Study on Flexural Bearing Capacity of Reinforced Concrete Beams with Artificial Shell Aggregate

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Abstract. Two reinforced concrete beams with different reinforcement ratios are designed by using the formulas and assumptions of normal section flexural bearing capacity of ordinary concrete, and the static flexural tests are carried out. The coarse aggregate used in the reinforced concrete beam is artificial shell aggregate. The strain curves of concrete with different cross-section heights prove that the RC test beam accords with the assumption of plane cross-section in the bending process. The crack distribution and mid-span deflection curve trend of the test beam show that the crack develops rapidly and the deflection of the beam increases sharply before the reinforced concrete beam with artificial shell aggregate is destroyed completely, which gives obvious damage omen and is consistent with that of the ordinary reinforced concrete beam. The strain curve of the mid-span steel bar shows that the shell aggregate above the steel bar is crushed under a certain load after the mid-span longitudinal tension steel bar is yielded, the stress of the steel bar is released, the phenomenon of strain retraction occurs, and the possibility of the mid-span steel bar being pulled off is reduced. The results show that the mechanical properties of reinforced concrete of artificial shell aggregate used as coarse aggregate of structural concrete are similar to those of ordinary concrete and it is possible to use artificial shell aggregate in structural components.

Keywords. artificial shell aggregate, concrete beam, strain, Crack distribution.

1. Introduction
With the development of urbanization, the amount of concrete is increasing. However, the low strength and high density of the traditional concrete result in the self-weight of the building, which limits the development of the traditional concrete to a great extent [1]. In recent years, scholars began to study the application of lightweight aggregate and lightweight aggregate concrete in structural concrete [2-4], and many kinds of properties are studied [5-8]. The use of lightweight aggregate concrete reduces the weight and cost of buildings and can be used in long-span and high-rise buildings. In this paper, the coarse aggregate used in the preparation of reinforced concrete beams is shell silicate aggregate, which is the artificial aggregate prepared by the author. It is made by hydrothermal synthesis of a variety of industrial wastes at 180 ℃ [9]. The apparent density of the artificial aggregate is about 1500kg/m³, the bulk density is about 850-1500 kg/m³, the cylinder compressive strength is 15-20MPa, and the effective elastic modulus in concrete is about 27.85MPa. The lightweight concrete prepare by using the artificial aggregate as coarse aggregate. The strength of the concrete can reach 50-70MPa, and the density is 1800-2000kg/m³. The concrete is a brand-new concrete system, which is a new type of composite structure composed of steel bar, shell aggregate and mortar matrix to resist various external effects [10-11]. The proportion of flexural members is the largest among the
structural members, so it is very important to study the flexural bearing capacity of artificial shell aggregate reinforced concrete.

In this paper, the flexural bearing capacity of reinforced concrete beams with artificial shell aggregate is studied, which provides reference and research basis for the design basis, code and performance study of artificial shell aggregate reinforced concrete. The results show that the rationally designed artificial shell aggregate reinforced concrete can basically meet the performance requirements of the reference concrete, and it is feasible to apply it to civil engineering.

2. Design of Experimental Plan

2.1. Component parameters
The purpose of the test is to study the bearing capacity, crack propagation and deformation behaviour of artificial shell aggregate reinforced concrete beams. Simply supported beam is used in the experiment. The total length of the beam is 1000mm, the calculated span is 900mm, and the section size is 100mm×200mm. Two beams with different reinforcement ratios were prepared. The reinforcing bars are truncated in the flexural region. The flexural section of the beam is pure flexural section. Figure 1 is the reinforcement bars of the test beams.

Figure 1. The reinforcement bars details of test beams.

2.2. Experimental Methods
The specimen is loaded by two-point concentrated force, and a 300 mm pure bending section is formed in the middle of the span. The loading mode was continuously and multi-stage loading, each loading 5 KN, the time interval was 10min, loading until the specimen was destroyed. Pre-loading is performed before the formal loading, and the pre-loading is performed with Grade 2 load.

Figure 2 is the layout diagram of measuring points of the experimental beams. The strain gauges are uniformly arranged from top to bottom on the side of the pure bending section of the beam to measure the strain of the concrete in the middle of the span. Stick strain gauges on the surface of the steel bar and measure the strain of the steel bar. The dial indicators are arranged at the bearing, mid-span and loading point of the beam, and the deflection of the beam is measured. After each load, the cracks of the beam are observed, recorded, the development form of the cracks is recorded, and the distribution map of the cracks is drawn.

3. Results and Discussion

3.1. Calculation of Ultimate Bearing Capacity of Normal Section
The basic assumptions of bearing capacity calculation of test beams are based on the basic assumptions of ordinary reinforced concrete in “Code for Design of Concrete Structures (GB50010-2010)”. The ultimate bearing capacity of normal section and shear bearing capacity of oblique section are calculated according to “Code for Design of Concrete Structures (GB50010-2010)”. Theoretical calculations are shown in Table 1. The results show that the tensile reinforcement of A-beam is 2₁₁₄, and the ultimate bearing capacity of A-beam is 120.13 KN, the shear force in this time is 60.07 KN, the maximum shear force is 72.36 KN, and the maximum shear force is larger than the shear force of A-beam under flexural failure. Therefore, the A-beam is flexural failure of normal section. The tensile reinforcement of B-beam is 2₁₀, and the ultimate bearing capacity of B-beam is 63.53 KN, the shear force in this time is 31.77 KN, and the maximum shear force of B-beam is 72.36 KN, and the B-beam is flexural failure of normal section too.

| Beam  | P₁=P₂ (KN) | Max bearing force P₁+P₂(KN) | Shear force Vu(KN) | Failure form                      |
|-------|------------|-----------------------------|-------------------|----------------------------------|
| A-beam| 60.07      | 120.13                      | 72.36             | flexural failure of normal section |
| B-beam| 31.77      | 63.53                       | 72.36             | flexural failure of normal section |

3.2. Crack Distribution of Test Beam

During the bending process of the test beam, the crack development process of the test beam is recorded and depicted as shown in figure 3. From the observation of the experimental process, it was found that the micro-cracks appeared near the tension zone of the concentrated loading point at first, and then the micro-cracks appeared in the tension zone of the mid-span. With the increase of load, new micro-cracks appear at random. The pure flexural section are mainly vertical bending cracks in the test beam, and shear oblique cracks appear in the bending-shear section near the concentrated load. The shear oblique cracks extend from the middle to both ends. As that load approach the yield load, From the crack distribution diagram of the two beams, it can be seen that the crack trends of the front and back sides of the two beams are similar, with vertical bending cracks in the middle of the span and shear oblique cracks in the concentrated force, showing a good flexural failure mode, which is in line with the flexural failure mode of the normal section of the ordinary reinforced concrete beams.

![Crack Distribution of Beam](image)

Figure 3. Drawing of crack distribution of beams.

3.3. Deflection of Artificial Shell Aggregate Reinforced Concrete Test Beams

The load-mid-span deflection curve after bearing displacement is deducted according to the measured mid-span and bearing displacement under various loads as shown in figure 4. It can be seen from the...
figure that the overall trend of the load-mid-span deflection curve of the test beams is similar to that of the ordinary concrete beam. There are two inflection points in the load-mid-span deflection curves of test A-beam and test B-beam. The first inflection point occurs when the concrete is cracked in the tension zone, and the second inflection point occurs when the steel bar in the tension zone is yielding. At the beginning of loading, the test A-beam and the test B-beam are in the elastic stage, and the initial stiffness is close to each other. When the tension zone of concrete cracks, the first inflection point appears, then the section of the test beam moves upwards, the height of the compression zone of the section becomes smaller, and the stiffness of the section decreases. After cracking of concrete in tension zone, the slope of load-mid-span deflection curve decreases, and the stiffness of test A-beam with high reinforcement ratio is slightly larger than that of test B-beam. When the steel bar yielded in the tension zone, the second inflection point appeared. After the steel bar yielded out of the working state, the deflection of the test beam increased rapidly under the condition that the load did not change or the increase was very small, and the load measured by the sensor hardly increased, and the curve was close to the level. From the experimental results, the flexural strength increases with the increase of the longitudinal reinforcement ratio, which indicates that the ductility of the members increases with the increase of the reinforcement ratio.

Table 2. The maximum deflection of beams.

| Beam   | concentrated load -1 (mm) | mid-span deflection (mm) | concentrated load -2 (mm) |
|--------|---------------------------|--------------------------|---------------------------|
| A-beam | 3.384                     | 4.015                    | 3.494                     |
| B-beam | 2.375                     | 2.711                    | 2.396                     |

Table 2 shows the deflection of the experimental beam under yield load of steel bar. The maximum deflection in the middle span of A-beam is 4.015 mm, and that of B-beam is 2.711 mm. According to the Code for Design of Concrete Structures, the maximum deflection of flexural members should not exceed \( L_0/200 \) when reinforced concrete beams are used as roof, floor and staircase members. For the test beams in this paper, the calculated span \( L_0 \) is 900mm and the maximum calculated deflection is 4.5 mm. Therefore, the deflection of artificial shell aggregate reinforced concrete test beams meets the requirements of the Code.

3.4. Stress-Strain Curve of Artificial Shell Aggregate Reinforced Concrete

In order to verify whether the plane section assumption is suitable for the reinforced concrete test beam with the artificial shell aggregate, strain gauges are affixed in the middle of the test beam along the direction of section height, and the strain of concrete with different section heights is measured.
Figure 5 is a strain curve of concrete at different cross-sectional heights under different loads. It can be seen from the figure that the average strain of concrete is linearly distributed and the cross-sectional strain is kept in a plane state under various loads. From the actual measured results, it can be seen that the bending process of the reinforced concrete test beams with artificial shell aggregate basically conforms to the assumption of plane cross-section. As can be seen from figure 5, the neutral axis of the test beam is not always in the center of the section under the action of the load, but gradually moves upward with the increase of the load. At the beginning of loading, the neutral axis of the test beam is at the height of 100 mm. With the increase of loading, the final neutral axis height of A-beam is about 132 mm, and that of B-beam is about 141 mm. It can also be seen from figure 5 that when the load of the A-beam reaches 60 KN, the tensile zone of the concrete in the middle of the span is cracked and the strain gauge at the bottom is broken. When the load of the B-beam reaches 50 KN, the tensile zone of the concrete is cracked in the middle of the span, and the cracks are longer, and the two strain gauges below are both broken.

3.5. Stress-Strain Curve of Reinforcement Bar
Figure 6 is the strain-load curve of the reinforcement bar in mid-span. It can be seen from the figure that the strain of the reinforcement bar in the A-beam is linearly related to the load before the steel bar yielded. With the increase of load, the concrete in tension zone cracks out of work, the section stress of the test beam is borne by the reinforcement bar, the reinforcement bar strain increases obviously, and there is an obvious turning point in the strain-load curve. When the load reaches 140 KN, the strain of the steel retracts. There is no obvious yield stage of steel bar in the B-beam, and the steel bar strain retracts at 90 KN. Figure 7 is the strain-load curve of the tensile reinforcement bar under concentrated load. The trend of strain-load curve under concentrated load is basically consistent with that at mid-span. The reinforcement bar under concentrated load also has yield stage, and there is no strain shrinkage of reinforcement bar.
The reason for the strain retraction of the reinforcement bar in the middle span is that the interface strength between the artificial aggregate and the mortar matrix is very strong, the cracks penetrate through the aggregate in the artificial shell aggregate concrete. As the load increases, the crack width gradually increases, and the stress and strain of the reinforcement bar also increases. The artificial shell aggregate contact with the steel bar in the region above the steel bar is crushed (region A of figure 8), leaving a space in the region above the steel bar, releasing the stress of the steel bar, and causing the steel bar strain to retract. This is quite different from the ordinary reinforced concrete beam, the stress release of the steel bar reduces the possibility of the steel bar being broken in the middle of the span.

(a) A-beam  
(b) B-beam

Figure 6. The strain-load curve of the reinforcement bar in mid-span.

Figure 7. The strain-load curve of the tensile reinforcement bar under concentrated load.

Figure 8. Aggregate crushing area above mid span reinforcement.
4. Conclusion
The coarse aggregate used in reinforced concrete beams is artificial shell silicate aggregate, which is different from ordinary concrete aggregate. Aggregate of ordinary concrete is hard phase in concrete, and silicate aggregate of shell is soft phase. In the bending process of the normal section of the test beams, the phenomenon and strain-load curve of reinforced concrete beams reinforced with artificial shell aggregate are similar to those of ordinary concrete beams, which indicates that the calculation of ultimate bearing capacity of normal section and shear bearing capacity of oblique section of ordinary concrete beams in the Code for Concrete Structures is also suitable for artificial shell aggregate reinforced concrete systems.

The experimental results show that the test beam is in elastic deformation stage before loading to cracking, and the deflection, concrete strain and steel strain increase linearly. When the load reaches a certain value, shear oblique cracks appear in the attachment of concentrated force loading, and vertical cracks appear in the pure bending section. After the cracks appear, the rigidity of the beam decreases, the number of cracks increases, the deflection, concrete strain and steel strain continue to increase, and the performance of the artificial shell aggregate reinforced concrete test beam with cracks is relatively stable in the working stage. As the load continues to increase, the reinforcement enters the strengthening stage, showing the characteristics of plastic deformation, the strain of reinforcement increases rapidly, the load-deflection curve enters the second inflection point, the deflection curve approaches a straight line, the crack increases rapidly and the width widens rapidly.

In the strain-load curve of the reinforcement bar in mid-span, it is found that when the load increases to a certain extent, the reinforcement bar stress retracts, which is different from that of ordinary concrete beams with suitable reinforcement bars. The reason is that the properties of the coarse aggregate are different, the artificial shell aggregate above the mid-span tensile steel bar is crushed by the reinforcement bar, the stress of the reinforcement bar is released, and the strain is reduced, which has the advantage of avoiding the mid-span tensile reinforcement bar from being broken due to excessive stress and strain.

Acknowledgments
Supported by the funding program for major disciplines academic and technical leaders of Jiangxi provincial in 2017(NO:20172BCB22022), the key project of advantageous science and technology innovation team of Jiangxi province in 2017(“5511”project) (NO:20171BCB19001),the key science and technology research project in Jiangxi province department of education(NO:GJJ151096), the Jiangxi province education department of teaching reform project(NO:JXJG-18-18-16), Nanchang Institute of Technology teaching reform project(NO:2018JG037).

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