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Research paper

Study on strain wave propagation and explosion resistance mechanism of rubber-cement composite plate structure under central explosion loading

Rongzhou Yang[1], Peiyuan Chen[2], Ying Xu[3]

Abstract: Rubber-cement composites (RCC) is an environmentally friendly, green, and sustainable cement-based energy-absorbing materials. To study the dynamic response characteristics of RCC under explosion shock, the central explosion tests of RCC plate specimens were carried out by using the two-dimensional plate blasting (TDPB) test system. In the aspect of strain wave propagation, the characteristics and laws of explosive strain wave propagation in RCC plate structure were analyzed. In terms of damage characteristics, the macro-damage modes of RCC plate specimens under central explosion were analyzed, and the formation and propagation mechanisms of radial explosion growth cracks and the formation mechanism of central annular spalling were revealed. In terms of explosion resistance characteristics, combined with the meso-fracture morphology of RCC, the synergistic characteristics of mechanics and energy dissipation among cement mortar matrix, rubber particles, and pore structure were analyzed from the meso-level, and the explosion resistance mechanism of RCC plate structure was further revealed. RCC effectively combined the explosion resistance concepts of "coupling rigidity with flexibility" and "overcoming rigidity by flexibility", showing excellent explosion resistance ability. Finally, in view of the key scientific problem existing in RCC, the scientific and effective solution was discussed deeply, and the development method and research directions of the new RCC were further prospected.

Keywords: rubber-cement composite (RCC), two-dimensional plate blasting (TDPB), central explosion loading, strain wave propagation, explosion resistance mechanism, damage mechanism

[1]PhD., Eng., School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, Anhui Hongchang New Materials Co., Ltd., Huaibei, 340621, China, e-mail: rongzhouy@outlook.com, ORCID: 0000-0002-0126-2446
[2]Assoc. Prof., PhD., Eng., School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, Anhui Hongchang New Materials Co., Ltd., Huaibei, 340621, China, e-mail: peiyuan29@126.com, ORCID: 0000-0002-5538-617X
[3]Prof., PhD., Eng., School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, China, e-mail: yxu@aust.edu.cn, ORCID: 0000-0001-8438-3130

1. Introduction

Energy-absorbing materials are the core part of multi-level protective structures, which play a key role in coordinating deformation and cushioning-giving way with high-strength resistant materials and weakening the strength of shock waves [1]. Therefore, the related research on energy-absorbing materials has always been a key concern in the field of protection engineering, which has important practical significance in improving the explosion resistance and impact resistance of multi-level protective structures (Fig. 1).

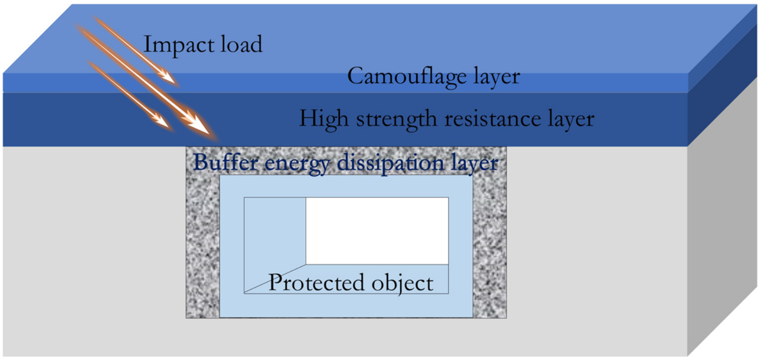


Fig. 1. Schematic diagram of a typical multi-level underground protective structure

Rubber polymers have mechanical properties such as low impedance, high damping, and viscoelasticity, and show excellent properties of energy absorption and isolation, which can reduce the peak value of stress waves and prolong the pressure rise time of stress waves [2]. When impacted by external forces, rubber viscoelastic damping materials can convert part of the input energy into thermal energy consumption by overcoming the internal friction work between macromolecular chains, so as to achieve energy absorption characteristics [3]. It is worth noting that with the rapid development of the automobile industry, waste tire rubber from all over the world has become a kind of "black pollution" [4]. Sustainable development has become a basic issue related to the present and future of mankind. In the face of environmental problems, countries around the world have proposed to speed up the green and low-carbon transformation to achieve green recovery and development. Combined with the background of the "double carbon strategy", rubber-cement composites (RCC) can be made by filling waste tire rubber particles into cement-based materials. RCC is environmentally friendly, green, and sustainable cement-based energy-absorbing materials [4, 5], which has important practical significance to promote the green development and engineering application of RCC.

However, although the research on the dynamic response of RCC under explosive shock loading has made remarkable progress [6, 7], more importantly, the strain wave propagation law and damage and explosion resistance mechanism of RCC under explosive shock loading are still not clear enough. Based on this, the central explosion tests of RCC plate specimens were carried out by using the TDPB test system. The characteristics and laws of explosion strain wave propagation in RCC plate structure were analyzed, and the formation and propagation mechanisms of radial explosion growth cracks, the formation mechanism of central annular spalling, and the mesoscopic explosion resistance mechanism were revealed. The research results provide a theoretical reference for further promoting the green development and engineering application of RCC in explosion resistance protection.

2. Materials and methods

2.1. Raw materials and preparation methods of RCC plate specimens

The size of the RCC plate specimens used in the central explosive shock test was l 300 mm × w 300 mm × h 30 mm. The RCC plate specimens were prepared by mold pouring. (1) Raw materials: the mixed water was laboratory tap water, the cementitious material was 42.5 grade ordinary Portland cement, the fine aggregate was natural river sand with a particle size of 0.075 ~1.18 mm (apparent density was 2680 kg/m^3), and rubber particles were waste tire rubber particles with a 20 mesh (apparent density was 1150 kg/m^3). (2) Rubber particles were mixed with equal volume instead of natural river sand, and the selected volume substitution ratios were 20%, 40%, 60%, and 80%, respectively. (3) Curing conditions (standard curing): curing humidity was more than 90%, curing temperature was (20 ± 2)°, and curing time was 28 days. The grain size distribution curves of the river sand and rubber particles for the test are shown in the Fig. 2. The mass mix proportion design of RCC is shown in Table 1. The static compression performance of RCC is shown in Table 2.

Table 1. Mass mix proportion design of RCC [8,9]

Sample types*	Water	Cement	Sand	Rubber
RCC-20%	1	2	3.2	0.343
RCC-40%	1	2	2.4	0.686
RCC-60%	1	2	1.6	1.030
RCC-80%	1	2	0.8	1.373

*Note: The values in the sample types are rubber content.

Table 2. Static compression performance of RCC [9]

Sample size	Sample types	Static strength (MPa)	Deformation modulus (GPa)
Φ 70 mm × h 140 mm	RCC-20%	22.91	3.802
	RCC-40%	9.26	1.615
	RCC-60%	7.32	1.311
	RCC-80%	6.18	1.021

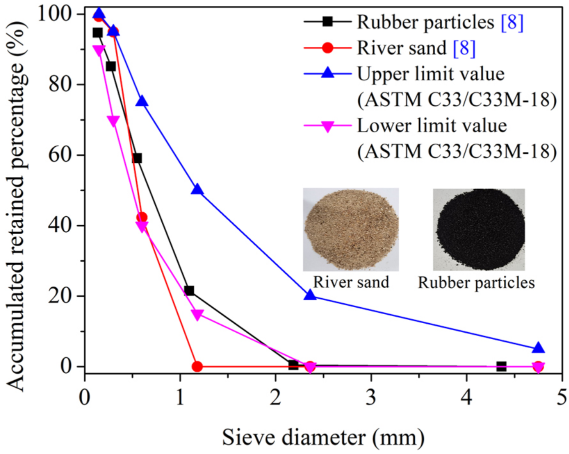


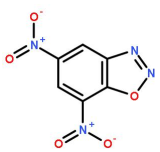
Fig. 2. The grain size distribution curves of the river sand and rubber particles for the test [8]

2.2. TDPB test system and test methods

The TDPB test system and test methods are shown in Fig. 3. The self-developed TDPB test system in the impact dynamics laboratory of Anhui University of Science and Technology is used in the central explosion shock test. The TDPB test system is mainly composed of the confining pressure loading system (jack, reaction frame, loading plate, motor, oil pump), control system (multi-directional compression-decompression controller), explosive loading system (detonating device, special small detonator with 0.3 g charge (Diazodinitrophenol, DDNP)), and data acquisition and processing system (strain gauge, bridge box, strain amplifier, oscilloscope, computer).

DDNP has been widely used as an initiating explosive for industrial detonators because of its advantages such as low mechanical sensitivity, fast detonation growth, high flame sensitivity, excellent initiation and explosion performance, abundant raw material sources, relatively safe production operation, and low cost [10, 11]. The parameters related to the explosive power and initiation performance of DDNP are shown in Table 3.

Table 3. Parameters related to the explosive power and initiation performance of DDNP

Structural formula	**Related parameters**					
	Chemical formula	Relative density (kg/m^3)	Explosive heat (kJ/kg)	Explosive volume (L/kg)	Explosive temperature (°)	Explosive velocity* (m/s)
	$C_6H_2N_4O_5$	1630	1400	600 ~700	4950	6600

*Note: When the density is 1.50 g/cm^3 and there are constraints, the explosive velocity is 6600 m/s [12].

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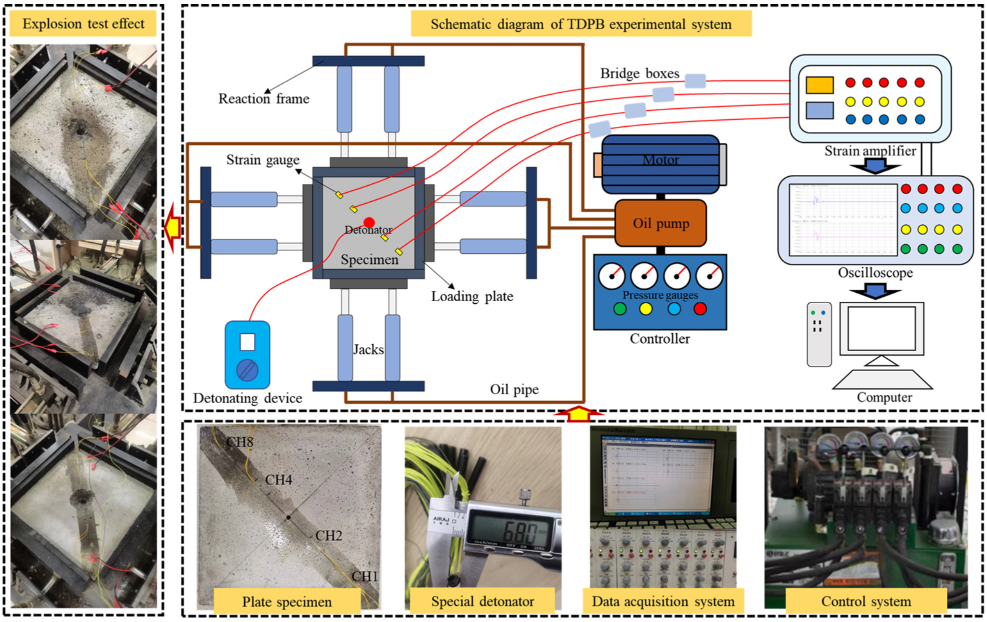


Fig. 3. Central explosion tests of RCC plate specimens

The diameter of the round blasthole at the center of the RCC plate specimen was 8 mm (the charge decoupling coefficient was 1.18). The explosion shock pulse signals were collected by pasting strain gauges. The strain gauges were pasted along the diagonal direction of the RCC plate specimen, and the four strain gauges correspond to four data acquisition channels (CH1, CH2, CH3, CH4). The active small confining pressure was applied around the plate specimen to prevent block separation and fragment ejection of the RCC plate specimen under explosive loading [9].

3. Results and analysis

3.1. Propagation laws of strain waves

Taking the acquisition channels CH1 and CH4 as examples, the strain wave propagation characteristics of the explosion tests in the center of the RCC plate specimens are shown in Fig. 4.

From Fig. 4(a,b), it can be seen that the strain waves of RCC plate specimens under central explosion showed several positive and negative strain peaks, and showed the evolution characteristic of attenuation with the increase of time. The positive and negative fluctuation of strain waves indicates that the measuring point is subjected to tension-compression action caused by explosive load. It is worth noting that the fluctuation of strain waves was more significant with the increase of rubber content, which indicated that RCC showed better deformability with the increase of rubber content.

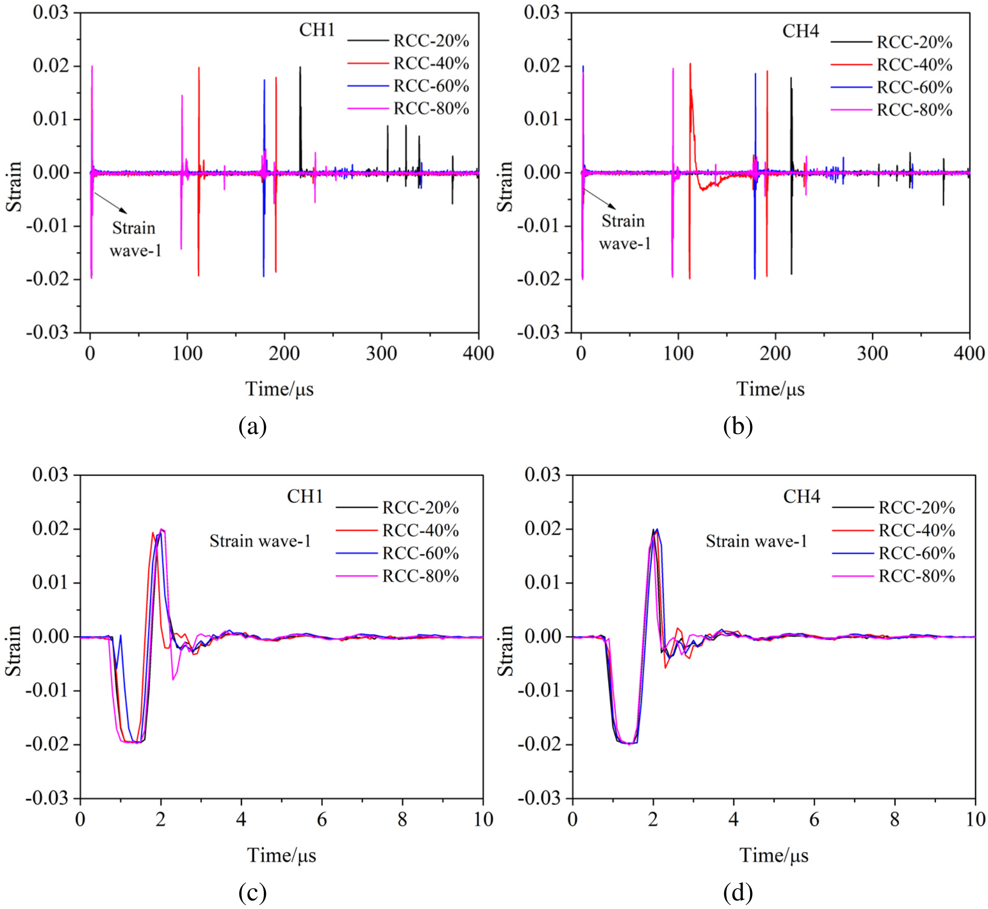
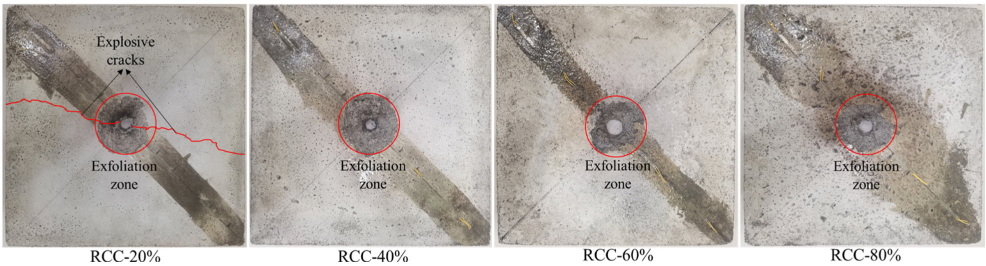


Fig. 4. Propagation characteristics of strain waves in central explosion tests of RCC plate specimens: (a) CH1-strain waves, (b) CH4-strain waves, (c) CH1-strain wave-1, (d) CH4-strain wave-1

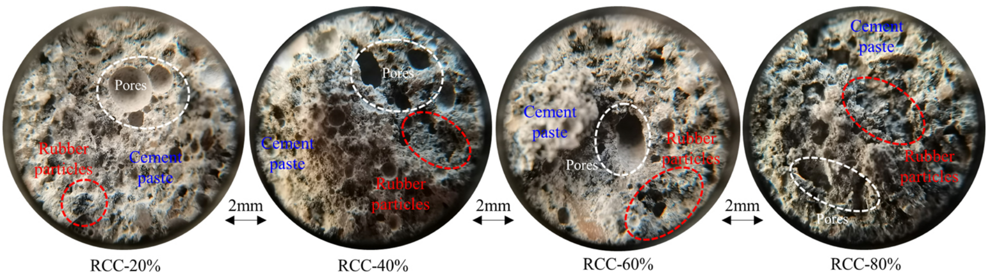
From Fig. 4(c,d), it can be seen that strain wave-1 was the first waveform collected by the channels, and strain wave-1 showed the evolution characteristic of "first negative then positive", which indicated that the RCC plate specimens were subjected to the stress of "first compression and then tension" under the central explosive load. It can be found that for channel CH4 with a short blast center distance, the strain wave-1 under different rubber content basically coincided completely. For channel CH1 with a long blast center distance, the coincidence degree of strain wave-1 decreased under different rubber content, and the fluctuation stability of strain wave-1 decreased with the increase of rubber content, but the amplitude of strain wave-1 had little difference under different rubber content. The above phenomena showed that the increase of rubber content enhanced the instability of the strain wave to some extent, but the effect of rubber content on the strain wave decreased obviously with the decrease of blast center distance.

3.2. Macro-damage mechanism and mesoscopic explosion resistance mechanism

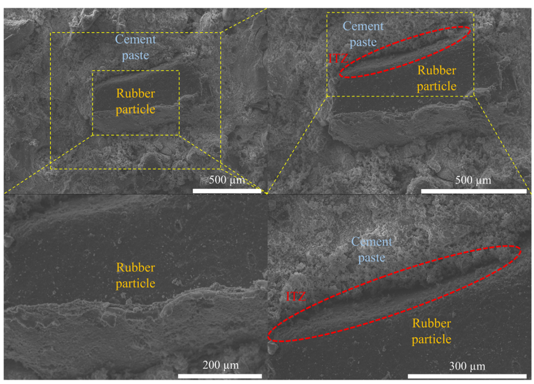
The macro-damage states of explosion in the center of RCC plate specimens and meso-fracture morphology are shown in Fig. 5. It can be seen from Fig. 5(a) that with the increase of rubber content, the RCC plate specimens showed the macro-damage evolution characteristics of “radial explosion growth cracks + central annular spalling + blasthole expansion → central



(a)



(b)



(c)

Fig. 5. Macro-damage states of explosion in the center of RCC plate specimens and meso-fracture morphology: (a) Macroscopic damage states, b) Meso-fracture morphology (OM), c) Meso-fracture morphology (SEM)

annular spalling + blasthole expansion". The comprehensive failure mode of "two radial explosion growth cracks + central annular spalling + blasthole expansion" mainly occurred in RCC-20%, while the comprehensive failure mode of "central annular spalling + blasthole expansion" mainly occurred in RCC-40%/60%/80%. The above phenomena showed that the explosion resistance of RCC plate specimens under central explosion load increased significantly with the increase of rubber content.

(1) Macro-damage mechanism

The RCC plate specimen is subjected to complex mechanical actions such as explosion shock stress waves and detonation gas expansion and extrusion under the central explosion load, which are the essential reasons for the comprehensive failure modes. Combined with explosion mechanics and energy theory, the damage mechanism of the above macro-damage modes was analyzed as follows [9, 13, 14]:

– The formation and propagation mechanisms of radial explosion growth cracks: According to the dynamic tensile stress failure criterion, it is precisely due to the combined effect of explosion shock stress waves and detonation gas expansion and extrusion that the tangential derived tensile stress is greater than the dynamic tensile strength of RCC-20%, resulting in radial tensile cracks in RCC-20% plate specimens. According to the minimum energy principle, the radial tensile cracks first extend vertically along the internal weak structure surfaces to the boundary of the specimen.
– The formation mechanism of central annular spalling: It is mainly the expansion and compression of detonation gas that causes the compression-shear fracture in the central blasting area, which leads to the formation of the central annular exfoliation zone in the central blasting area. In addition, under the action of the bottom sealing constraint, the blasthole will also form the energy-concentrated jet effect of transmitting the explosion energy upward, which further aggravates the formation of the central annular exfoliation zone.

(2) Mesoscopic explosion resistance mechanism

Meso-morphology is an important reflection of macroscopic characteristics [8, 15–18]. It can be seen from Fig. 5(b,c) that the meso-morphology of RCC was mainly composed of complex porous or multicellular structural surfaces formed by the bonding of cement mortar matrix, rubber particles, interfacial transition zone (ITZ), and pore structures, and the number and density of pores increased with the increase of rubber content. Therefore, combined with the mechanical and energy dissipation characteristics of different materials in RCC, the explosion resistance mechanism of RCC can be further analyzed from the meso-level:

– Cement mortar matrix: Cement mortar matrix is an elastic-plastic material formed by cement hydration reaction together with fine aggregates. Because of its better skeleton bearing capacity and stress resistance, resulting in outstanding rigid explosion resistance ability of RCC plate specimens under central explosive load.
– Rubber particles: Rubber particles are a high-damping viscoelastic material that can reflect the dual effects of elastic solid energy storage and viscous liquid energy dissipation [19–21]. Due to its excellent viscous cushioning deformation and energy dissipation characteristics, the attenuation of stress waves is achieved effectively, resulting in outstanding flexible explosion resistance ability of RCC plate specimens under central explosive load.

– Pore structures: The pore structures are a multicellular plastic material formed during the preparation of fresh RCC due to the introduction of air. Due to its excellent plastic cushioning deformation and energy dissipation characteristics, the stress wave attenuation and shock absorption are achieved effectively, resulting in outstanding flexible explosion resistance ability of RCC plate specimens under central explosive load.

To sum up, based on the mechanical and energy dissipation characteristics of different materials, RCC effectively combined the explosion resistance concepts of "coupling rigidity (cement mortar matrix) with flexibility (rubber particles, pore structures)" and "overcoming rigidity (explosive shock load) by flexibility (cushioning deformation, energy dissipation, stress wave attenuation)", which realized the synergism between different materials and showed excellent explosion resistance ability.

4. Discussion and prospect

4.1. Key scientific problem existing in RCC and effective solution

Compared with fiber-reinforced concrete and plastic concrete, RCC has more outstanding performance in fatigue resistance, impact resistance, and explosion resistance. However, the low strength of RCC is the key factor that makes it difficult to be used as the main impact resistance and bearing structures, which undoubtedly limits the scope of engineering application for RCC. If a kind of ultra-high strength rubber concrete (UHSRC) that can withstand high strength load and dissipate impact energy is developed, it will be able to better realize the application of RCC in protection engineering and seismic engineering and promote the resource utilization of waste tire rubber.

So far, whether physical or chemical modification of rubber particles or fiber reinforcement, not only the process is complex, but also the modification effect is not satisfactory, and even there are obvious differences in the research results of many scholars [22]. To solve this problem, the author's research team conducted key exploratory research in the previous stage, and achieved satisfactory results (Figs. 6, 7) [22]. A kind of UHSRC was developed by reducing the

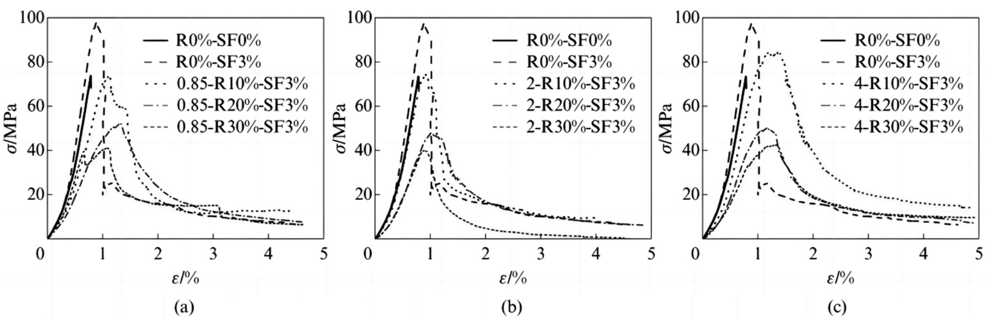


Fig. 6. Stress-strain curves of UHSRC specimens under three kinds of rubber particle sizes [22]: (a) $n = 0.85$ mm, (b)) $n = 2.00$ mm, (c)) $n = 4.00$

water-cement ratio and using steel fiber and silica fume to control the strength at the same time, and the static uniaxial compression test was carried out. The effects of the rubber substitution ratio and its particle size on the strength, deformation, and toughness of UHSRC specimens were analyzed, and the crack initiation mechanism and energy transformation relationship of UHSRC were clarified by combining meso-fracture morphologies and macro-failure morphologies.

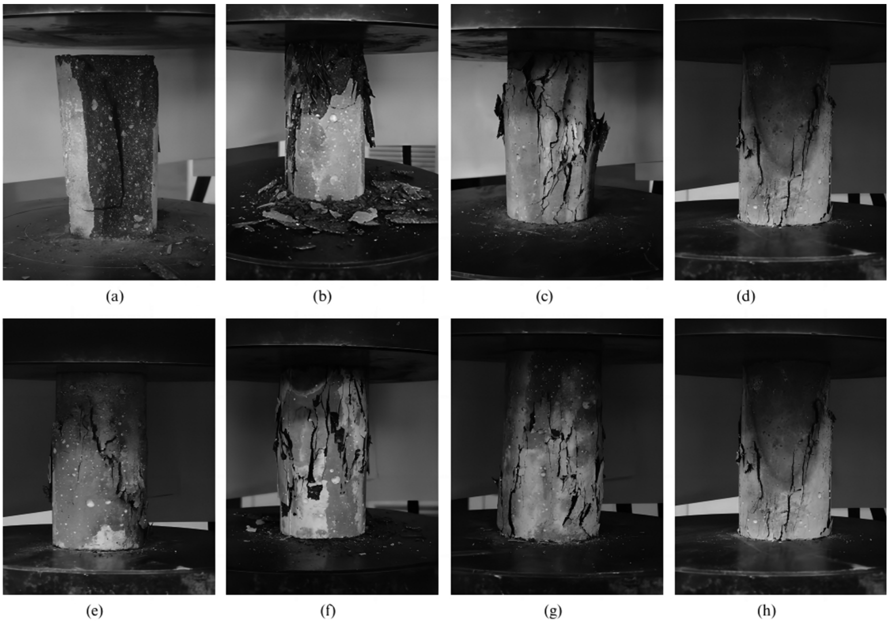


Fig. 7. Macro-failure morphologies of UHSRC specimens under three kinds of rubber particle sizes [22]: (a) R0%-SF0%, (b) R0%-SF3%, (c) 0.85-R10%-SF3%, (d) 0.85-R20%-SF3%, (e) 0.85-R30%-SF3%, (f) 4-R20%-SF3%, (g) 2-R20%-SF3%, (h) 0.85-R20%-SF3%

4.2. Experimental limitations and follow-up study

In this research work, only the central explosion tests of single plate specimens with different rubber content have been carried out, the anti-impact and explosion tests of UHSRC and its multi-level protective structure have not been carried out, and there is a lack of corresponding numerical simulation analysis. At present, to further verify the test results of single plate specimens with different rubber content under central explosion, the corresponding numerical simulation analysis was carried out, and the numerical simulation analysis of multi-level protective structure with "rock-RCC-rigid concrete (rigid-flexible-rigid)" under impact load was carried out (Fig. 8). The results showed that RCC had excellent energy absorption and explosion resistance, and it can coordinate the deformation with rigid protective materials in the protective structure, and effectively change the stress wave propagation path and improve the protective ability. It should be noted that more scientific, rigorous, accurate, and effective numerical simulation analysis will be carried out in the follow-up research.

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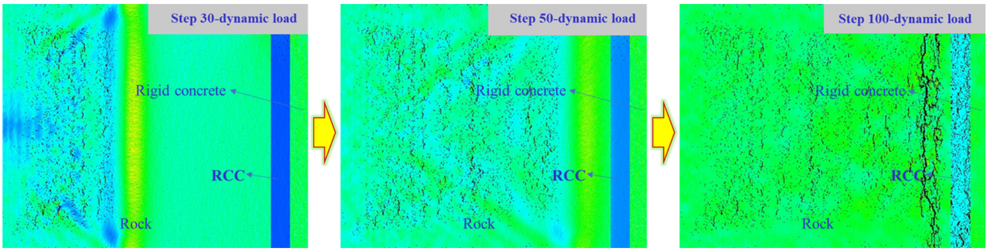

Fig. 8. Numerical simulation test of explosion shock wave action for multi-level protective structure

In the later research, focusing on the background of "protection needs" and "double carbon strategy", aiming at the above problems, it is proposed to further develop a multi-medium structural cement-based energy absorbing material, namely the multi-cell viscous fluid rubber concrete energy absorbing material (MCVFRCEAM). The dynamic mechanical behavior and damage evolution characteristics of MCVFRCEAM under impact load will be studied systematically, and the deformation characteristics and energy dissipation mechanism, the law of stress wave propagation and attenuation, and the dynamic coupling action mechanism between different media will be further revealed. The focus of the research is to establish the coupling energy dissipation model of MCVFRCEAM according to the energy dissipation models of different characteristic elements (Fig. 9). The purpose of this later research is to improve the meso-energy dissipation structure design and dynamic energy dissipation theory system of RCC.

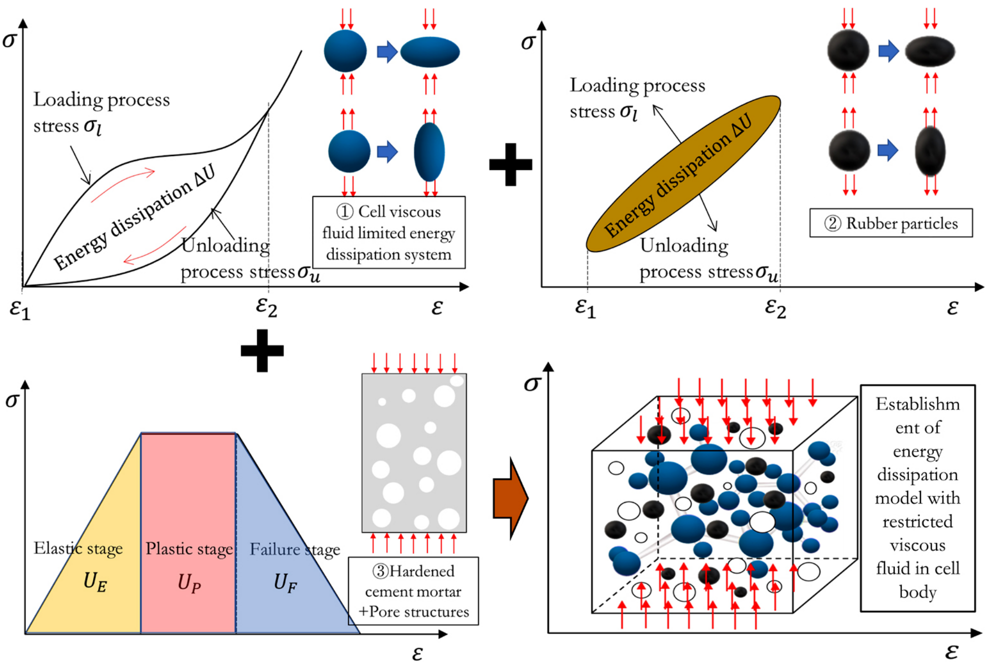

Fig. 9. Schematic diagram of energy dissipation model with restricted viscous fluid in cell body of MCVFRCEAM

5. Conclusions

In this work, combined with the environmental protection concept of explosion-resistant materials and the high damping and energy dissipation characteristics of waste tire rubber, a new method for preparing green and sustainable RCC from waste tire rubber with high damping was proposed. The central explosion shock tests of RCC plate specimens were carried out by using the self-developed TDPB test system. The following conclusions were drawn:

1. The fluctuation of strain waves was more significant with the increase of rubber content, which indicated that RCC showed better deformability with the increase of rubber content. The increase of rubber content enhanced the instability of the strain wave to some extent, but the effect of rubber content on the strain wave decreased obviously with the decrease of blast center distance.
2. With the increase of rubber content, the RCC plate specimens showed the macro-damage evolution characteristics of "radial explosion growth cracks + central annular spalling + blasthole expansion → central annular spalling + blasthole expansion", which showed that the explosion resistance of RCC plate specimens under central explosion load increased significantly with the increase of rubber content.
3. The RCC plate specimen is subjected to complex mechanical actions such as explosion shock stress waves and detonation gas expansion and extrusion under the central explosion load, which are the essential reasons for the comprehensive failure modes.
4. Based on the mechanical and energy dissipation characteristics of different materials, RCC effectively combined the explosion resistance concepts of "coupling rigidity with flexibility" and "overcoming rigidity by flexibility", which realized the synergism between different materials and showed excellent explosion resistance ability.
5. The research results of this work profoundly revealed the law of explosive strain wave propagation, dynamic damage mechanism, and explosion resistance mechanism of RCC plate structure under central explosive load, and further provided a theoretical reference for the green development and engineering application of RCC in explosion protection.

Acknowledgements

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References

[1] H. Zhou, H. Ren, X. Wu, Z. Yi, K. Huang, C. Mu, and H. Wang, "A review of sacrificial claddings in multilayer protective structure", *Explosion and Shock Waves*, vol. 42, no. 11, pp. 3–28, 2022, doi: 10.11883/bzycj-2022-0280.

[2] A. Grincova, M. Andrejiova, and D. Marasova, "Failure analysis of the impact resistance of protective rubber panels", *Engineering Failure Analysis*, vol. 139, 2022, doi: 10.1016/j.engfailanal.2022.106481.

[3] S. Mei, Q. Sheng, Z. Cui, and X. Mei, "Experimental study on energy absorption property of viscoelasticity damping layer", *Chinese Journal of Geotechnical Engineering*, vol. 44, no. 6, pp. 997–1005, 2022, doi: 10.11779/CJGE202206003.

[4] S.M.A. Qaidi, Y.Z. Dinkha, J.H. Haido, M.H. Ali, and B.A. Tayeh, "Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review", *Journal of Cleaner Production*, vol. 324, 2021, doi: 10.1016/j.jclepro.2021.129251.

[5] H. Li, W. Long, and K.H. Khayat, "Efficient recycling of waste rubber in a sustainable fiber-reinforced mortar and its damping and energy dissipation capacity", *Cement and Concrete Composites*, vol. 138, 2023, doi: 10.1016/j.cemconcomp.2023.104963.

[6] F. Yang, Z. Ke, W. Feng, X. Li, S. Chen, and H. Li, "Effects of crumb rubber particles on the dynamic response of reinforced concrete beams subjected to blast loads", *Engineering Structures*, vol. 300, 2024, doi: 10.1016/j.engstruct.2023.117181.

[7] F. Yang, W. Feng, F. Liu, L. Jing, B. Yuan, and D. Chen, "Experimental and numerical study of rubber concrete slabs with steel reinforcement under close-in blast loading", *Construction and Building Materials*, vol. 198, pp. 423–436, 2019, doi: 10.1016/j.conbuildmat.2018.11.248.

[8] R. Yang, Y. Xu, and P.Y. Chen, "Experimental study on dynamic stability of rubber-cement composites by SHPB and high-speed slicing", *Archives of Civil Engineering*, vol. 68, no. 1, pp. 319–334, 2022, doi: 10.24425/ace.2022.140170.

[9] R. Yang, Y. Xu, J. Liu, J. Ding, and H. Xie, "Dynamic damage characteristics of two-dimensional flat plate of rigid-flexible coupling surrounding rock supporting structure under blast loading", *Journal of Central South University (Science and Technology)*, vol. 54, no. 6, pp. 2513–2528, 2023, doi: 10.11817/j.issn.1672-7207.2023.06.036.

[10] D. Zhang, "Study on preparation and thermal sensitivity of DDNP/PETN micro-initiating explosive", *Coal Mine Blasting*, no. 3, pp. 17–20+24, 2018.

[11] P. Zhao, "Study on the effect of pH on the diazo reaction of DDNP", *Coal Mine Blasting*, vol. 39, no. 2, pp. 9–12, 2021.

[12] J. Ge, "Experimental study on crack propagation of rock blasting under initial stress state", *Anhui University of Science and Technology*, 2021.

[13] K. Cao, Q. Fu, W. Ma, C. Zhang, C. Tang, and L. Zhang, "Study on the underwater anti-explosion mechanism and damage grade prediction of wall panels reinforced by corrugated steel-concrete slab composite structures with different wave heights", *Structures*, vol. 60, 2024, doi: 10.1016/j.istruc.2024.105922.

[14] J. Feng, S. Liu, H. Du, and H. Liu, "Quantitative prediction of ultra-deep tight sandstone fractures based on the theory of minimum energy dissipation", *Geoenergy Science and Engineering*, vol. 226, 2023, doi: 10.1016/j.geoen.2023.211749.

[15] X. Yao, Y. Yang, M. Zheng, J. Wang, C. Liu, J. Sun, and G. Wu, "Enhanced corrosion resistance of magnesium-neodymium alloy in simulated concrete pore solution by predesigned corrosion product", *Materials Today Communications*, vol. 32, 2022, doi: 10.1016/j.mtcomm.2022.104027.

[16] J. Mo, F. Ren, Y. Ye, S. Tian, and C. Lai, "Effect of different crumb rubber particle sizes on the flexural properties of crumb rubber concrete", *Materials Letters*, vol. 326, 2022, doi: 10.1016/j.matlet.2022.132960.

[17] R. A. Assaggaf, M. Maslehuddin, S. U. Al-Dulaijan, et al., "Cost-effective treatment of crumb rubber to improve the properties of crumb-rubber concrete", *Case Studies in Construction Materials*, vol. 16, 2022, doi: 10.1016/j.cscm.2022.e00881.

[18] R. Yan and Y. Xu, "Experimental study on dynamic compression behavior characteristics and stress wave propagation law of rigid-flexible combinations under cyclic bi-directional impact loading", *Journal of Materials Research and Technology*, vol. 25, pp. 925–945, 2023, doi: 10.1016/j.jmrt.2023.05.261.

[19] L. Qiao, M. Zhou, J. Yang, and Q. Li, "Experimental study on energy absorption of high damping rubber for rock under dynamic loads", *Chinese Journal of Rock Mechanics and Engineering*, vol. 37, no. 4, pp. 961–968, 2018, doi: 10.13722/j.cnki.jrme.2017.1096.

[20] J. Zhi, S. Wang, H. Wang, H. Lu, W. Lin, and C. Qiao, "Analysis on energy loss of rubber under dynamic load", *Acta Polymerica Sinica*, no. 4, pp. 708–715, 2017, doi: 10.11777/j.issn1000-3304.2017.16172.

[21] J. Zhi, H. Lu, H. Wang, et al., "Analysis on dynamic compression performance of tire rubber based on generalized Maxwell model", *Acta Polymerica Sinica*, no. 7, pp. 887–894, 2016, doi: 10.11777/j.issn1000-3304.2016.15332.

[22] Y. Xu, J. Liu, R. Yang, J. Ding, and K. Gu, "Mechanical properties and energy evolution of ultra high strength rubber concrete", *Journal of Building Materials*, vol. 26, no. 6, pp. 612–622, 2023, doi: 10.3969/j.issn.1007-9629.2023.06.006.

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