 0.25 mm is used for A-M ITZ and R-M ITZ.

The critical technology for model generation is the need to repeatedly generate

aggregates, rubber particles, and voids until the content of these three components reaches a predetermined volume fraction. The whole process of particle filling consists of three procedures: input- taking- placing. The input procedure is to input the dominant information to generate randomly distributed aggregate, rubber particles, and voids structure. The taking process produces aggregates, rubber particles, and pores consistent with the random size and distribution demand. All the generated particles are then placed into pre-defined areas irregularly and randomly according to pre-set physical boundaries of the specimen. When placing particles into a given area, the essential principle is that the aggregate, rubber particles, and pores cannot intersect or overlap. In this paper, a direct, effective and easy method to implement 3D spherical overlap detection is proposed which can be easily fulfilled by meeting the following three requirements: (1) each particle must be contained within the volume of the concrete, which can be satisfied by controlling the maximum and minimum values of the particle coordinates; (2) there is no overlapping and intersect between all particles; (3) the distance between all particles and the boundary of the concrete specimen should be within a specific range, and the particles do not intersect with the concrete boundary. As shown in Equation (4), for two sphere particles, the intersection and overlap conditions can be easily checked by comparing the particle centre distance and the sum of the two radii.

$$\sqrt{(x'_0 - x_0)^2 + (y'_0 - y_0)^2 + (z'_0 - z_0)^2} \leq r + r' \quad (4)$$

x_0, y_0, z_0 are the center coordinates of the existed sphere, r is the radius of the sphere,

x'_0 , y'_0 , z'_0 are the center coordinates of the newly generated sphere, and r' is the radius of the newly generated sphere.

Based on the above algorithm, a MATLAB code is compiled to generate concrete specimens with randomly distributed aggregates, rubber particles, and voids. The flow chart of the code to generate random particles is shown in Fig. 3.

To reduce the number of three-dimensional model elements and improve the computational efficiency, the size of the 3D model specimens was set as $50\text{mm} \times 50\text{mm} \times 150\text{mm}$, half of the test specimens. In this paper, four groups of mesoscale numerical models were generated with the same composition and particle gradation as in the test specimens. As shown in Fig. 4, the aggregate and rubber content of the mesoscale model is the same in the test specimen.

3.3 Uniaxial tensile simulation of the concrete prism

The uniaxial tensile test of the concrete prism is conducted by the electro-hydraulic servo tester simultaneously applies a tension force to the specimen at both ends through a ball hinge. In the numerical simulation, to obtain the stress-strain relationship from the simulation results, the specimen was fixed at one end, and the displacement load was applied on all nodes at the other end. The solution was obtained through the standard analysis of Abaqus. The simulation parameters used in this paper are shown in Table 3. Similar to previous works [13,15,21,31–33], it is assumed that the aggregate is linear elastic material which will not be damaged, and

the crack will not develop inside the aggregate. The rubber is originally an elastic material, and its material parameters maintain its inherent material properties. The selection of mortar parameters is inferred from the test results of SCC without adding rubber. The study on the R-M ITZ parameters is not so common, but the study of [5] shows the porosity of the R-M ITZ is quite larger than that of the A-M ITZ, and the microstructure is worse than that of the A-M ITZ. It can be inferred that the mechanical properties of the R-M ITZ are worse than the A-M ITZ. The parameters of the A-M ITZ and the parameters of the R-M ITZ are obtained by referring to the parameters in literature [11,12,15,24,33] and through trial calculation. The rationality of the parameters used in this paper is verified by comparing the test and the simulation results in section 4.

4. Comparison of test results with numerical simulation results

One of the RSCC-0 tensile tests failed during the testing process, so there was only one effective test result of the RSCC-0 specimen. All the other specimen group has two sets of test results, which can be used for validation. To prevent the low reliability of simulation results caused by the difference in composition and the random distribution of aggregate and rubber particle of a single model, three random mesoscale models of each component were selected for numerical simulation. The comparison of numerical simulation results and test results of each specimen group is shown in Fig. 5, and the crack pattern and location of the test specimen and simulation specimen are shown in Fig. 6.

308 As can be seen from Fig. 5, the consistency between the simulated result and the
309 test result is very high before the peak stress, indicating that the selected elastic modulus
310 is appropriate. The uniaxial tensile strength of the numerical simulation results is
311 basically within the range of the two groups of tests results. Moreover, the dispersion
312 of the uniaxial tensile strength of the three random mesoscale models is minimal,
313 indicating that the numerical model has a superior performance for predicting the
314 uniaxial tensile strength. The concrete specimen is damaged quickly after the peak
315 stress, and the strength decreases rapidly, but due to the diverse distribution of aggregate
316 and rubber particles, the difference between the mesoscale model and actual
317 components of the concrete prism, the simulation results of the post-peak period has
318 slight difference with the test results. It can also be seen from the test curves of Fig. 5
319 (b), (c) and (d) that due to the different internal composition and aggregate, rubber
320 particle distribution, the test results of two concrete specimens of the same component
321 also have dispersion in the post-peak section. After reaching the ultimate strength, the
322 micro-cracks in the concrete gather rapidly, nucleation, develop into macroscopic
323 cracks, and eventually lead to the final failure of the whole structure. The development
324 of cracks is closely related to the distribution of aggregates, rubber particles, defects
325 and voids of the specimen itself. The existence of defects and voids can provide a
326 development channel for cracks and promote its development rate. So the stress-strain
327 response after the peak stress of different specimen will be different, but the overall
328 development trend of the stress-strain curve is similar. In conclusion, the proposed

3D mesoscale model can reflect the properties and the overall performance of RSCC; the simulation elastic modulus is very consistent with the elastic modulus of the material itself; the material strength floats in a certain error range. The material performance of the post-peak section has slight discrepancy due to the different components and aggregate distribution of the specimen. The global trend of the stress-strain curve is consistent with the test results, which shows that the proposed 3D mesoscale model in this paper can produce the overall performance of RSCC and verified the feasibility of the proposed model. As can be seen from Fig. 6, the position and morphology of the cracks in the numerical simulation results are very close to the experimental results, which supports that the 3D mesoscale simulation results are reasonable and reliable.

5. Discussion

5.1 Effect of rubber content on the tensile strength of RSCC

Figure 7 shows all the test results of RSCC under uniaxial tension. A conclusion can be drawn from the figure that as the rubber content increases, the peak stress of the specimen decreases, while the strain corresponds to the peak stress of the specimen increases, indicating that with the increase of rubber content, the material strength decreases, and toughness slightly increases. Due to the test conditions, the environment influence, and the different structure of each specimen, the test results have a certain degree of dispersion. From Fig. 6, the numerical simulation results

of the RSCC of each component have a small dispersion and maintain a high degree consistent with the test results. A numerical simulation result was randomly selected from each group of all the simulation results and plotted in Fig. 8 (a) to facilitate the discussion and analysis of the simulation results. It can be seen in Fig. 8(a) that the elastic modulus of the material decreases with the increase of rubber content before the peak stress. The material strength decreases clearly with the increase of rubber content, while the corresponding peak strain increases, and the material toughness increases. With the increase of rubber content, the failure speed of the material decreased during the post-peak period. The strength of the RSCC is decreased, and the peak strain is significantly improved as compared with the reference SCC (concrete without rubber particles). For all RSCC specimens, the strength of the specimen decreases as the rubber content increases, and the peak strain increases as the rubber particle content increases. The reason for the above test and simulation results is that the addition of rubber particles in the concrete can increase the toughness of the concrete but reduce the strength simultaneously. The reason for the toughness enhancement of concrete is that the size of rubber particles is small, which can fill the defects and voids of concrete. Besides, the rubber particles can also play a role in optimizing the gradation of fine aggregate and coarse aggregate. The elastic modulus of rubber is smaller than all the other components; rubber can effectively relieve the stress concentration at the tip of the crack, thus slowing down the expansion of cracks and enhancing the toughness of concrete

during the process of loading. Besides, the incorporation of rubber particles is equivalent to introducing new initial defects into the concrete due to the small elastic modulus of rubber. Rubber belongs to the organic materials; the concrete belongs to the inorganic materials. The different material type makes the cohesion at the interface transition zone between rubber and mortar weaker. The rubber particle can also play the role of air-entraining agent; the addition of rubber particle will increase the gas content in concrete. With the increase of rubber content, the concrete porosity increases, resulting in the reduction of the overall strength of the material.

5.2 Effect of rubber content on crack development

5.2.1 Analysis of microcrack development

Due to the limitation of test detection technology, it is impossible to observe and analyze the development of internal cracks of concrete in the process of tensile failure. Therefore, the development process of internal cracks of concrete is compared and analyzed using mesoscale simulation technology. After verifying the reliability of the simulation results through the comparison between the above test results and the simulation results, the simulated specimens which are consistent with the specimen setting and have good crack morphology development are selected for comparative analysis on the development of micro-cracks. Figures 9, 10, 11, and 12 show the development and distribution of microcracks in the four

specimen types. The points in Figures. 9 (a), 10 (a), 11 (a) and 12 (a) mark the same loading times for the four different models under uniaxial tension. Figures 10 (a), 11 (a) and 12 (a) have one additional point, p_0 , compared with Figure. 9(a). This is the point where microcracks appear in specimens containing rubber, while no microcracks that can be seen by the naked eye at the same loading time in ordinary SCC. This is further demonstrated in Figs. 9 (b), 10 (b), 11 (b) and 12 (b), where microcracks of RSCC appear earlier than the SCC specimen under the same load. The green and red parts in these figures represent increasing degree of damage, i.e. microcrack generation. Additionally, it is shown that the number of microcracks in RSCC specimen is great than that of SCC specimen, and the degree of damage in RSCC is larger at the same loading time point.

During the initial stage, shown by points p_1 , p_2 , p_3 in Figs. 9 (b), 10 (b), 11 (b) and 12 (b), microcracks appear in the weakest parts of the specimens – the ITZs. With microcracks extension and coalescence one of these develops into the main crack, which eventually leads to destruction of the specimen. It can be seen from the figures that the concrete specimen is not destroyed immediately after the peak stress, as the internal cracks are still in the microcrack stage, a macrocrack has not been formed yet. This illustrates that concrete is a quasi-brittle heterogeneous material, not an entirely brittle material, where its microstructure controls the development of cracks. After reaching the tensile strength, the development of internal cracks is intensified and aggravated, and the material performance

significantly declines, underpinned by the formation of macrocracks. After this point, the energy required for crack development is much less than the energy required for crack propagation before the peak stress. Comparing Fig. 9 (b) and Fig. 10 (b), it is seen that time for microcracks generation in RSCC specimen is less than in the ordinary SCC before the peak stress, and the microcrack development in RSCC before the peak stress is faster. This shows that the incorporation of rubber particles increases the overall defects in the structure and weakens the material performance of the pre-peak phase, which also supports the conclusion in section 5.1. In the initial phase, microcracks appear throughout the specimen, not just located at the position which will lead to macrocrack and the final failure of the specimen. The macrocrack location is closely related to the spatial distribution of the concrete components as suggested by the crack location in Figs. 10 (b), 11 (b) and 12 (b); different realisation of the randomly distributed components will result in a different crack pattern.

5.2.2 Effect of rubber content on the development of macroscopic cracks

Based on the analysis of 5.2.1, this section selects RSCC-0 and RSCC-15 specimen to conduct a comparative analysis on the development process of macroscopic cracks to further analyse the influence of rubber incorporation on the development of macrocracks in concrete. The crack development after the peak stress of the selected mesoscale specimen, corresponding to time points of $s_1 \sim s_4$, is shown in Figs. 9 (c) and 12 (c). As can be seen from these figures, the rate of macrocrack propagation after the

peak stress is higher in RSCC-0 than in RSCC-15. The microcracks in RSCC-0 specimens have been clustered into nuclei at the time s_1 after the peak, while the microcracks in RSCC-15 are more dispersed at the same time. At the moment s_4 , the concentrated internal damage in specimen RSCC-0 is very high and the overall failure of the material is observed, while the concentrated internal damage in specimen RSCC-15 is lower, indicating that the addition of rubber improves the overall toughness of the material and reduces the rate of macrocrack propagation.

5.3 Effect of rubber content on crack morphology

Figure 13 shows the morphology of the final failure surfaces for the four specimen types. As can be seen in Fig. 13(a), the crack in RSCC-0 mainly occurs at the transition interface between aggregate and mortar. During the crack development process, some big voids will appear in the crack surface, as the crack avoids aggregates which cannot be damaged. The number of such voids in Figs. 13 (b), (c) and (d) is significantly smaller, indicating that the addition of rubber optimizes the gradation of concrete aggregate, and the area of the interface transition zone is significantly increased. As can be seen from Figs. 13(b), (c), (d), the number of large voids in the whole crack surface of the specimen decreases, and more small size voids appear with the increase of rubber content. This is due to the increase of the number of rubber particles, which enables the crack to develop and extend at both A-M ITZ and R-M ITZ. The size decrease of the voids indicates that the crack will preferentially develop at the R-M ITZ, and the smaller size rubber particles can be easily bypassed. At the same time, because of the size of

the rubber particle is smaller, the energy needed to bypass a rubber particle is much lower than a bigger size aggregate. Therefore, the crack surface will produce some smaller size voids when the specimen contains many rubber particles. The final crack pattern also conforms to the hypothesis and setting of the mechanical parameters of the material. Rubber particles and coarse aggregate are linear elastic materials, which will not be damaged. Elastoplastic damage can occur in the mortar, A-M ITZ, and R-M ITZ. The mechanical properties of A-M ITZ and R-M ITZ are inferior to mortar, so the cracks mainly occur in these two areas. Since rubber is an organic material and mortar is an inorganic material, the mechanical properties of the interface transition zone between two different types of materials are inferior to the interface transition zone between the same type of material. And it is known that the porosity of R-M ITZ is significantly higher than that of A-M ITZ [4]. It is further known that the strength of mortar materials is closely related to the porosity [36,37]. When the porosity is high, the material strength is low, and when the porosity is low, the material strength is high. Therefore, the interfacial transition zone between rubber and mortar is the weakest interface in the material; the crack will preferentially develop at the R-M ITZ, followed by the A-M ITZ.

6. Conclusions

Based on uniaxial tension test results of rubberized concrete, this paper explores the application of mesoscale modelling to improve understanding of damage and failure of

such materials in view of their potential for economic and environmental benefits. The following conclusions can be drawn from the work:

1. By comparing test and numerical simulation results for stress-strain response and crack pattern and location, it is demonstrated that the proposed 3D mesoscale model can be used to analyse damage evolution and crack development in RSCC. In addition, the mesoscale model has the potential to be used in analysis of other mechanical properties of RSCC.

2. The results of the RSCC prism test and numerical simulation show that the toughness of RSCC is improved compared with that of SCC, and the bearing capacity is reduced. When the rubber particle gradation is the same, with the increase of rubber content, the strength of the specimen decreases, the toughness of the specimen increases, and the overall damage rate of the material is reduced.

3. The final morphology of the uniaxial tensile cracks of RSCC shows that the incorporation of rubber particle reduces the failure rate. Due to the incorporation of rubber particles, the pores and defects of the concrete are filled, the gradation of the concrete sand and aggregate is optimized, and the porosity of the test piece is reduced to some extent. However, the total area of the interfacial transition zone is increased significantly. The special properties of rubber materials lead to extremely high interfacial porosity between rubber particles and mortar. The porosity brought by the increased interfacial transition zone is much higher than that reduced by the optimization of particle grading, so the overall strength of the material will still decline.

494 4. The R-M ITZ is the weakest constituent of rubberized concrete due to high porosity
495 and weak cohesion between two different types of material. Microcracks are easy to
496 nucleate and grow in this region, and eventually develop into macrocracks resulting in
497 the overall failure of the material.

498 **Acknowledgments**

499 The research is based upon the work supported by the National Natural Science
500 Foundation of China (Grant No. 51779085).

501 **Reference**

- 502 [1] E.N. N., S.A. B., Rubber-Tire Particles as Concrete Aggregate, *J. Mater. Civ.*
503 Eng. 5 (1993) 478–496. doi:10.1061/(ASCE)0899-1561(1993)5:4(478).
- 504 [2] H.A. Toutanji, The use of rubber tire particles in concrete to replace mineral
505 aggregates, *Cem. Concr. Compos.* 18 (1996) 135–139.
- 506 [3] İ.B. Topcu, Assessment of the brittleness index of rubberized concretes, *Cem.*
507 Concr. Res. 27 (1997) 177–183.
- 508 [4] G. Li, M.A. Stubblefield, G. Garrick, J. Eggers, C. Abadie, B. Huang,
509 Development of waste tire modified concrete, *Cem. Concr. Res.* 34 (2004)
510 2283–2289.
- 511 [5] F. Hernandez-Olivares, G. Barluenga, M. Bollati, B. Witoszek, Static and
512 dynamic behaviour of recycled tyre rubber-filled concrete, *Cem. Concr. Res.*
513 32 (2002) 1587–1596.
- 514 [6] F. Hernández-Olivares, G. Barluenga, B. Parga-Landa, M. Bollati, B.
515 Witoszek, Fatigue behaviour of recycled tyre rubber-filled concrete and its
516 implications in the design of rigid pavements, *Constr. Build. Mater.* 21 (2007)
517 1918–1927.
- 518 [7] L. Zheng, X.S. Huo, Y. Yuan, Experimental investigation on dynamic
519 properties of rubberized concrete, *Constr. Build. Mater.* 22 (2008) 939–947.
- 520 [8] F. Liu, G. Chen, L. Li, Y. Guo, Study of impact performance of rubber
521 reinforced concrete, *Constr. Build. Mater.* 36 (2012) 604–616.

- 522 [9] W.H. Yung, L.C. Yung, L.H. Hua, A study of the durability properties of waste
523 tire rubber applied to self-compacting concrete, *Constr. Build. Mater.* 41 (2013)
524 665–672.
- 525 [10] O. Youssf, J.E. Mills, R. Hassanli, Assessment of the mechanical performance
526 of crumb rubber concrete, *Constr. Build. Mater.* 125 (2016) 175–183.
- 527 [11] F. Liu, G. Zhong, X. Xia, L. Li, Mechanical analysis of rubberized concrete
528 subjected to uniaxial compression on meso-level, *J. Build. Mater.* 13 (2010)
529 733–738.
- 530 [12] Z.H. Xie, Y.C. Guo, Q.Z. Yuan, P.Y. Huang, Mesoscopic numerical
531 computation of compressive strength and damage mechanism of rubber
532 concrete, *Adv. Mater. Sci. Eng.* 2015 (2015).
- 533 [13] P. Grassl, D. Grégoire, L.R. Solano, G. Pijaudier-Cabot, Meso-scale modelling
534 of the size effect on the fracture process zone of concrete, *Int. J. Solids Struct.*
535 49 (2012) 1818–1827.
- 536 [14] S.Y. Alam, P. Kotronis, A. Loukili, Crack propagation and size effect in
537 concrete using a non-local damage model, *Eng. Fract. Mech.* 109 (2013) 246–
538 261.
- 539 [15] P. Grassl, M. Jirásek, Damage-plastic model for concrete failure, *Int. J. Solids*
540 *Struct.* 43 (2006) 7166–7196.
- 541 [16] P. Badel, V. Godard, J.-B. Leblond, Application of some anisotropic damage
542 model to the prediction of the failure of some complex industrial concrete

543 structure, *Int. J. Solids Struct.* 44 (2007) 5848–5874.

544 [17] S.-M. Kim, R.K.A. Al-Rub, Meso-scale computational modeling of the plastic-
545 damage response of cementitious composites, *Cem. Concr. Res.* 41 (2011)
546 339–358.

547 [18] J. Lubliner, J. Oliver, S. Oller, E. Oñate, A plastic-damage model for concrete,
548 *Int. J. Solids Struct.* 25 (1989) 299–326.

549 [19] J. Lee, G.L. Fenves, Plastic-damage model for cyclic loading of concrete
550 structures, *J. Eng. Mech.* 124 (1998) 892–900.

551 [20] W. Tian, F. Dang, Y. Xie, Quantitative study on crack of meso-damage and
552 fracture concrete based on CT technique, *Sadhana.* 40 (2015) 263–276.

553 [21] X.Q. Zhou, H. Hao, Modelling of compressive behaviour of concrete-like
554 materials at high strain rate, *Int. J. Solids Struct.* 45 (2008) 4648–4661.

555 [22] R.R. Pedersen, A. Simone, L.J. Sluys, Mesoscopic modeling and simulation of
556 the dynamic tensile behavior of concrete, *Cem. Concr. Res.* 50 (2013) 74–87.

557 [23] Z. Tu, Y. Lu, Mesoscale modelling of concrete for static and dynamic response
558 analysis-Part 1: model development and implementation, *Struct. Eng. Mech.* 37
559 (2011) 197–213.

560 [24] Y. Huang, Z. Yang, W. Ren, G. Liu, C. Zhang, 3D meso-scale fracture
561 modelling and validation of concrete based on in-situ X-ray Computed
562 Tomography images using damage plasticity model, *Int. J. Solids Struct.*
563 (2015). doi:10.1016/j.ijsolstr.2015.05.002.

- 564 [25] B.D. Barnes, S. DIAMOND, W.L. Dolch, Micromorphology of the interfacial
565 zone around aggregates in Portland cement mortar, *J. Am. Ceram. Soc.* 62
566 (1979) 21–24.
- 567 [26] E.J. Garboczi, D.P. Bentz, Analytical formulas for interfacial transition zone
568 properties, *Adv. Cem. Based Mater.* 6 (1997) 99–108.
- 569 [27] J.G.M. Van Mier, M.R.A. van Vliet, T.K. Wang, Fracture mechanisms in
570 particle composites: statistical aspects in lattice type analysis, *Mech. Mater.* 34
571 (2002) 705–724.
- 572 [28] X.Q. Zhou, H. Hao, Mesoscale modelling of concrete tensile failure mechanism
573 at high strain rates, *Comput. Struct.* 86 (2008) 2013–2026.
- 574 [29] Y. Lu, Z. Song, Z. Tu, Analysis of dynamic response of concrete using a
575 mesoscale model incorporating 3D effects, *Int. J. Prot. Struct.* 1 (2010) 197–
576 217.
- 577 [30] H. Chen, B. Xu, Y.L. Mo, T. Zhou, Behavior of meso-scale heterogeneous
578 concrete under uniaxial tensile and compressive loadings, *Constr. Build. Mater.*
579 178 (2018) 418–431.
- 580 [31] J.G.M. Van Mier, M.R.A. Van Vliet, Influence of microstructure of concrete on
581 size/scale effects in tensile fracture, *Eng. Fract. Mech.* 70 (2003) 2281–2306.
- 582 [32] A. Caballero, C.M. López, I. Carol, 3D meso-structural analysis of concrete
583 specimens under uniaxial tension, *Comput. Methods Appl. Mech. Eng.* 195
584 (2006) 7182–7195.

- 585 [33] X. Wang, M. Zhang, A.P. Jivkov, Computational technology for analysis of 3D
586 meso-structure effects on damage and failure of concrete, *Int. J. Solids Struct.*
587 80 (2016) 310–333.
- 588 [34] Z. Yang, W. Ren, M. Mostafavi, S.A. McDonald, T.J. Marrow, Characterisation
589 of 3D fracture evolution in concrete using in-situ X-ray computed tomography
590 testing and digital volume correlation, in: *VIII Int. Conf. Fract. Mech. Concr.*
591 *Concr. Struct.*, Toledo, Spain CIMNE, 2013: pp. 1–7.
- 592 [35] Y. Huang, Z. Yang, W. Ren, G. Liu, C. Zhang, 3D meso-scale fracture
593 modelling and validation of concrete based on in-situ X-ray Computed
594 Tomography images using damage plasticity model, *Int. J. Solids Struct.* 67
595 (2015) 340–352.
- 596 [36] X. Chen, S. Wu, J. Zhou, Influence of porosity on compressive and tensile
597 strength of cement mortar, *Constr. Build. Mater.* 40 (2013) 869–874.
- 598 [37] Y. Wu, X. Zhou, Y. Gao, L. Zhang, J. Yang, Effect of soil variability on
599 bearing capacity accounting for non-stationary characteristics of undrained
600 shear strength, *Comput. Geotech.* 110 (2019) 199–210.
- 601
- 602

603 **List of figure captions**

604 **Fig. 1.** Test device and specimen

605 **Fig. 2.** The uniaxial stress-strain curve with damage plasticity

606 **Fig. 3.** Flowchart of random aggregates, rubber particles and voids generation

607 **Fig. 4.** Concrete mesoscale models with different compositions

608 **Fig. 5.** Stress-strain curve of each group RSCC specimen under uniaxial tension

609 **Fig. 6.** Crack pattern and location of each group RSCC specimen under uniaxial tension

610 **Fig. 7.** Stress-strain curve of RSCC under tension test

611 **Fig. 8.** Simulation result of RSCC with different rubber content under uniaxial tension

612 **Fig.9.** Simulation result of RSCC-0 specimen under uniaxial tension

613 **Fig.10.** Simulation result of RSCC-5 specimen under uniaxial tension

614 **Fig.11.** Simulation result of RSCC-10 specimen under uniaxial tension

615 **Fig.12.** Simulation result of RSCC-15 specimen under uniaxial tension

616 **Fig. 13.** Final crack morphology of RSCC specimens with different rubber content

617 **List of table captions**

618 Table 1 The mix proportion of RSCC (kg/m^3)

619 Table 2 Coarse aggregate size distribution

620 Table 3 Material parameters for RSCC mesoscale model

621

622

Table 1 The mix proportion of RSCC (kg/m^3)

Specimen	Cement	Fly ash	Silica Fume	Water	Water Reducer	Rubber particle	Sand	Gravel
RSCC-0	385	139	26	200	7.5	0	1080	800
RSCC-5	385	139	26	200	7.5	52	1080	672
RSCC-10	385	139	26	200	7.5	104	1080	542
RSCC-15	385	139	26	200	7.5	156.5	1080	413

623

624

Table 2 Coarse aggregate size distribution

Sieve size (mm)	Total passed percentage (%)
10	100%
8	60%
6	0

625

626

627

Fig. 1. Test device and specimen

628

(a) Concrete response under uniaxial tension

(b) Concrete response under uniaxial compression

Fig. 2. The uniaxial stress-strain curve with damage plasticity

Fig. 3. Flowchart of random aggregates, rubber particles and voids generation

Fig. 4. Concrete mesoscale models with different compositions. Gray spheres are coarse aggregate, and purple spheres are rubber particles

Table 3 Material parameters for RSCC meso-scale model

	Tensile strength (MPa)	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio	Density (Kg/m ³)
Mortar	4.4	60	42	0.2	2200
Coarse aggregate	--	--	40	0.2	2600
Rubber particle	--	--	7	0.4	1050
A-M ITZ	3	45	21	0.2	1800
R-M ITZ	1.5	25	12.5	0.2	1500

645

646

647

(a) Stress-strain curve of RSCC-0

(b) Stress-strain curve of RSCC-5

648

649

(c) Stress-strain curve of RSCC-10

(d) Stress-strain curve of RSCC-15

650

Fig. 5. Stress-strain curve of each group RSCC specimen under uniaxial tension

651

(a) RSCC-0 specimen with no rubber particle content

652

(b) RSCC-5 specimen with 5% rubber particle content

653

(c) RSCC-10 specimen with 10% rubber particle content

(d) RSCC-15 specimen with 15% rubber particle content

Fig. 6. Crack pattern and location of each group RSCC specimen under uniaxial tension

Experiment result of concrete specimen with different content

Fig. 7. Stress-strain curve of RSCC under tension test

(a) Stress-strain curve of RSCC under tension simulation

(b) Column chart of specimen strength with different rubber content

Fig. 8. Simulation result of RSCC with different rubber content under uniaxial tension

665

666

667

(a) Stress-strain curve of RSCC-0

668

669

(b) Microcrack development status of mesoscale RSCC-0 specimen at time p0, p1, p2, p3, p4, p5

670

(c) Macrocrack development status of mesoscale RSCC-0 specimen at time s1, s2, s3, s4

Fig. 9. Simulation result of RSCC-0 specimen under uniaxial tension

(a) Stress-strain curve of RSCC-5

(b) Microcrack development status of mesoscale RSCC-5 specimen at time p0, p1, p2, p3, p4, p5

Fig. 10. Simulation result of RSCC-5 specimen under uniaxial tension

(a) Stress-strain curve of RSCC-5

(b) Microcrack development status of mesoscale RSCC-10 specimen at time p0, p1, p2, p3, p4, p5

Fig. 11. Simulation result of RSCC-10 specimen under uniaxial tension

(a) Stress-strain curve of RSCC-5

(b) Microcrack development status of mesoscale RSCC-15 specimen at time p0, p1, p2, p3, p4, p5

691

p5

s1

s2

s3

s4

692

693

(c) Macrocrack development status of mesoscale RSCC-15 specimen at time s1, s2, s3, s4

694

Fig. 12. Simulation result of RSCC-15 specimen under uniaxial tension

(a)RSCC-0

(b)RSCC-5

(c)RSCC-10

(d)RSCC-15

695

696

Fig. 13. Final crack morphology of RSCC specimens with different rubber content